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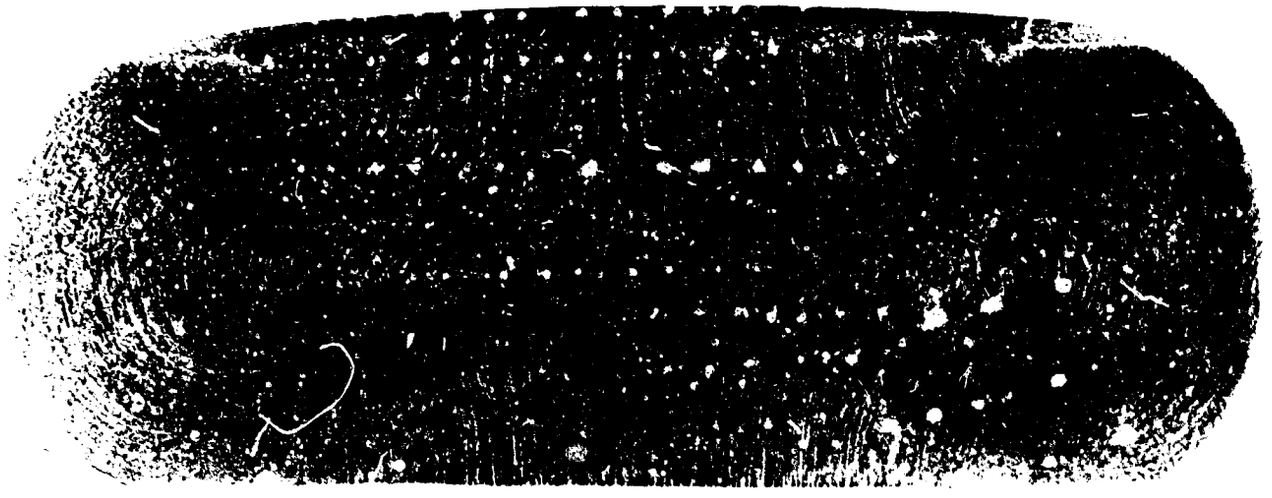
METAL DEFORMATION PROCESSES: FRICTION AND LUBRICATION



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Techniques of Fractional Solidification

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344 pages, illustrated

The contributors of *Purification of Inorganic and Organic Materials* explore the most important methods for characterizing and storing pure organic and inorganic chemicals. The realization that techniques such as zone melting, progressive freezing, and column crystallization are now available for the production of chemicals with hitherto unattainable purity, has captured the imagination of the chemical industry. This book is valuable to the chemist, chemical engineer, and metallurgist, serving the needs of both the researcher and the engineer.

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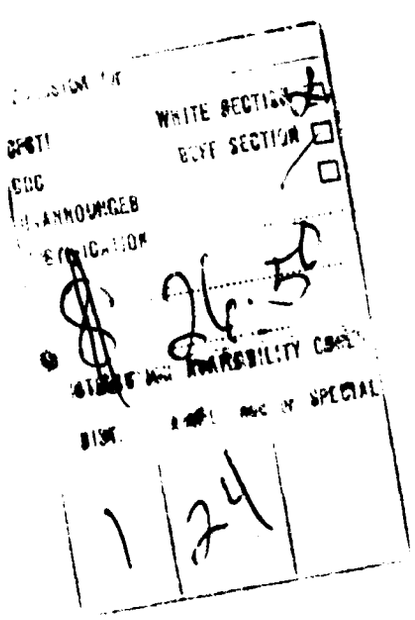
about the book . . .

Progress in the field of metalworking lubrication technology has been limited because of a lack of communication between specialists in lubrication and metalworking. In response to the need for a systematic text dealing with this interdisciplinary subject, the Air Force Materials Laboratory of the Air Force Systems Command sponsored work on a monograph of metalworking lubrication.

This book is the result of the Air Force project. For the first time a comprehensive treatment of all aspects of friction and lubrication in metal deformation processes is presented. The text deals with both theoretical and practical connotations of the subject, gives a detailed review of published work, and concludes with an appraisal of theories, experiments, and practical experiences pertaining to various processes.

The book is addressed to a broad audience. Metallurgists, mechanical engineers, chemists, physicists, and production engineers will find the systematic and broad coverage of both fundamentals and applications to be of great help in all facets of this multidisciplinary subject.



about the editor . . .

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Dr. Schey is a Fellow of the Institution of Metallurgists, London, a member of the Institute of Metals, London, and belongs to the American Society for Metals, and Sigma Xi.

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Metal Deformation Processes / *Friction and Lubrication*

MONOGRAPHS AND TEXTBOOKS IN MATERIAL SCIENCE

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1. METAL DEFORMATION PROCESSES: FRICTION AND LUBRICATION
Edited by John A. Schey

OTHER VOLUMES IN PREPARATION

METAL DEFORMATION PROCESSES

FRICTION AND LUBRICATION

Edited by

JOHN A. SCHEY

UNIVERSITY OF ILLINOIS
AT CHICAGO CIRCLE
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1970

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Fig. 11.3 Dr. D.V. Wilson, University of Birmingham, England.

PREFACE

The importance of friction and lubrication in deformation processes such as rolling, wire drawing, extrusion, forging, and sheet metalworking has long been recognized by those practicing these processes. Although substantial advances have been made largely on an empirical basis, the need for a more systematic approach has become evident in the last two decades. Progress in this direction has, however, been rather slow, mainly because the subject does not fit conveniently into any of the established, classical scientific disciplines. Metal deformation processing itself is the domain of specialists working on the borders of metallurgy and mechanical engineering; metalworking lubrication necessitates a further involvement in fields traditionally cultivated by chemists and physicists.

In 1962, an ad hoc committee of the Materials Advisory Board of the National Academy of Science was organized for providing guidance to the Metalworking Processes and Equipment Program (a coordinated effort of the Army, Navy, Air Force, and NASA). This Committee identified the lack of communication between specialists in lubrication and specialists in metalworking as one of the prime factors limiting metalworking lubrication technology. The absence of a systematic text dealing with various aspects of this interdisciplinary subject presented a serious difficulty in establishing wider communication; consequently, the Air Force Materials Laboratory of the Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, sponsored —through its Contract AF33(615) - 5342 with IIT Research Institute—work on a monograph of metalworking lubrication, with particular emphasis on aerospace materials.

The interdisciplinary nature of the subject is reflected in the composition of the group engaged in this project. Chapters 3 and 4 were written by

Dr. C. H. Riesz, Senior Chemist, IITRI; Chapters 8 and 9 by Professor S. Kalpakjian, Associate Professor of Mechanical Engineering at Illinois Institute of Technology; and Chapters 7, 10, and 11 by Dr. J. A. Newnham, Assistant Manager of Metalworking, IITRI (now with SPS International, Shannon, Ireland). The task of coordinating the project, editing the text, and writing Chapters 1, 2, 5, and 6 fell to me, at that time Metallurgical Advisor at IITRI (now Professor of Metallurgical Engineering at the University of Illinois at Chicago Circle). In the course of writing it became evident that a monograph dealing almost exclusively with aerospace materials would be of rather limited utility and, consequently, our team undertook to expand the effort and present a comprehensive treatment of the entire field, including friction and lubrication in the deformation processing of the more common materials.

The subject of metalworking lubrication is, all too frequently, a controversial one, and in writing this text some occasionally arbitrary decisions had to be taken. I have endeavored to assure a unity of outlook and a continuity of presentation, and I am grateful to my colleagues in this venture for their willing cooperation.

Material was collected from the open literature, including Government reports. Periodicals have been systematically searched up to and including the year 1967; the most important publications of 1968 have also been reviewed whenever possible. The secrecy surrounding industrial lubrication practices resulted in a rather disappointingly meager return of questionnaires sent to companies engaged in metalworking and in the manufacture of lubricants. We are all the more indebted to those few who provided meaningful information.

Special mention must be made here of the contribution of two colleagues. Dr. G. W. Rowe of the University of Birmingham, England, critically read the entire draft and offered countless helpful suggestions for improvement and additions, most of which were incorporated in the final manuscript. Miss Violet Johnson of IITRI read and corrected, with infinite patience, the entire manuscript.

I would like to express here our thanks to Mr. Vincent DePierre of the Processing and Nondestructive Testing Branch, Metals and Ceramics Division, Air Force Materials Laboratory, who directed the project and offered stimulating discussion and helpful criticism; to Mr. T. D. Cooper,

Head of the aforementioned Branch, and to Dr. N. M. Parikh, Director of Metals Research Division, IITRI, for their interest, encouragement, and support. We are also indebted to Mr. R. P. Daykin of Ladish Company, Cudahy, Wisconsin, for helpful suggestions on Chapter 9. Our acknowledgments would not be complete without expressing gratitude to our wives for their understanding and patience. My wife helped me greatly in attending to the many tasks connected with bringing this book into print.

The original project objective called for the production of an authoritative monograph, to serve both as a textbook and a reference. The reader will have to decide how far short of this objective the final product fell. I hope that a future updating will also permit improvements and rectification of omissions; suggestions in these directions will be most gratefully received.

John A. Schey

Chicago, Illinois
1969

NOTATION—RECURRENT SYMBOLS

A	area (cross-sectional)
A_r	real area of contact
A_a	apparent area of contact
b	width
B	back tension (force)
C	constant; specific heat
d	diameter (of wire, extruded bar, deep drawing punch)
D	diameter (of extrusion billet, sheet blank)
E	Young's modulus
f	friction angle ($\tan f = \mu$)
F	frictional (lateral, tangential) force
G	shear modulus
h	height, thickness
J	mechanical equivalent of heat
K	constant
l	length, distance
L	length of contact between die and workpiece
m	multiplying factor for interface shear strength ($\tau_i = m \tau_o$)
N	speed (rpm)
p	normal stress, interface pressure
$\bar{p}$	average interface pressure
p_m	yield pressure (indentation hardness)

P	applied load, normal force
r	reduction (in height or in area)
R	Radius
R_E	extrusion ratio
S	die separating force
S_f	forward slip
t	temperature °C; strip tension in rolling
T	absolute temperature °K; torque
v	velocity (ips, fps, or fpm)
V	volume
W	work, work of adhesion
Z	viscosity
α	entry angle in rolling; die half-angle; multiplying factor
β	half-angle of draw mandrel or plug; multiplying factor
γ	surface energy
ϵ	natural (logarithmic) strain
η	absolute viscosity (poises; centipoises cp)
θ	angle; angle of contact in wetting
λ	position of neutral plane in rolling as a fraction of L
μ	coefficient of friction
ν	Poisson's ratio; kinematic viscosity (stokes; centistokes, cs)
ρ	density
σ	normal stress
σ_o	yield strength in uniaxial tension or compression
σ_m	average uniaxial yield strength during deformation
τ	shear stress

τ_o	yield strength in shear
τ_i	interface yield strength
τ_m	average shear strength of welded asperities
ϕ	redundant work factor in wire drawing
ϕ_o	neutral angle in rolling

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Chapter 1

BACKGROUND AND SYSTEM OF APPROACH

John A. Schey

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1.1 HISTORICAL BACKGROUND

Metalworking is probably the earliest technological occupation known to mankind; native metals must have been forged and shaped more than 7000 years ago. Considering the importance of lubricants in deformation processes, it is rather amazing that no account of their use can be found until relatively recent times.

There are, perhaps, three main reasons for this anomaly: first, the composition, manufacture, and use of lubricants were—and to some extent, still are—closely guarded secrets of the whole operation. Second, nature very kindly provided some of the best lubricants known even today, so that the artisan engaged in metalworking did not have to rely on the skills and knowledge of other crafts, arts, or sciences; he was not compelled to reveal his practices, and the nonexpert observers reporting on metalworking processes failed to grasp the significance of the little they may have been allowed to see. Third, lubricants must have assumed a vital role only at a relatively late stage of development, as the following brief review will show.

1.11 Forging

There is little doubt that forging was the first and, for a long time, the only bulk deformation technique. Native gold, silver, and copper were hammered into thin sheets and then shaped into jewelry and household utensils as early as 5000 B. C. [1]. These metals, and later copper reduced from ores, were readily cold worked without a lubricant. Some unintentional lubrication may have occurred—for instance, when sheet was driven into asphalt for shaping or placed between animal skins for thinning down to metal (gold) leaf. Copper was annealed around 4200 B. C. [2], and hot forging must have soon followed. Copper oxide is a good parting agent, as is the oxide of iron, which was worked with great skill by the Hittites in the 13th century B. C.

Iron became the dominant material for weapons, tools, and agricultural implements from 800 B. C. on, replacing the cast bronze that dominated earlier centuries [3]. This marks the ascendancy of the blacksmith, with his Greek god Hephaistos [4]. The cold forming of metals, neverthless, continued uninterrupted. Cast bronze forms were used for drawing decorative parts from sheet, and the first known coin was driven into such a form with several punch strokes in the 7th century B. C. Again, no reference to lubricants is known and it is probable that natural contaminants, even if only from greasy fingers, provided all that was needed.

One must not forget, though, that seed oils, animal oils, tallow, and waxes were available in early antiquity [5]; Egyptians used them for the lubrication of skids on which their colossal statues were moved. In the 5th century B. C. Herodotus already wrote about the extraction of bitumen and light oil from petroleum, and Pliny the Elder (about A. D. 60) described the manufacture of soap [6]. Soap was actually identified as the axle lubricant of an Egyptian chariot dated about 1400 B. C. [5]. Thus, at whatever point of development the first lubricant may have been used, a variety of eminently suitable substances certainly must have been available.

Forging continued to be the dominant metalworking process for many centuries. Coin pressing achieved high standards under the Romans who shaped the blank from both sides with a hand punch of suitable profile into a counterforming die [3]. The first forgings made in closed dies were found in the northern Germanic areas, where local iron ores yielded higher carbon iron and, therefore, better weapons. Chain mail was probably first made there and, while the starting material would ideally be drawn wire, it is now

generally conceded that this wire was actually forged in swaging dies. Cast bronze anvils survived from the bronze age with indentations that served probably for the forging of needles, and the gold- and silversmiths had no problem in shaping their precious metal into decorative wire. The drawing of wire through dies is a later art, and it is the one that almost certainly led to the first conscious use of metalworking lubricants.

Forging is, nevertheless, the only hot working process that can claim a long history of lubrication. Steel rifle parts were forged in die impressions for interchangeability as early as the 18th century [3]; lubrication practices were probably not too different from those found even today, with sawdust, a thin smear of a heavy oil (cylinder oil), or oil mixed with graphite serving as a lubricant.

1.12 Wire Drawing

The argument on the earliest date of wire drawing is still not settled. There is no doubt that it was practiced in the 11th century, since Theophilus, writing in the 11th [7] or early 12th [8] century treats wire drawing as an established art. He refers to steel dies used for drawing a tin-lead alloy, and to oak dies for smoothing hammered gold and silver wire. Iron and steel plates bearing a number of holes, connected with a surface channel, have been identified by many researchers as drawing dies, on the assumption that the surface channel served for retaining the lubricant [9]. The earliest such finds date back to the first century A. D. and, if the interpretation of the channels is correct, these would provide circumstantial evidence of the use of metalworking lubricants for two millenia.

Guilds of wire drawers were registered and regulated as early as the 13th century [10], and water power was introduced in the 14th [11]. Yet, the first written reference to wire drawing lubrication is of much later date. Biringuccio [12], writing of drawing gold and silver wire, admonishes to "remember that while you are working it you must always keep it greased with new wax, for besides easing its passage through the holes, this also keeps its color yellow and beautiful." Rather casual references to oil-soaked rags, applied to the iron wire before it entered the draw die, were made by early 18th century observers [7]. It is likely that the lubricant was a locally available product, probably lard oil in the north, vegetable oils in the south of Europe [5]. Records show that olive oil was imported into Altena, the

center of the German steel wire drawing industry, far in excess of any conceivable household needs, and it is reasonable to assume that this was used for drawing the highest grade iron and, later, steel wires [10].

It was in Altena that the first surface treatment was discovered. For many centuries the wire was prepared for drawing by hand scouring it with bricks or sand, and it was only in the 17th century that bundles were mechanically threshed with a waterwheel, with frequent dashes of water and sand [10]. With the usual grease or oil lubrication, it was possible to draw the clean rod, but only if made of the softest, best quality Osmund iron. Steel, while known to be superior for many applications including needles, fish hooks and the like, could not be drawn presumably because high friction caused the wire to break. It remained for one Johann Gerdes to discover the value of a surface treatment around 1650, the story being recorded by a wandering minstrel only a few years later. As related by Lewis [10], after an unsuccessful effort Gerdes threw the steel rods out of the window, into the area where "men came to cast their water." After a while, he retrieved the rods and—without bothering to remove the soft, brown film that formed on them—found that they now drew with great ease. This orginal sull-coating technique was used for almost 150 years. Then dilute sour beer was found just as effective, and in another 50 years it was recognized that plain water would serve equally well, although the original technique has survived in some places until this century.

Prior to the introduction of sulfuric and hydrochloric acids, light scale was removed or softened on the wire surface by lengthy immersion in weak solutions of tartaric acid, brewers yeast, or similar organic liquids. Acid cleaning was first used for iron sheet in the early 19th century. Pickling, lime coating, and baking were developed for steel wire in the middle of the 19th century when large quantities of signal wire were demanded by the expanding railroad networks.

Wet drawing practices employing oils, emulsions, or greases as lubricants remained dominant in Europe until recent years, and were often aided by the deposition of a thin copper or copper-tin coat on the steel wire by drawing from baths containing copper sulfate. Like so many innovations, this too was a result of accident; the coating was observed to develop when hot brass ingots were used for warming up an acid pickling bath [13]. While thin steel wire was drawn wet with a copper-tin coat, dry drawing with a

soap was the main production technique for heavier gages in the U. S. [7] but found general acceptance in Europe only in the last few decades. The latest change affecting lubrication in wire drawing came with the introduction of the sintered tungsten carbide die in 1923 [11] and phosphate coating of steel in 1934 [14].

1.13 Rolling

Rolling lubricants, which now occupy such an important position, have a much shorter history. Rolling itself was first applied to metals in the cold working of lead and gold in the 15th century [4], and for narrow strips of coinage alloys in the 16th century [2]. The first sketch of a mill is due to Leonardo da Vinci. The 17th century saw the appearance of the slitting mills in which forged flats were split with collared rolls, then rounded by forging and finally drawn into wire. Grooved rolls were used in 1728 in France by a M. Fleuer some 60 years before they were patented by Henry Cort in England. To quote Lewis [15], "these early ironmasters never scrupled to make use of a process many years before it had been invented." Nevertheless, it was another hundred years before wire rod was regularly rolled, and Bedson's continuous mill appeared in Manchester in 1862 [16]. Rounds and sections, however, always were and still are rolled without any lubricant, and we must look to the rolling of sheet to trace the development of lubricants.

Sheet was traditionally hammered from a cast ingot, with up to 50 layers forged in a pack for tinplate [4]; rolling had to wait until rolls could be turned accurately. Wide lead sheet was rolled in the 18th century, and nonferrous metal sheets were soon cold rolled in gradually increasing widths. However, lubrication requirements of copper and copper-base alloys were relatively modest and, until well into this century, an occasional smear with a lubricant of jealously guarded composition was sufficient. The lubricant was usually based on mineral oils (available in quantity since 1860) and compounded with animal and vegetable fats and oils. The cold rolling of aluminum sheet, gaining prominence in the 20th century, presented probably the first challenge of developing lubricants on a more systematic basis. Light mineral oils chosen for their low staining propensity, sometimes compounded with a small quantity of additives such as lanolin, were soon found to be adequate for the low speeds then employed.

Until the same period, steel was rolled cold in relatively narrow widths at low speeds, for which cooling with water and a rather marginal lubrication with some heavy and possibly contaminated mineral oil sufficed. Wider plate was hot rolled in the mid 18th century, while thin sheets were hot rolled in packs and thus needed no lubricant at all [4]. The first continuous wide strip mill which was built in Teplitz (at that time, Austria) in 1892 made little impact, but the hot rolling of wide strip became general practice after the success of Townsend and Naugle's plant at Columbia Steel Company, Pennsylvania, in 1926 [17, 18]. In the same year, the Revere Copper and Brass Company of America introduced the tandem cold mill, soon followed by similar mills for steel and some years later for aluminum.

Tinplate had its beginnings in the early 14th century in Germany [19]. As with all sheet, it was first forged (hammered) and, in the 18th century, rolled. Finally, hot rolling in packs was established around 1790. The increasing consumption of tinplate promoted the installation of wide strip mills for cold rolling. These first presented a serious problem, because the usual mineral oil based lubricants proved completely inadequate. An inspired guess by A.J. Castle [20] in 1930 resulted in the immediate acceptance of palm oil—previously used on tinning lines—as a rolling lubricant. It spread from the U.S. to all parts of the world and is still a lubricant of recognized quality. High rolling speeds also created a substantial problem of roll heating, and water—applied either separately or in the form of an aqueous dispersion or emulsion—gained in importance.

1.14 Extrusion and Other Processes

Lubrication techniques in other cold metalworking operations such as tube drawing, deep drawing, and cold heading usually drew upon experience gained in wire drawing and rolling, although a good deal of interaction must have existed. By and large, highly viscous oils, greases, fats, and soaps, often fortified with filler materials, were chosen for low-speed deformation at high reductions and lower viscosity or aqueous lubricants for lighter duties.

Extrusion was a relative latecomer among the metalworking processes. Like so many others, it was first practiced on lead [21]. Joseph Bramah patented a tube extrusion press in 1797; copper and its alloys had to wait until 1894, when Dick successfully extruded brass. Lubrication was and is

important, but simple oils and graphited mixtures were found acceptable. A complete absence of lubricants was found to assure the best quality extrusions in aluminum.

Two of the most significant lubricant developments occurred during World War II. The phosphate conversion coating was adopted in Germany for severe cold deformation (such as drawing and extrusion) of steel, and glass pad lubrication was successfully developed in France for the hot extrusion of steel. These are, however, developments that bear upon present-day practices and will be discussed in more detail in the appropriate chapters dealing with metalworking lubrication.

1.15 Theory

The reader will note that until about 30 years ago most of the noteworthy developments in metalworking lubrication came about by accident, inspiration, or, at best, as a result of persistent experimentation. Nevertheless, some theoretical background for a more systematic approach has been available for a considerable time. Leonardo da Vinci recognized the basic law of friction in 1508 [22] which was then rediscovered by Amontons in 1699 [23]. Since then, the concept of a coefficient of friction has been adopted, but almost a century passed before Coulomb [24] developed a theory postulating that friction was due to both surface roughness and adhesion. Another hundred years later, at the end of the 19th century, the principles of the hydrodynamic theory of lubrication were developed by a number of scientists, all working within a time span of 20 years [25]. Boundary lubrication, which plays such an important role in metalworking processes, was closely investigated by Hardy [26] in the years 1919-1933, and his work is still a foundation stone of present knowledge. Development of theories relating to dry and lubricated friction had to await the forties, when research centers devoted entirely to this subject formed around leading scientists in a number of countries. The science of friction, lubrication, and wear (tribology) is being recognized as a discipline of its own, although it is still practiced by researchers trained in related classical disciplines. It is customary, therefore, to refer to tribology as an interdisciplinary science.

It is evident from this brief survey that the theoretical background that could have influenced metalworking lubrication development was rather weak until relatively recently. The first measurements of friction in deformation

processing date from the late twenties and form properly the subject matter of later chapters. Elemental and sometimes rather obscure theories were often drawn upon for explaining lubrication effects, as is evidenced by the otherwise excellent chapter on lubrication in the book on wire drawing by Bonzel [27]. Detailed theories relating the effects of friction to the distribution and magnitude of forces and power requirements are also young, dating back to the early twenties.

1.16 Summary

We have seen that natural lubricants (mostly fats and fatty oils) or their modifications obtained through design or accident provided satisfactory lubricants for most purposes until recent times. On prolonged standing or in continued use, many fatty substances develop free fatty acids, later recognized as being among the most useful boundary lubricants. Favorite lubricants or lubricant combinations were often made to work by sheer persistence and by adjusting process conditions until optimum results were obtained. However, a need for a more systematic approach became increasingly evident from the forties on. More powerful drives permitted increased production rates, heavier reductions, higher speeds, and imposed more severe conditions on the lubricant. New metals that were introduced to satisfy the needs of the developing aerospace, chemical, and electronic industries often had properties quite different from the more common metals previously used, and have presented some of the most difficult lubrication problems. This resulted in an unprecedented upsurge in interest, experimentation, and analysis; in consequence, this book is largely a digest of developments since World War II.

1.2 SYSTEM OF DISCUSSION

This book attempts to fulfill a dual role: that of a textbook for the novice and a reference book for the specialist. In order to accomplish these purposes, fundamental information bearing on metalworking lubrication is discussed first, followed by specific surveys of individual processes. We have earlier stated that the subject is a truly interdisciplinary one, and this is reflected in the next three chapters.

Chapter 2 on "Friction Effects in Metalworking Processes" deals with selected elements of the theory of deformation processes—in particular,

with the effect of friction on forces, power requirements, strain and velocity distribution, as well as with the process limitations set by friction.

Chapter 3 on "Friction, Lubrication, and Wear Mechanisms" presents a survey of concepts developed from fundamental research on friction, lubrication, and wear. Most of this work relates to bodies in elastic contact, since hardly any fundamental research relevant to bulk deformation was carried out until recently. Nevertheless, application to deformation processes is highlighted whenever possible.

Chapter 4 on "Lubricants" discusses the basic properties of lubricants, with particular emphasis on substances that find widespread use in metalworking processes. This chapter is still preparatory in a sense that it deals with general classes of lubricants rather than formulations for any particular metalworking purpose.

The background provided by the above chapters allows a systematic discussion of "Lubricant Properties and Their Measurement" in Chapter 5. This chapter draws freely on concepts of the theory of deformation processing, and a familiarity with basic lubricating mechanisms is assumed. It also discusses some of the very important side effects of lubrication and friction, such as wear of the die or workpiece material, surface finish of the deformed product, and staining appearing on the surface after deformation—all of them aspects of great importance but not necessarily amenable to a quantitative treatment.

Subsequent chapters present a detailed, critical survey of present knowledge on metalworking lubrication, grouped according to the deformation process. While the detailed subheadings in each chapter are dictated by the subject material and, therefore, are not identical, a general plan is invariably adhered to: a discussion of friction and lubrication phenomena of general validity is followed by a survey of the applicable lubricant classes. Finally, specific experiments and published work practices relevant to the main classes of industrially important workpiece materials are given.

The best sequence for treating the great variety of metalworking processes is always open to some argument. Depending on the point of interest, processes are often divided into hot and cold, primary and secondary, or large-scale and small-scale techniques. For a treatment of lubrication, none of these subdivisions offer any special advantage. The mode of contact between tool and workpiece material surfaces and the continuous or

repetitious nature of contact are much more important. Therefore, the essentially steady-state processes of rolling (Chapter 6) and wire drawing (Chapter 7) are discussed first, followed by the batch processes of extrusion (Chapter 8), forging (Chapter 9), and sheet metalworking (Chapter 11), in which the steady-state element decreases in this same order. However, the deformation temperature does have a significant bearing on lubrication practices; therefore, a further subdivision is made, whenever warranted, into hot and cold working techniques. In particular, it was found necessary to discuss cold forging and cold extrusion lubrication separately in Chapter 10, while general observations on frictional effects are included in Chapters 8 and 9, dealing with lubrication in hot extrusion and hot forging, respectively. The technology of various processes is also touched upon very briefly in these chapters, if only for the purpose of clarifying the usage of specialized terms.

In choosing an appropriate system of notations and units of measurements, U. S. usage was normally followed. Temperatures are generally given in degrees Celsius. Only viscosities are quoted in a variety of units, as they occur in the original references. An appropriate conversion graph will be found in the Appendix.

It should be noted that Chapters 2 through 4 are meant to provide a background and, as such, present a digest of information relevant to the topic of lubrication in deformation processing. In order to facilitate further reading on the subject, books and review articles are cited as references whenever possible. It is hoped that these chapters will be found adequate for most nonspecialists as an introduction to the subject.

The text beginning with Chapter 5 aims at a complete coverage of relevant information, and a serious effort has been made to include all important references pertaining to the field. This meant that a great mass of scattered information and references had to be brought together and treated in a systematic fashion. The rather diffuse nature of the subject material made it mandatory that some arbitrary decisions be made regarding the best method of treatment, and available information had to be fitted into this framework. Topics covered in one publication may be discussed under various headings for the sake of uniform treatment; references are always collected at the end of each chapter.

In order to provide some guidance for the nonspecialist, it was also required to apply a critical treatment, pointing to strengths and weaknesses of various approaches. Such judgment necessarily involved personal views; great care has been taken to separate—by unequivocal wording of the text—the views of the original authors from those attributable to the writers and editor of this book. It is hoped that such treatment will preserve the value of the book as a reference source, even though some of the judgments are bound to become outdated by new information coming to light in the course of future research.

An obvious alternative method of discussion would be the treatment of each individual deformation process in its entirety. This would have meant grouping the effects of friction, techniques of measuring friction, and specific lubricants in chapters devoted to rolling, wire drawing, etc., making it easy reading for those concerned only with a single deformation process. However, in choosing this method, the opportunities of showing unifying concepts would have been lost. In particular, lubrication concepts and techniques of proven value in any one metalworking process could often be applied to other processes; it is all too obvious that narrow specialization can lead to unnecessary duplication of effort. Therefore, it was felt that the benefit of the broader treatment outweighs the advantages of the narrower, more specialized approach. This also means that the text should be at least scanned through in the sequence as presented, even if only some of the deformation processes covered are of deeper interest; it is hoped that this will not prove an obstacle to the reader.

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Note added in proof:

Since the completion of the manuscript, the following books have appeared that many readers will find useful:

Boundary Lubrication; An Appraisal of World Literature, American Society of Mechanical Engineers, New York, 1969.

J.J. O'Conner, ed.-in-chief, Standard Handbook of Lubrication Engineering, McGraw-Hill Book Co., Inc., New York, 1968.

P.M. Ku, ed., Interdisciplinary Approach to Friction and Wear, NASA SP-181, Washington, D.C., 1968.

Chapter 2

FRICTION EFFECTS IN METALWORKING PROCESSES

John A. Schey

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Lubricants are called upon to fulfill a number of functions. The bulk of existing knowledge relates to their ability to reduce friction, which, in turn, lowers forces and energy requirements and permits greater deformations to be taken with available equipment. From the practical point of view they may have more important functions: to govern the surface quality of the finished product, and to reduce, control, or eliminate pickup of workpiece material on the tool surface, wear of the die, and scoring of the finished product. Lubricants may also contribute to the success of the operation by preventing heat loss from a hot workpiece, by insulating the die from the heat of the workpiece, or by cooling the workpiece and die that would otherwise heat beyond acceptable limits because of the heat of friction and deformation.

Of all lubricant functions, that of reducing friction is most readily measured and theoretically analyzed. Some critics of metalworking lubrication research regard the concentration on friction measurements as an obsession, and point out that wear or surface finish may be far more important in some practical applications. While the basis of this criticism is valid, it should be recognized that friction alone is readily measurable and amenable to a quantitative or semiquantitative treatment at the present time. Therefore, this chapter will be devoted exclusively to a systematic examination of the effects of friction on forces and material flow in metalworking processes. This will be done with reference to elements of plasticity theory that enable us to assign numerical values to complex interactions. The purpose of this

chapter is not to present a summary of the theory of deformation processing; rather, it is to develop an understanding of what plasticity theory can offer in interpreting lubricating effects. The reader interested in the theory of deformation processing is referred to a number of excellent treatments available [1-12].

2.1 PLASTIC FLOW AND INTERFACE FRICTION

Before any meaningful discussion of frictional effects can be embarked upon, it is important that some of the basic terms generally used in plasticity theory should be unequivocally defined.

2.11 Plastic Yielding

First of all, it should be recognized that plasticity theory takes a simplified, mechanistic view of metalworking processes. It normally assumes that the deforming material is continuous, homogeneous, and isotropic. Greater simplicity of treatment is achieved if the material is also assumed to behave as a rigid/perfectly plastic (non-hardening) substance. This means that the material shows no elastic deformation but suddenly begins to deform plastically when the yield criterion is satisfied. In simple tension or compression this occurs when the uniaxial yield stress of the material σ_0 (also denoted by Y in the British and by k_f in the German literature) is reached. It is then assumed to continue to flow at the same stress (Fig. 2.1a). Of course, all real materials first suffer elastic deformation and—especially in cold working—also strain hardening, leading to a continuous rise in the

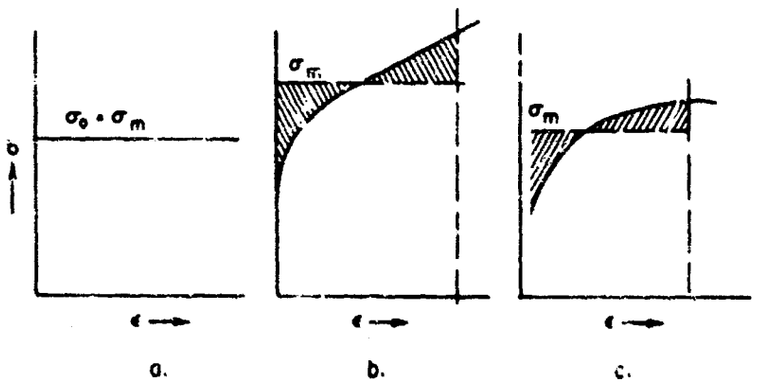


Fig. 2.1. Some typical stress-strain curves: (a) ideal rigid-plastic material, (b) cold working, and (c) hot working.

yield stress (Fig. 2.1b). The ideal, perfectly plastic behavior is sometimes approximated in hot working (Fig. 2.1c) or by some heavily strain-hardened metals (e.g., aluminum) in cold working.

The deforming workpiece material is subjected to an often rather complex combination of compressive, tensile, and shear stresses; these can be reduced to three (compressive and/or tensile) principal stresses. Plastic flow sets in only if the stress state satisfies the yield criterion. The yield criterion of Tresca states that yielding occurs when the difference of the maximum and minimum principal stresses reaches σ_0. The more accurate and generally used von Mises criterion takes also the intermediate principal stress into consideration.

The difference between the stresses predicted for yielding by the two criteria is not great, and reaches a maximum of 15% in the theoretically and practically important situation of plane strain. A material is deformed in plane strain when no deformation is allowed to occur in one of the principal directions; for example, the rolling of thin wide sheet proceeds in an almost pure plane-strain system, because the sheet thickness is reduced and length increased without a material change in width. Under these constrained conditions, Tresca still predicts yielding at σ_0, while the measured values usually agree better with the von Mises criterion that places yielding at $1.15\,\sigma_0$ (the latter is usually written as 2k in the British literature). The difference is small enough to be ignored for our purpose. Besides plane-strain, axisymmetrical deformation, typified by an axis of rotational symmetry (e.g., extrusion and drawing of rounds), is often encountered; yielding then occurs at σ_0.

In the following, the mean yield stress σ_m will be used for calculations of force and power. It is obtained by taking the average height of the area under the yield stress curve, between the strain limits prevailing during the deformation process, and it accounts for the effects of strain hardening or hot working in the simplest way (Fig. 2.1). For a meaningful solution it is, of course, important that the stress-strain curve should be known for the temperatures and strain rates typical of the process.

2.12 Interface Friction

Metals are able to accommodate only a limited amount of tensile strain; necking and fracture soon occur. Much greater deformation may be

achieved without fracture in compression; therefore, most practical metalworking processes effect plastic deformation by applying a force through a suitable tool or die. Friction inevitably arises at the die-workpiece interface, and it is this friction that is the subject of our considerations. Mathematically, two basic views of the friction relationship may be taken: first, the interface friction may be characterized by the coefficient of friction:

$$\mu = F/P \tag{2.1}$$

or, for a unit area

$$\mu = \tau/p \tag{2.2}$$

where F and τ are, respectively, the lateral force and lateral (tangential) stress resisting relative movement between the die and workpiece, while P and p, respectively, are the load and stress normal to the surface.

The second view of frictional phenomena assumes that the interfacial zone may be represented—as a first approximation—by an idealized or actual material of a constant shear strength, τ_i. This may be taken as a material constant, independent of the interface pressure, and a constant fraction m of the shear strength τ_o of the deforming body:

$$\tau_i = m\,\tau_o \tag{2.3}$$

Neither μ nor τ_i gives any information about contact conditions at the die-workpiece interface; these will be discussed in Chapter 3. However, the two mathematical representations of the same physical phenomenon have an important bearing on the quantitative treatment of relationships between friction and other process parameters.

In most metalworking operations, interface pressures p developed by the major active force reach at least the uniaxial yield stress σ_o but, depending on the prevailing stress system, they may readily attain a multiple of σ_o (Fig. 2.2). In contrast, the tangential shear stress τ can never be larger than the yield strength of the workpiece material in shear, τ_o. Once this value is reached, movement along the interface is arrested (sticking friction) and deformation continues by subsurface flow, or shear, in the workpiece material. Since the shear strength τ_o of materials is $0.5\ \sigma_o$ according to the Tresca yield criterion (or $0.577\ \tau_o$ according to von Mises yield criterion), the coefficient of friction cannot exceed 0.5 (or 0.577) at the onset of bulk plastic flow, at least in a non-strain-hardening material. If, for simplicity, it is assumed that deformation is approximately uniform

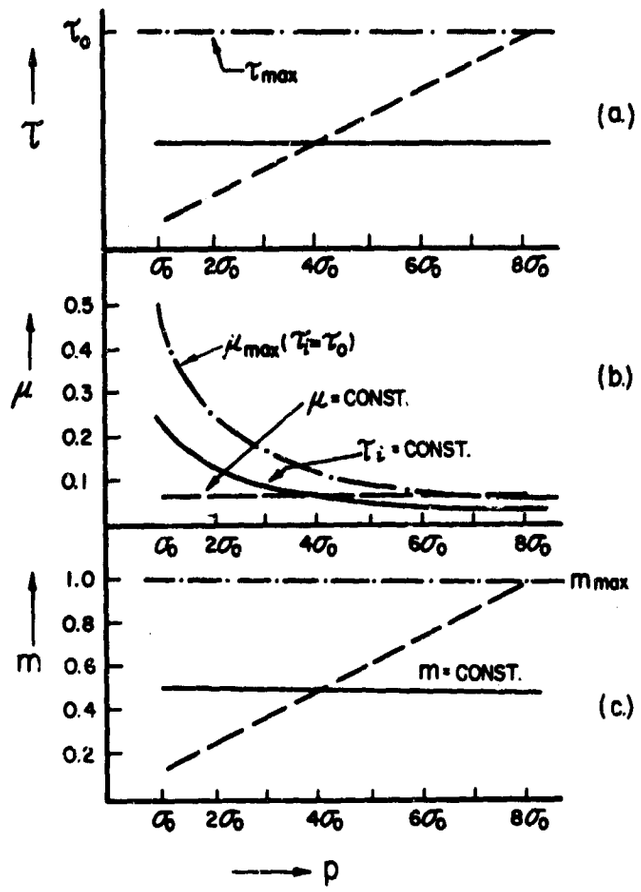


Fig. 2.2 Examples of the variation of frictional stress with normal pressure: (a) variation of shear stress, (b) coefficient of friction, and (c) interface shear strength factor.

in the whole body, then the shear strength increases at the same rate as the compressive yield strength and the maximum value of the friction coefficient can never exceed 0.5 (or 0.577) even in a strain-hardening material.

As mentioned above, interface pressures may reach a multiple of the uniaxial yield stress in most metalworking operations. Since available evidence indicates that the shear yield strength of the workpiece material is not affected by normal pressure, the frictional stress prevailing in sticking friction remains constant (Fig. 2.2a, dash-dot line). When represented as a coefficient of friction, the friction value decreases in inverse proportion to interface pressure (Fig. 2.2b) by virtue of the method of calculation (Eq. 2.2). This is obviously an anomalous situation that could cause misinterpretation of results and render friction coefficients meaningless unless

the interface pressures at which measurements were taken are specified. A friction coefficient is really meaningless for sticking friction and is best avoided; the method of calculation also introduces uncertainties in sliding friction. A constant μ (broken lines in Fig. 2.2) actually corresponds to a situation in which the shear strength of the interface increases with increasing pressure and the interface has, therefore, no constant properties.

The dependence of the friction coefficient on interface pressure has led a number of researchers to advocate the use of an interface shear stress τ_i (Eq. 2.3) which, in unlubricated contact, would always be equal to the shear strength τ_o of the softer material, giving a constant multiplying factor m = 1 (Fig. 2.2c). If the lubricant introduced between the die and the workpiece is of constant shear strength, equal to a fraction m of the shear strength τ_o of the workpiece material, τ_i will be lower than τ_o but will still remain constant irrespective of the interface pressure (solid lines in Fig. 2.2a). This would result in a lower coefficient of friction, again sensitive to interface pressure, but is correctly indicated as a pressure-independent constant when the concept of interface shear strength τ_i is used (Fig. 2.2c).

In practice, the situation is seldom as simple as in any of the above examples. Frictional interface stresses may vary from point to point in the zone of contact between the die and workpiece; this difficulty is usually circumvented by assuming an average friction stress (or coefficient of friction) along the contact zone. If friction rises because of gradual breakdown of the lubricant, the coefficient of friction may still remain constant if, fortuitously, pressure rises at the same rate. Unfortunately, the concept of a constant interface shear strength is not readily applicable either, since it would be necessary to assume that m is variable and a function of interface pressure. Evidently, the plot of m against p (Fig. 2.2c) is nothing more than a repeat of the original frictional stress vs. interface pressure curve (Fig. 2.2a).

Reluctantly, one is forced to arrive at the rather unsatisfactory conclusion that there is no fully acceptable way of representing frictional conditions mathematically. In the following sections, it will be noted that most existing theoretical solutions are built on the concept of a coefficient of friction.

In this chapter, arranged according to deformation processes, a standard outline will always be followed. First, various elements of the process are described, so as to clarify definitions. Next, the speed

relationships prevailing in the process are discussed, in order to define the relative sliding velocities that are operative for the lubricants applied to the interface. Then interface pressures, their distribution over the contact zone, and their averages are examined. Quantitative solutions are referred to whenever they provide a better understanding of the effect of friction. Plastic deformation is, by definition, associated with shape changes, and the effect of friction on strain distribution needs to be discussed in some detail. Bulk deformation and surface friction act to increase temperatures in the deformed product and at the interface; since temperature is often vital in determining the usefulness of a lubricant, this aspect is given consideration, quantitatively if possible. Finally, friction may determine the very possibility of successful deformation; therefore, process limitations as affected by friction are discussed last. Theoretical analyses are usually limited to simple deformation processes and, in many instances, it is necessary to rely on a qualitative assessment of the conditions that affect friction and lubrication. A discussion of confirmatory experimental evidence will be found in Chapters 6 to 11 dealing with individual processes.

2.2 ROLLING

Rolling accounts for the greatest volume of materials worked by deformation processes; good general accounts of it have been given by Larke [13] and by Starling [14]. Even though the operation may appear very simple at a first glance, it is extremely complex.

From the mechanical point of view, the rolling of long strips is a steady-state process, but complications enter as soon as surface contact is investigated. First, very high local pressures and abnormal material flow occur at the nose and tail of the workpiece which may cause particular difficulties in lubrication, especially in the hot working of some materials such as aluminum. Second, the contact zone between the workpiece and the roll changes continuously, and any part of the roll surface contacts the workpiece surface only once during every roll revolution. Thus, contact is really of a cyclic nature as far as lubricant breakdown, roll pickup, and surface temperatures are concerned. In the "idle" period of the cycle, accidental or intentional changes to the surface may occur, for example, through rubbing against scrapers, wipers, or wire brushes. The consequences of this cyclic contact will be appreciated in the course of discussing lubricating

effects in Chapter 6. Third, the direction of interface sliding reverses at the neutral point, imposing an arduous duty on the lubricant.

2.21 Definitions

In the rolling of a sheet or strip, thickness is reduced from h_1 to h_2 by rolls of R radius (Fig. 2.3). The absolute reduction in a single pass is:

$$h\Delta = h_1 - h_2 \tag{2.4}$$

or in relative (or percentage) terms:

$$r = (h_1 - h_2)/h_1 \tag{2.5}$$

or

$$r\% = 100\ (h_1 - h_2)/h_1 \tag{2.6}$$

Reduction expressed in terms of the natural strain

$$\epsilon = \ln(h_1/h_2) \tag{2.7}$$

is of greater theoretical value and has the advantage that strains imposed in individual passes may be added up; it is, however, relatively little used in rolling.

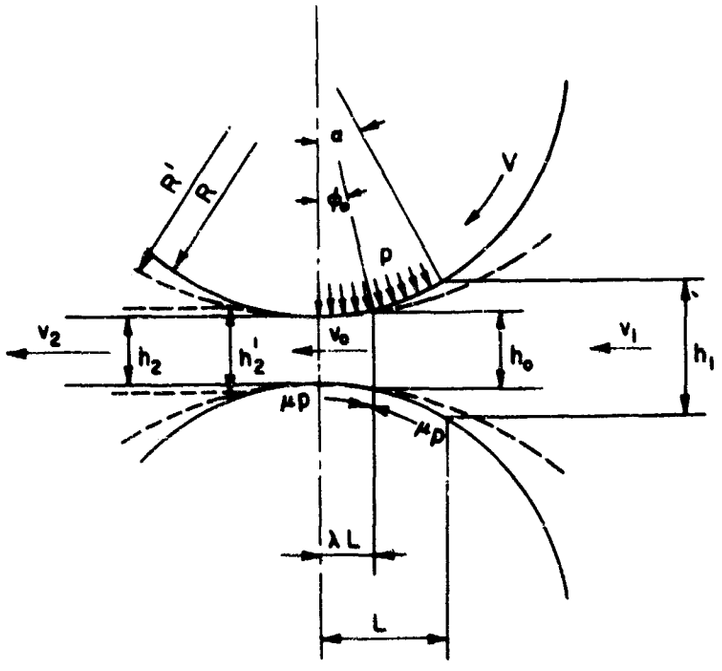


Fig. 2.3. Geometry of roll pass and associated velocities.

The strip may be repeatedly rolled on the same mill in several passes or subsequent passes may be taken on several mills placed in a line (tandem mill). The material displaced by reducing the thickness of the workpiece increases mostly in its length, although some width increase (spread) also occurs. Spread decreases as the width of the workpiece increases, and is zero at an infinite width (plane strain). In practice, spread may be neglected and the problem regarded as one of plane strain when the width of the workpiece is not less than 6 to 8 times the average thickness. Long strips are rolled in coil form; back tension applied at the entry and front tension applied at the exit help to keep the strip running straight and flat, and also reduce roll forces.

The workpiece may be rolled into a shape other than a flat rectangular cross-section by using rolls into which appropriate grooves (roll passes) have been cut. Relationships are much more complex than in flat rolling, and total production quantities are much less; consequently, theoretical work has also lagged. Differences between flat and shape rolling will be mentioned only qualitatively at the end of this section.

2.22 Velocity Distribution

The continuity of an incompressible material may be maintained only if the product of thickness and velocity is constant at any point along the zone of contact. For rolling with a constant width, the constancy of volume may be written in the following form:

$$v_1 h_1 = v_2 h_2 = v_o h_o \tag{2.8}$$

The constancy of volume demands that the exit speed of the strip should be increased in proportion to the pass reduction and, unless skidding occurs, the rolls will have to move at some speed intermediate between entry and exit speed. There can be only one point in the arc of contact where strip velocity is identical to roll velocity; at this point there is no relative slip between the two surfaces. It is described, therefore, as the no-slip or neutral point or, if looked upon in a three-dimensional presentation, the neutral pane. At all other points along the arc of contact the strip is moving either slower than the rolls (backward slip between entry and neutral point) or faster than the roll (forward slip between neutral point and exit). The speed difference between roll and strip surface is shown by the shaded areas in Fig. 2.4.

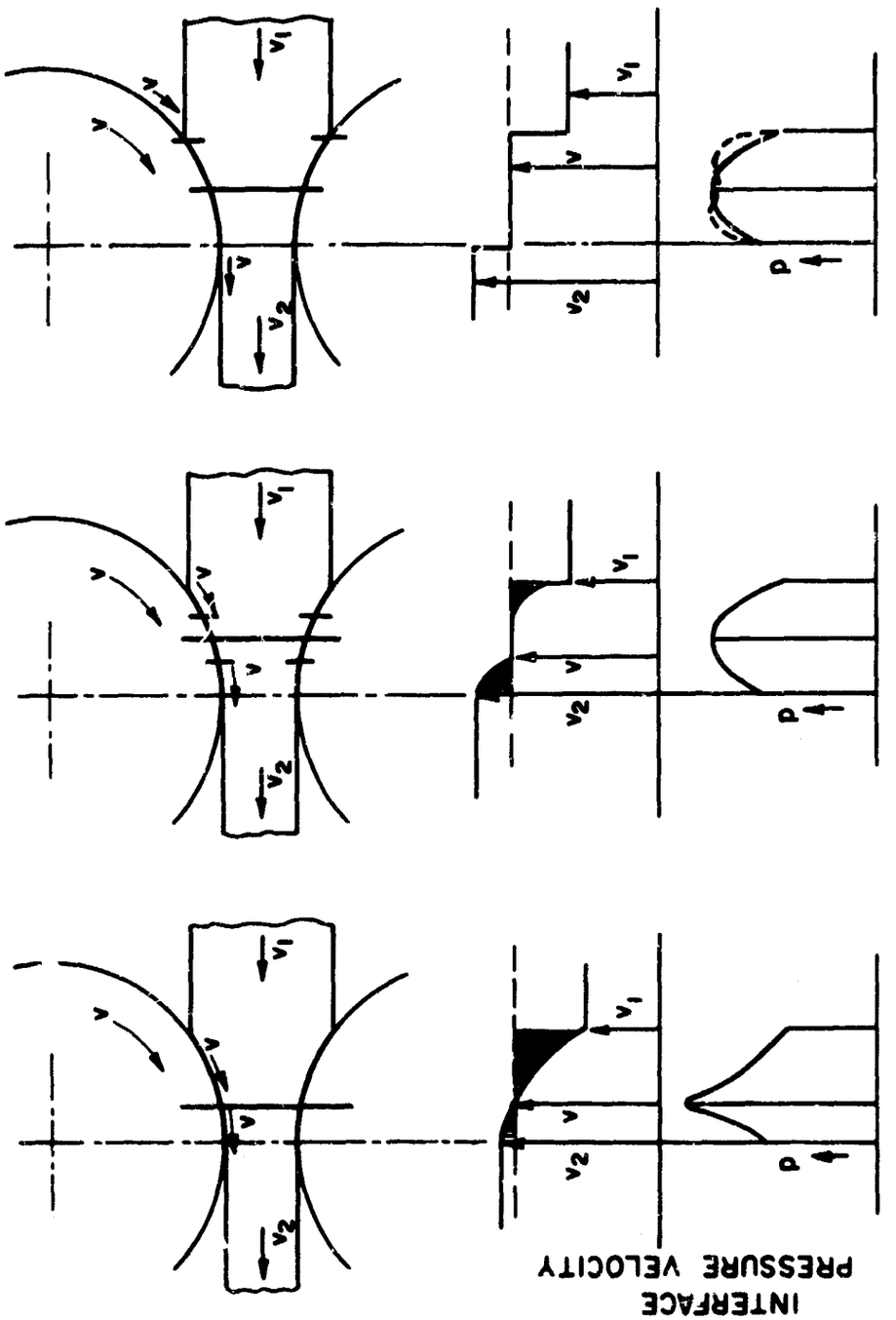


Fig. 2.4. Interface sliding velocities and the friction hill in rolling with (a) complete sliding, (b) partial sticking, and (c) full sticking.

The importance of relative slip between strip and roll surface can hardly be overstated. In a typical rolling situation, forward slip will seldom exceed 15%; the rest of the speed differential is taken up in the backward slip zone. Therefore, the strip enters the roll gap at a high interface sliding velocity which diminishes very rapidly, within a space of typically 1 in. or less, to zero in the neutral zone, only to pick up again as the strip leaves the roll gap. This relative sliding and its reversal, while helpful in many respects, also account for most of the problems encountered with lubrication in strip rolling.

Single pass reductions usually range up to 40-50%. Rolling speeds of up to 5000 fpm are encountered in the cold rolling of steel, thus interface sliding may reach 2500 fpm at the entry point and 1000 fpm at the exit point. Slower speeds are usual in hot rolling, and some difficult-to-form materials are hot and cold rolled at only 50-100 fpm, with correspondingly low interface sliding velocities.

The magnitude of relative slip is a function of the position of the neutral plane. The angle of the neutral plane ϕ_o may be calculated only if some broad simplifying assumptions are made. Fortunately, it appears that many of the errors introduced by these assumptions offset each other; therefore, a number of solutions have shown reasonable validity. Early work has been reviewed in detail by Underwood [15]; since then, further derivations have been produced by Ford et al. [16] and Geleji [5]. Of the existing solutions, that due to Ekelund [15, 17] is rather convenient to handle. In common with other solutions, it assumes that deformation is homogeneous, slipping friction exists everywhere in the roll gap except in the neutral plane, and radial roll pressure p and interface friction μ are constant along the arc of contact. These two latter assumptions are certainly unjustified, but the very approximate symmetry of the friction and pressure profiles around the neutral zone ameliorates the situation. Relative slip between strip and roll surface creates frictional forces (μp in Fig. 2.3) in a direction opposite to that of the slip. From the balance of the horizontal components of all acting forces, the position of the neutral plane may be derived according to Ekelund as

$$\phi_o = \frac{\alpha}{2} - \frac{1}{\mu}\left(\frac{\alpha}{2}\right)^2 \qquad (2.9)$$

where α is the angle sustained at the entry point of the strip. From the pass geometry, if $\Delta h = h_1 - h_2$ is small compared to the roll radius R, the length of the projected arc of contact L (Fig. 2.3) is

$$L = \sqrt{R\Delta h} \tag{2.10}$$

and the angle of entry

$$\sin \alpha = \frac{L}{R} = \frac{\sqrt{R\Delta h}}{R} = \sqrt{\frac{\Delta h}{R}} \tag{2.11}$$

Substituting Eq. 2.11 into Eq. 2.9

$$\phi_o = \sqrt{\frac{\Delta h}{4R}} - \frac{1}{\mu}\frac{\Delta h}{4R} \tag{2.12}$$

Thus, the angle between the neutral and exit planes is completely determined by the pass geometry and the coefficient of friction.

Alternatively, the position of the neutral plane may be derived from the pass geometry and forward slip. If forward slip S_f is defined as the proportion by which the exiting strip velocity v_2 exceeds that of the roll velocity v, then

$$S_f = (v_2 - v)/v \quad \text{or} \quad S_f\% = 100(v_2 - v)/v \tag{2.13}$$

From the geometry of the pass, forward slip is approximately equal to

$$S_f = \frac{1}{2}\phi_o^2\left[\frac{2R}{h_2} - 1\right] \tag{2.14}$$

As will be seen later, the measurement of forward slip offers a direct way of determining an average coefficient of friction from Eq. 2.12 and 2.14.

We have seen in conjunction with Fig. 2.2 that as soon as the product of the interface pressure and coefficient of friction reaches the yield strength of the workpiece material in shear, sticking of the interface sets in and deformation continues by subsurface shear in the bulk of the workpiece material. With a relatively poor lubricant, this condition is first met near the neutral plane where pressures reach a maximum. Thus the situation illustrated in Fig. 2.4b develops; the neutral plane broadens into a neutral zone—a condition which, in the opinion of many, should reduce forward slip. The fallacy of this argument is best seen when considering rolling with sticking over the whole arc of contact (Fig. 2.4c). Since no relative sliding takes place at the interface, rolling may be imagined to proceed by a continuous forward

and backward extrusion of material. The rate at which the material is extruded forward will be determined by the position of a plane that divides flow in the two directions; this plane may now be denoted as the flow-dividing plane [18]. As a result of the extrusion effect, material enters the rolls at a speed lower than the roll surface speed, leaves the gap at a higher speed, and the constancy of volume is preserved.

The position of the neutral plane is very sensitive to the presence of tensions. When tension imbalance exists and back tension predominates, backward slip increases (the neutral plane moves forward), whereas front tension increases forward slip (the neutral plane moves backward). Since tension variations present symptoms similar to changes due to friction, they may lead to confusion in interpreting observations.

The preceding discussion was based on the assumption that the width of the strip remains sensibly constant. However, on relatively narrow stock the increase in width (spread) cannot be ignored. Because most of the spread develops between the entry and the neutral zone, spread primarily affects backward slip, although some lowering of forward slip must be recognized. No universally valid formulae have been found for expressing spread in terms of pass geometry and friction; it is known, however, that spread increases with pass reduction, roll diameter, and friction [19]. These effects are readily understood qualitatively, since increasing arc of contact and friction pose greater obstacles to longitudinal flow, thus aiding lateral flow or spread.

2.23 Stress Distribution

Interface friction not only affects the position of the neutral plane, but also contributes to the interface pressure and, thereby, to the total roll force and power requirements.

Pressures and forces generated in rolling are the subject of voluminous literature on the theory of rolling; excellent reviews of the subject have been given by Underwood [15] and more recently by Ford [20]. All but the very simplest theories recognize that one of the most important controlling factors, besides the yield properties of the rolled material and geometry of the roll pass, is friction. The mathematical treatment becomes possible only if a number of simplifying assumptions are made, some of which are familiar from the discussion of forward slip equations. Thus, rolling is

regarded as a problem of plane strain with sliding friction along the arc of contact except at the neutral point, performed on an ideal rigid-plastic material of constant yield strength. It is also assumed that deformation is homogeneous—that is, originally vertical sections remain vertical during rolling. This latter assumption restricts the validity of these solutions to relatively thin sheet. Von Kármán [21] was the first to write the differential equations for the equilibrium of horizontal forces acting on a vertical section of dx thickness, taken at distance x from the exit plane (Fig. 2.5a). Assuming that friction is low and x is small relative to the roll radius R, the radial roll pressure p may be considered approximately identical to the vertical component p_v of the pressure, and the equilibrium can be expressed as

$$\frac{d(\sigma h/2)}{dx} = p_v (\sin \phi \pm \mu \cos \phi) \tag{2.15}$$

where the minus sign refers to the zone of backward slip and the plus sign to the zone of forward slip. The horizontal compressive stress σ is assumed to be uniformly distributed over the height h of the section.

A point-to-point integration of Kármán's equation shows that the interface pressure rises to the neutral plane as a result of the contribution of friction (Fig. 2.4a); accordingly, the shape of the pressure distribution curve is usually referred to as the friction hill. More generalized solutions presented by Orowan [22] and later by Geleji [5] eliminated some of the unrealistic assumptions; notably, strain-hardening of the workpiece material, inhomogeneous deformation, and the presence of a sticking zone are allowed for. In consequence, the shape of the friction hill changes too. Because of strain-hardening, interface pressure is higher at the exit than at the entry point and, if friction is high enough to arrest relative sliding between roll and workpiece around the neutral plane, the peak of the friction hill becomes flattened (Fig. 2.4b).

When the rolled material thickness h is large relative to the length of the arc of contact L, deformation becomes somewhat similar to indentation of a thick slab by a narrow anvil (see Section 2.53) and the restraining effect of the undeformed material adjacent to the deformation zone cannot be ignored. Because of this restraint, the resistance to deformation of the material increases, raising the level of interface stresses. This is a common occurrence in hot rolling and, coupled with the often very high friction

and consequent widening of the sticking zone almost over the entire arc of contact, gives rise to a greatly flattened friction hill (Fig. 2.4c).

The labor of solving the basic differential equations used to be great especially before the advent of the computer. However, for practical purposes of roll force calculations, it is sufficient to find an average interface pressure $\bar{p}$ and a great number of solutions have been proposed to accomplish this task. Depending on the number of additional simplifying assumptions adopted, the complexity of these solutions varies. In the final analysis, all can be expressed in the form

$$\frac{P}{b} \propto L\sigma_m f(\mu) \tag{2.16}$$

where b is the width of the flat rolled product and $f(\mu)$ signifies a specific function that takes into account the contribution of friction. When friction is low (e.g., lubricated rolling of steel) the contribution of the friction hill may be as little as 5-10% but it may raise forces to two or more times the frictionless value in hot rolling or, if lubrication is poor, on materials that show high adhesion to the roll surface (e.g., aluminum or titanium). Theoretical solutions based on the concept of a constant interfacial shear strength have also been produced (e.g., Avitzur [2]) but offer little advantage since friction is likely to vary along the arc of contact (Section 6.24).

Friction also affects the power consumption in rolling. The rolling torque may be calculated by assuming the roll force concentrated at a distance λL from the centerline of the rolls (Fig. 2.3); the total torque for both rolls becomes

$$T = 2\lambda L P \tag{2.17}$$

It will be appreciated that the position of the lever arm is determined by the actual shape of the friction hill. In the neutral plane, reversal of interface friction takes place, giving rise to opposing torques. Consequently, any shift in the position of the neutral plane will be reflected in a substantial change of the net torque. When the friction hill is symmetrical around the neutral plane, $\lambda = 0.5$; this is, however, a rare occurrence except for some hot rolling operations. In the absence of external tensions, λ values ranging from 0.3 to 0.6 have been found; $\lambda = 0.45$ is frequently used for approximate calculations in cold rolling. Calculations, however, will be accurate only if the exact shape of the friction hill can be derived, even if

other than the lever arm method is used; for this reason, theoretical solutions tend to be less accurate for torque than for force. For the latter, a shift in the position or shape of the friction hill peak may be of minor significance because it does not necessarily affect the average level of interface pressures.

If the rolling torque is known, the net horsepower of deformation is readily determined from

$$HP = 2\pi TN/33,000 \tag{2.18}$$

where N is the roll speed (rpm) and T is in units of lb-ft. For the reasons discussed in conjunction with rolling torque, calculations of horsepower often suffer from the inadequate knowledge of the actual shape of the friction hill.

Tensions have a twofold effect: first, they move the position of the neutral plane and thus affect the shape of the friction hill and, second, they lower the interface pressure, which in turn may also cause a change (usually a drop) in the coefficient of friction and thus flatten the friction hill. In consequence, roll force and torque decrease. Theory is again more adequate in predicting the changes in roll force than those in torque, mainly because the position of the neutral plane shifts with external tensions (Section 2.22).

2.24 Strain Distribution

In an idealized case of flat rolling, a rectangular body would be deformed into another rectangular body of greater length and slightly increased width. By definition, all originally vertical sections of the workpiece would remain vertical. The ideal of homogeneous deformation is approached in the rolling of thin wide strip, where the length of the arc of contact is a multiple of the average strip thickness—that is, the L/h ratio is high. In general, deformation remains virtually homogeneous as long as sliding friction prevails along the whole arc of contact (except in the neutral plane). However, as soon as a zone of sticking develops, the formation of a rigid, nonmoving wedge of material must be assumed, as has been done by Orowan [22] and shown in more detail in a slip-line solution of hot rolling by Alexander [23]. As explained earlier, this must lead to an extrusion effect, causing a backward convexity of originally vertical planes in the entry zone, and a forward curvature in the exit zone. This additional material movement requires extra work, often described as redundant work. Because friction

determines the extent of the sticking zone, it also affects the magnitude of this redundant work and, through this, the total efficiency of the rolling operation. It is worth noting that, occasionally, friction may be higher on one roll than on the other; the rolled slab then curls around the roll with the higher friction.

Whether sliding or sticking friction prevails, new surfaces are generated on the strip during its passage through the rolls. Thus, if a 50% reduction is taken, half of the surface will be old (covered with absorbed films, oxides, contaminants, etc.) and half of it will be virgin metal. The generation of new surfaces occurs along the arc of contact when sliding friction predominates, but surfaces must break up just before entering the roll gap when sticking friction prevails (see also Section 6.26).

The preceding discussion assumed that deformation takes place in plane strain. In reality, some lateral spread always occurs, leading to an inhomogeneity of deformation in the lateral dimension. Increasing friction limits material flow in the length dimension and therefore increases the over-all spread. However, friction also restricts material flow at the interface in the width direction; therefore, it is likely that higher friction results in greater outward bowing of the side faces. When heavy reductions are taken on a relatively thin material ($L/h > 1$) bowing is concentrated in the center, giving a barrel shape. High friction and relatively light reductions on a thick workpiece ($L/h < 0.5$) lead to double barreling as shown by Mican [24].

Friction also affects the flatness of the rolled product, but the interaction is too complex for a quantitative treatment; therefore, a discussion of these effects will be found in Section 6.28.

Through its influence on the homogeneity of deformation, friction may also affect the occurrence of rolling defects. Edge cracking is a result of secondary tensile stresses generated at the edges of the rolled workpiece in the longitudinal direction. Secondary tensile stresses become especially large when a workpiece barrels severely; therefore, the likelihood of edge cracking must decrease with decreasing friction. Friction, especially sliding friction, has also been suspected [25] to contribute to opening up the billet in the horizontal center plane (crocodiling, alligatoring); unfortunately, no evidence or detailed analysis is available to support these assumptions.

Occasionally, surface cracking is encountered in the hot rolling of difficult-to-work materials, usually due to a combination of low ductility at less than optimum hot working temperatures and of secondary tensile stresses generated by cooling the workpiece surface in contact with the roll. Lubricants may alleviate the problem, although probably mostly through their heat-insulating properties.

2.25 Heat Generation

Most of the deformation energy in rolling is converted into heat, and this would cause a temperature rise in the workpiece even if friction were totally absent. Friction contributes to heat generation through at least two sources. First, extra work is required to maintain interface sliding against frictional resistance, and this energy is transformed into heat at the interface itself. Secondly, inhomogeneity of deformation requires additional effort in excess of that corresponding to homogeneous deformation, and this redundant work is also transformed into heat.

Frictional heat must raise the surface temperature of the rolled workpiece; however, heat diffusion is usually very rapid in metallic materials and equalization of workpiece temperatures occurs soon after the strip emerges from the roll gap, especially in cold rolling. On the other hand, substantial temperature gradients may exist in the hot rolling of thicker slabs where the cooling effect of the rolls, lubricant, and/or coolant and the radiation to the environment cause surface temperatures to drop. Frictional heat is seldom, if ever, sufficient to offset the heat losses. The total heat input, however, may be sufficient to maintain a constant or even increasing bulk workpiece temperature, if rolling speed and rates of deformation are high enough. While heating is a common occurrence in cold rolling, in hot rolling it is limited to fast continuous lines and to mills that take exceptionally heavy reductions (e.g., planetary mills).

Undoubtedly, a substantial part of the frictional heat must pass into the rolls, raising their temperature. Since the contact zone with the workpiece varies continuously and the same point of the roll surface is exposed to a succession of heating and cooling cycles, calculation of the heat balance becomes extremely complex. Heat flow in the workpiece material further complicates the situation; the rate of heat diffusion determines how much of the generated heat is conducted back into the undeformed workpiece, and

heat transfer between workpiece and roll determines how much of the heat finds its way into the roll. For practical purposes it is sufficient to know that unless the lubricant radically alters the rate of heat transfer from strip to roll, increasing strip temperature is always an indication of increasing friction (see also Section 5.22).

2.26 Process Limitations

In a few instances, friction not only influences process variables but also determines the very possibility of performing the rolling operation itself.

Angle of Acceptance

It is common experience that the workpiece cannot be made to enter the roll gap if the rolls are very smooth or well lubricated: the rolls "refuse to bite." This condition is reached when the horizontal component of the frictional force F is equal to the horizontal component of the radial force P_r.

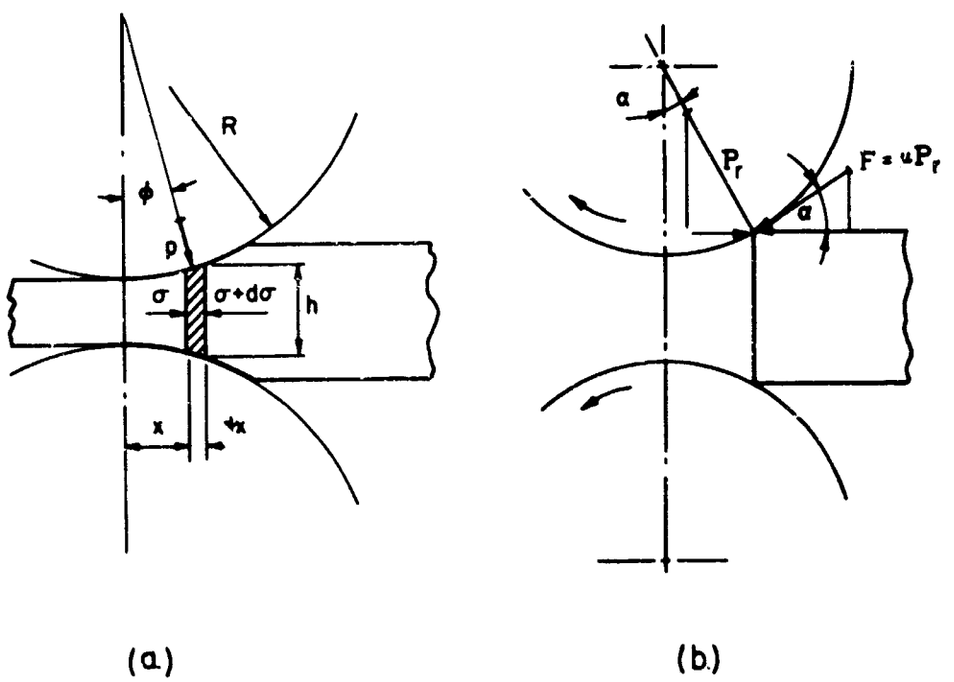


Fig. 2.5. Stresses acting on a vertical slab of the rolled workpiece (a) and forces acting at the entry point (b).

From Fig. 2.5b (2.19a)

$$F \cos\alpha \geqq P_r \sin\alpha$$

or

$$\frac{F}{P_r} \geqq \tan\alpha \tag{2.19b}$$

From the geometry of the pass, the maximum possible draft is

$$\Delta h_{max} = \mu^2 R \tag{2.20}$$

Since $F/P_r = \mu$ may be expressed as tan f (where f is the friction angle), it is usual to state that the bar will enter the rolls unaided only if the friction angle f exceeds the contact angle α.

Limiting Reduction

The discussion of stress relationships assumed that the rolls and the workpiece material were both absolutely rigid. This assumption is, of course, untenable. The rolls behave as elastic bodies in compression and, according to Hitchcock [26], it may be assumed that the elastic distortion results in an increased flattened roll radius R' (Fig. 2.3); for rolls with a Poisson's ratio of ν and modulus E

$$\frac{R'}{R} = 1 + \frac{16P(1 - \nu^2)}{\pi E\, b\, \Delta h} \tag{2.21}$$

In reality, the strip cannot be regarded as an ideal rigid-plastic material either. Adjacent to the plastic deformation zone there must be a zone of elastic precompression on the entry side, and a zone of elastic recovery on the exit side. The strip leaves the roll gap at a thicker h'_2 gage, and the arc of contact may lengthen substantially (Fig. 2.3). Frictional forces developed over these elastic arcs of contact develop an increased horizontal pressure ("negative strip tension") at the interfaces with the plastic zone.

The harder and thinner the rolled strip, the more important the elastic effects become. In the limiting case, the rolls flatten to the point where strip deformation is all elastic, and no further reduction may be taken. This is commonly referred to as limiting gage. A number of theoretical solutions have been proposed for predicting the minimum gage. These have

been reviewed by Ford and Alexander [27], who also proposed a solution that takes the elastic properties of the strip material into account:

$$h_{min} = \left[\frac{14.22\mu^2 R(1 - \nu_s^2)}{E_s} + \frac{9.05\,\mu R(1 - \nu_r^2)}{E_r}\right]\left[\sigma_m - t\right] \qquad (2.22)$$

This relationship shows that for a strip material with a Young's modulus of E_s and Poisson's ratio of ν_s, the minimum thickness may be reduced only by increasing the tension t, decreasing the roll diameter R, increasing the roll elastic modulus E_r (e.g., with tungsten carbide rolls), or reducing the friction μ. Since equipment and material characteristics are often limited or predetermined, the only broadly available control is that of the coefficient of friction through a suitable choice of lubricants. It should be noted that one theoretical solution [28] denies the existence of a limiting thickness; however, practical experience indicates that with no tension applied, difficulties can be expected as soon as the strip thickness is reduced to 1/400-1/600 of the roll diameter.

The effect of friction on rolling defects, already discussed in Section 2.24, could also be regarded as an example of process limitations.

2.27 Shape Rolling

Conditions existing in shape rolling processes have not yielded yet to an analysis as detailed as exists for flat rolling. Even in the simplest case—say, that in the rolling of a diamond or an oval section—the active roll diameter changes from point to point along the width of the section. Since the section retains its continuity, great variations in sliding speed between roll and workpiece surface must exist. The neutral plane probably changes into a three-dimensional curve and friction would pose a very difficult problem were not reductions normally limited to lower values than acceptable in flat rolling. Friction is particularly harmful when deep grooves machined into one of the two rolls are to be filled, because it hinders radial material flow.

Friction is, however, often desirable, especially in the hot rolling of complex sections, because the so-called "indirect draft" used for developing thin vertical sections relies on friction and on speed differences between top and bottom roll surfaces. While the absolute magnitude of forces and power requirement is of interest [5], it is used mostly as a design factor

for calculating rolling mill and drive requirements. Friction reduction is attempted only if it aids filling difficult shapes or improves the surfaces.

2.3 DRAWING OF WIRE, BAR, AND TUBE

Wire drawing is a steady-state process from the mechanical and the frictional point of view. The wire is normally long enough to make end effects insignificant, the same die surface is always exposed to contact with the wire surface, and new wire surface is continuously drawn into the die. In consequence, wire drawing lubrication usually reaches a well-defined equilibrium after a relatively short running time; temperatures reach a steady level and a lubricating mechanism typical of the interface pressures, temperatures, velocities, die geometry, and lubricant quality develops, and generation of wear debris from the wire and from the die assume a constant rate. Such equilibrium may not be obtained, of course, if the lubricant breaks down, causing die pickup and rising forces until the wire breaks, or if wear of the die changes its geometry significantly. These practical considerations may, however, be ignored for a consideration of the mechanics of the process.

2.31 Definitions

In drawing operations the cross-section of the workpiece is reduced, occasionally with a concomitant change in the outline of the cross section. The term wire drawing is normally applied to material of circular cross-section (Fig. 2.6a). The initial diameter d_1 is reduced to d_2; consequently, the cross-sectional area changes from A_1 to A_2. The reduction is then

$$r = (A_1 - A_2)/A_1 \quad \text{or} \quad r\% = 100(A_1 - A_2)/A_1 \tag{2.23}$$

The natural strain ϵ is preferred for theoretical purposes:

$$\epsilon = \ln \frac{A_1}{A_2} = \ln \frac{1}{1 - r} \tag{2.24}$$

Wires are drawn in long lengths, with a power-driven drum providing the draw force. Single drums (bull blocks) are used for heaviest wires, but the large number of passes required to produce thinner gages can be economically taken only on wire drawing machines in which the wire passes through a succession of dies. Between dies, the wire may be accumulated

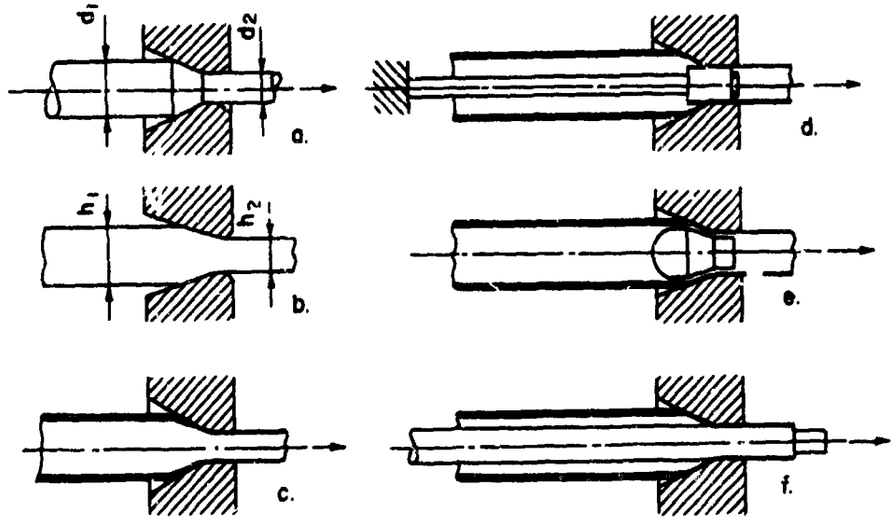


Fig. 2.6. Basic bar and tube drawing operations [73].

on drums, and the machine may be regarded as a succession of individual bull blocks. When drawing with slip, two to three turns of wire are wound on drums (capstans) rotating slightly faster than the speed of the emerging wire; the friction thus generated provides the draw force.

A relatively modest quantity of wire is also made with a rectangular cross-section; from the theoretical point of view, the special case in which a wide flat wire (a sheet) is drawn between two inclined die halves has special significance. The technique is somewhat similar to rolling in its geometry, except that now the die faces are stationary (Fig. 2.6b) and are usually bounded by straight lines. As in rolling, plane strain is attained over most of the strip width if the width-to-thickness ratio is larger than 8. Large-diameter round products, usually drawn in straight lengths, are called bars.

Tube drawing may be performed in four basically different forms. Sinking (Fig. 2.6c) is closest to wire drawing in that the tube is drawn through a die, reducing its diameter and, usually, slightly increasing its wall thickness. A mandrel (in Britain: plug) held in the deformation zone (Fig. 2.6d) or shaped so as to float there (Fig. 2.6e) is used to control the internal diameter of the tube; thus both the diameter and the wall thickness of the tube are reduced. Similar deformation but very different sliding conditions are obtained in drawing on a bar (in Britain: mandrel, Fig. 2.6f); the additional strength of the bar and friction on the bar-tube interface allow

heavier reductions to be taken. The tube is then reeled away. The reduction in tube drawing is usually expressed in terms of the change in cross-sectional area, as in Eq. 2.23 and 2.24. When drawing on a mandrel or a bar, it is also usual to distinguish between sink (change in diameter) and draw (change in wall thickness); the proportion of these is usually kept within some empirically determined limits for optimum product quality. Sink is generally kept small.

There are a great number of tube piercing, reducing, and elongating processes, conducted mostly hot. They present severe demands on lubrication when the inside of the tube is formed against a plug or mandrel, but no systematic studies of the frictional conditions appear to have been made [5]. The outer surface is usually readily lubricated or needs no lubrication at all, if deformation proceeds with rolls. Rolling contact eliminates most of the relative sliding between the workpiece and the die, and thus offers favorable conditions even for materials that would otherwise adhere to the die surface. For this reason, drawing in and pushing between roller dies has also been used for a number of years [5] and is now gaining wider recognition.

2.32 Velocity Distribution

Positive sliding over the die face takes place along the entire contact length in wire drawing and, since the constancy of volume again holds, a wire entering at a cross-sectional area A_1 and speed v_1 will leave at a cross section of A_2 and speed of v_2, the product of the corresponding A and v values being constant. As a close enough approximation, it may be assumed that the interface sliding velocity increases linearly in plane-strain drawing between two inclined flat dies and parabolically in axially symmetric drawing in a conical die. Small deviations are caused by inhomogeneous deformation and changes in friction, but these may be neglected for our purposes.

Interface sliding velocities are much more complex in tube drawing. In sinking, sliding against the die increases in speed as the cross-sectional area is reduced; if the decrease in diameter were counterbalanced by wall thickening, a constant interface velocity would be attained throughout the whole contact zone. Sliding prevails both on the mandrel and on the die surface in mandrel drawing, but is more limited on the bar surface in bar drawing. The exact interface velocity profiles are affected by the

draw: sink ratio, the draw angle, and friction; relationships are too complex for a detailed analysis. However, from the lubrication point of view, the absolute draw velocity (v_2) can be taken as a guide; since reduction in area seldom exceeds 40-50%, the interface sliding velocity is practically never less than half the exit velocity. In drawing on a bar, sink can approach zero, and sliding on the bar is then much restricted.

Drawing speeds are typically of the order of tens of feet per minute for bar and tube, several hundred feet per minute for heavier wire, and they may reach several thousand feet per minute on finer wire. High drawing speeds may present lubrication problems if the heat of deformation and friction is not sufficiently counterbalanced by cooling; on the other hand, high interface sliding velocities are extremely useful in building up a hydrodynamic lubricant film, provided that the die geometry is favorable (i.e., the die angle is low enough).

2.33 Stress Distribution

In drawing, just as in rolling, friction affects interface pressures (normal pressures on the die wall), draw forces, and thereby the energy requirements. Excellent summaries have been produced by MacLellan [29] and Wistreich [30], and plane-strain theories have been reviewed by Green [31]. Even though no rigorous theory of wire drawing has been developed yet, a number of approximate solutions are adequate to explain the effects of friction.

One of the useful solutions is due to Siebel [32], who assumed a constant coefficient of friction μ (for convenience, this may also be expressed as the friction angle $\tan f = \mu$). Since both the die half-angle α and the friction angle f are small in practice (Fig. 2.7), the die force Q is much greater than the draw force P; deformation thus occurs primarily under the influence of the mean die pressure $\bar{p}$. Making the further simplifying assumptions that the mean die pressure $\bar{p}$ is equal to the mean yield stress of the material σ_m and is not affected by μ,

$$P = Q \sin(\alpha + f) \quad \text{and} \quad Q = \sigma_m (A_1 - A_2)/\sin \alpha$$

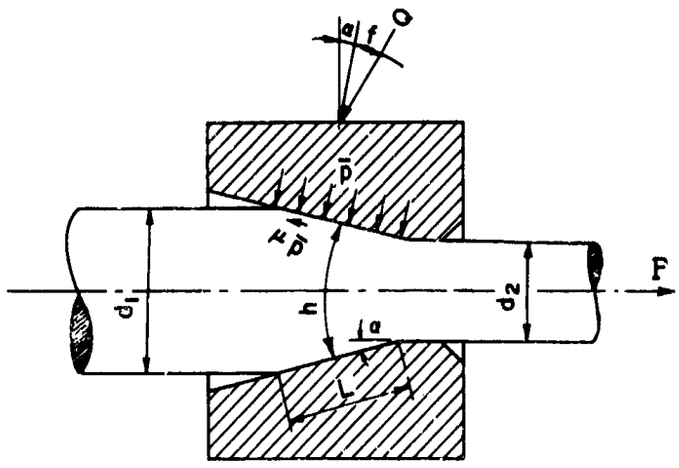


Fig. 2.7. Stresses acting in drawing a round wire.

which then leads to the simple formula for draw force P (for small angles $\sin\alpha \approx \tan\alpha \approx \alpha$):

$$P = \sigma_m(A_1 - A_2)\frac{\sin(\alpha + f)}{\sin\alpha} = \sigma_m(A_1 - A_2)\left(1 + \frac{\mu}{\alpha}\right) \tag{2.25}$$

An alternative formula for draw force may be derived from the work done by unit volume; from the analogy of the simple tensile test, the draw force for frictionless drawing P*

$$P^* = \sigma_m A_2 \ln(A_1/A_2) \tag{2.26}$$

Similarly to Eq. 2.25, this may be rewritten in the following form

$$P = \sigma_m A_2\left(1 + \frac{\mu}{\alpha}\right) \ln(A_1/A_2) \tag{2.27}$$

thus accounting for the force required to overcome interface friction (the term μ/α is often written in the form of $\mu \cot\alpha$).

A frequently encountered formula is due to Sachs [7]:

$$P = \sigma_m A_2\left[\frac{1 + B}{B}\left\{1 - \left(\frac{d_2}{d_1}\right)^{2B}\right\}\right] \tag{2.28}$$

where $B = \mu \cot\alpha$. Friction in the die land has been considered by some authors, but is difficult to separate and has remained a point of controversy [30].

It is clear from these expressions that the draw force always increases with friction. However, not all the increase over the frictionless draw force P* should be attributed to friction, because the contribution of redundant work must also be considered. Redundant work arises from the need of shearing the material from entry to the exit boundaries, so as to change the direction of material flow on entering and leaving the die. Forces necessary to overcome redundant work may be allowed for in a number of ways, for example, by introducing a multiplying factor ϕ which is always greater than 1 and results in an equation of the following form [30]

$$P = \sigma_m A_2 (1 + \mu \cot \alpha) \phi \ln(A_1/A_2) \tag{2.29}$$

Redundant work is a function of die geometry, conveniently described by the ratio of the length of circular arc spanning the midpoint in the contact zone (h in Fig 2.7) to the length of contact between wire and die (L in Fig. 2.7). This ratio characterizes the die geometry in a somewhat similar manner as the h/L ratio does for rolling (Section 2.24) and for forging (Fig. 2.21). In most practical wire drawing operations, the value of h/L ranges between 0.8 and 2.5. Other parameters may be chosen to describe the draw geometry but do not offer special advantages [33,34]. The contribution of redundant work to the draw force may be calculated rather simply from the die geometry; for example, by adding [32]

$$\frac{2}{3} \alpha \sigma_m A_2 \tag{2.27a}$$

to the draw force calculated from Eq. 2.27 or, according to Körber and Eichinger [35], by adding

$$\frac{4\alpha}{3\sqrt{3}} \sigma_m A_2 \tag{2.28a}$$

to the draw force calculated from Eq. 2.28. Experimentally determined multiplying factors for Eq. 2.29 are little affected by friction [33] and may be expressed approximately as

$$\phi = 0.90 + 0.15\ h/L \tag{2.30}$$

Johnson and Rowe [33] have also confirmed reasonable agreement with the redundant work predicted by Eq. 2.27a and 2.28a.

With increasing die angles (increasing h/L) redundant work increases while the frictional force decreases; therefore, there will be an optimum angle at which the draw force is a minimum. Obviously, the optimum die angle is a function of both reduction and coefficient of friction, and has been derived by Herrmann [36] from Siebel's formula in the following form:

$$\sin 2\alpha = \sqrt{6\mu \ln (A_1/A_2)} \tag{2.31}$$

A number of other solutions exist for the optimum die angle—for example, those due to Geleji [5] and Avitzur [2] and the empirical formula of Wistreich [37]. For most practical conditions, the optimum die angle is 6-8°.

The pressure exerted on the die is overwhelmingly a function of die geometry and reduction. With light reductions and large die angles the draw geometry is unfavorable (the factor h/L is large), deformation is not uniform across the wire thickness, and the die pressure may reach up to three times the yield strength of the material. With the more typical reductions of 20-40%, and die half-angles $\alpha = 4\text{-}12°$, die pressures are in the vicinity of the yield strength of the material [37], in agreement with Siebel's assumption. Both analytical and slip-line field solutions indicate that the die pressure should decrease with increasing friction. The differences are, however, rather small—less than 10% for an increase of μ from 0.05 to 0.1. Probably because of the concentration of redundant work at the entry and exit zones, measured interface pressures also exhibit peaks there (Section 7.25), which may be significant in causing lubricant breakdown.

Just as in rolling, a back tension may be applied to the wire with a consequent reduction in die pressures. While the absolute change in die pressures may not be very dramatic, it may be sufficient to cause a change in the lubrication mechanism and, therefore, in friction. The potential use of back-tension effects for the determination of friction will be discussed in Section 5.23.

Although the above discussion utilized the concept of a coefficient of friction, a constant interface shear strength may be equally readily postulated. The differences are likely to be small, because interface pressures are not much in excess of the yield strength of the material.

The drawing of a flat strip (the plane-strain counterpart of wire drawing, Fig. 2.6b) is theoretically important because it allows slip-line field solutions including the effects of friction and redundant work [31].

Calculated draw forces and the effects of friction are, however, similar to those derived for the drawing of round wire, and need not be expanded upon here; the only material difference is that redundant work is less in strip drawing.

Friction conditions in tube sinking are in no way different from those prevailing in wire or bar drawing. However, as soon as a mandrel or bar is used to control internal surfaces, additional frictional forces are generated. When drawing on a mandrel or on a floating plug, the inner surface of the tube slides over the plug and the direction of the frictional force is the same as that on the outer interface. If reduction is mostly by draw rather than by sinking, the effect of this additional friction may be taken into account by inserting the term

$$(\mu_1 + \mu_2)/(\tan\alpha - \tan\beta) \tag{2.32}$$

for $\mu \cot \alpha$ in Eq. 2.25 or 2.27 (μ_1 is friction on the outer interface, μ_2 on the inner interface, and β is the angle of the mandrel cone).

In drawing on a bar, the tube material slides over the surface of the bar; therefore, the frictional force at the interface opposes that of the outer interface. Consequently, the expression to be substituted for $\mu \cot \alpha$ in Eq. 2.27 now takes the form

$$(\mu_1 - \mu_2)/\tan\alpha \tag{2.33}$$

since $\tan\beta = 0$. The consequences of this are rather interesting. While the additional friction over the mandrel increases the total drawing stress, the friction between the bar and tube actually decreases it. If friction on the bar is the same as on the die, the contribution of friction is eliminated, and if friction over the bar is larger than over the die (a not altogether unlikely circumstance), the drawing stress may be actually less than in frictionless drawing.

2.34 Strain Distribution

Uniformity of deformation is a function of the draw die geometry as expressed by the ratio h/L. Only if this ratio is large will deformation become markedly inhomogeneous and, in the extreme case, some bulging of the wire ahead of the die will occur. Friction increases inhomogeneity of deformation, as shown in Fig. 2.8 for two die angles [10] for the drawing of 0.360 in. diameter copper bar for 36% reduction in area. It has been

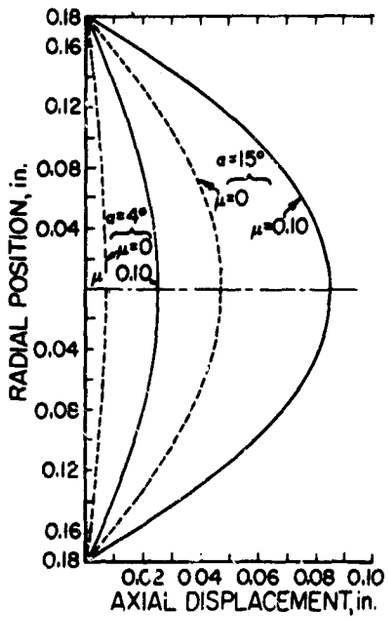


Fig. 2.8. The effect of friction and die angle on the distortion of a vertical line scribed on the cross-section of a round bar [10].

repeatedly observed also that the wire continues to thin beyond the die, the thinning being larger with die geometries that cause greater inhomogeneity. It could be assumed, therefore, that friction would increase this continued thinning.

No matter how large and how inhomogeneous deformation may be, sliding must prevail over the whole contact area; therefore, new surfaces are generated uniformly along the whole contact length. Since reductions may reach 50% per draw, up to half of the surface will be new.

Inhomogeneous deformation may have a number of side effects. In milder forms, residual stresses remain in the bar and tensile stresses in the surface layers may cause cracking when the bar is exposed to corrosion. The magnitude of these residual stresses is obviously influenced by friction through its effect on inhomogeneity, although no detailed analysis of the situation appears to have been made.

More important from the point of view of the immediate success of the process is the occurrence of center bursts (cup and cone fracture) in the drawn wire or strip. Qualitatively, this phenomenon may be understood if inhomogeneous deformation is considered, with die geometries yielding high h/L ratios. Since the surfaces are more heavily deformed than the

central portions, secondary tensile stresses are generated at the center in the axial direction. If these stresses are large enough (usually as a result of a succession of small passes with steep draw angles), separation of the material occurs in the center [38]. Since friction increases the inhomogeneity of deformation, it could be expected that, for the same die geometry and reductions, center burst is more likely to occur in a poorly lubricated die. An analysis of Avitzur [2], based on a comparison of power requirements with and without central burst, predicts such tendency; however, it does not account for the variations due to the basic ductility of the workpiece material. A complete analysis of the problem is not available yet.

2.35 Heat Generation

Sensible heat in the wire results from the heat due to deformation and surface friction, less the heat lost to the die and the environment. Compared to rolling, the situation is rather simple because a thermal equilibrium is soon reached in the die. Since lubricants may break down if exposed to a higher temperature for a prolonged time, knowledge of the actual interface temperature would be desirable.

Surface temperatures may be estimated from simplified analyses of heat flow, such as has been produced by Siebel and Kobitzsch [39]. Surface temperatures may then be substantially (often 200-300°C) higher than core temperatures (Fig. 2.9). For an actual calculation of the maximum

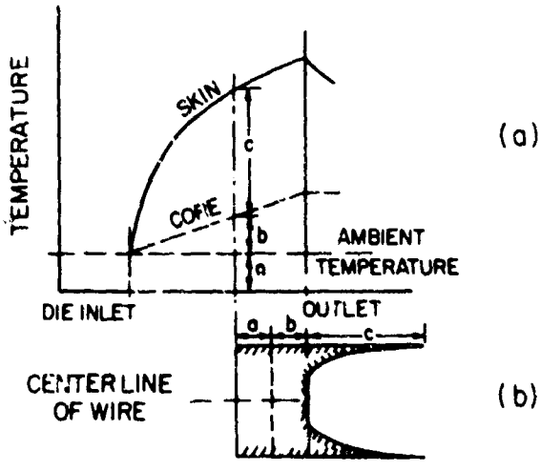


Fig. 2.9. Temperature distribution (a) along the wire and (b) across the wire [39].

temperature rise, it is necessary to know die temperatures [40] and heat lost to the drums and the coolant. A more detailed discussion of the theoretical and experimental aspects of wire temperatures may be found in Wistreich [30]. Because of the rather high heat conductivity of all metals, temperature equalizes rapidly, and uniform temperatures are attained as close as 1 in. from the die exit point. Therefore, unless the true interface temperature can be measured in the die, the effect of friction can be judged only from the bulk temperature of the wire which will, of course, increase with increasing friction.

2.36 Process Limitations

Because the force required to deform the wire is supplied by the pull on the deformed product, an obvious limitation exists. If the drawing stress exceeds the strength of the deformed wire, tensile separation occurs. The maximum allowable reduction is readily obtained from the equations of draw force by equating the draw force with the strength of the drawn wire. Assuming no strain hardening, a maximum reduction of 63% would be possible in the absence of friction. With increasing friction, the maximum possible reduction drops, unless it is counter-balanced by strain hardening. Any prediction of the maximum reduction allowable in the presence of friction will, of course, be dependent on the particular draw force equation accepted as valid. As an example, maximum reductions are given as a function of the die half-angle α and the friction coefficient μ according to Avitzur in Fig. 2.10 for a non-strain-hardening material. In practice, dynamic effects such as occur on starting the draw bench or draw block, as well as accidental variations in workpiece surface quality and in friction, hold feasible reductions below the maximum values. Reductions of 45-50% are regularly obtained with materials that show little adhesion against the die material and, therefore, develop relatively constant draw forces.

Center bursts represent a very practical process limitation and, as discussed in Section 2.34, are also influenced by friction.

2.4 EXTRUSION

As a matter of convenience, extrusion is most often regarded as a steady-state process in plasticity theory. This is only approximately valid. In reality, all extrusion billets have a definite and sometimes rather short

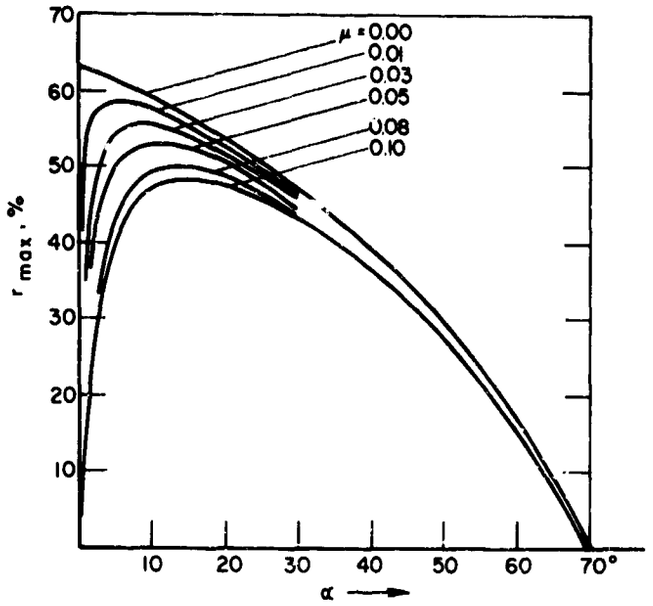


Fig. 2.10. The effect of friction and die angle on the maximum reduction in wire drawing [2].

length. Forces build up gradually in the beginning until plastic flow is initiated; thereafter, pressures, sliding velocities, and deformation patterns become stable for a considerable portion of the stroke, until the press is stopped or the tail end of the billet is extruded. At this point, lubrication conditions are bound to change. When the next billet is introduced into the container, friction may again be affected by lubricant residues from the previous extrusion. For this reason, extrusion is best regarded as a batch process as far as lubrication is concerned.

2.41 Definitions

In practical applications, the billet is almost always round, and it is extruded through an orifice (die) into a round bar, tube, or a section of often very complex cross-section. Sometimes, extrusion proceeds through several dies, causing substantial complications in material flow and sliding conditions; this special case is best ignored here. Extrusion is carried out on a hydraulic or mechanical press. The billet is placed in a (usually) stationary container and is pushed through the die with a punch attached to the press ram. A follower block is placed between the billet and the punch in hot extrusion to protect the punch from excessive heat.

Restricting our discussion to the extrusion of bars and tubes of circular cross-section, deformation may be characterized by reduction in area as in Eq. 2.23, although the extrusion ratio R_E

$$R_E = A_1/A_2 \tag{2.34}$$

is preferred because of the large reductions normally encountered.

In forward or direct extrusion (Fig. 2.11 a, b, and c) the press ram moves in the same direction as the extruded product, while they move in opposite directions in indirect (reverse, inverted) extrusion (Fig. 2.11d and e). A special technique uses no ram; instead, a hydraulic fluid pushes out the billet (hydrostatic extrusion, Fig. 2.11f). Occasionally, the term impact extrusion is applied to extrusion carried out on mechanical presses. This designation has no real physical significance; the process itself remains either direct or reverse extrusion. Some parts are produced by a combination of direct and reverse extrusion, in a single press stroke, using a suitably shaped die.

Extrusion of a flat bar through a container of infinite width (plane-strain extrusion) is never practiced but is important theoretically because it permits attempts at exact solutions of the stress, strain, and velocity

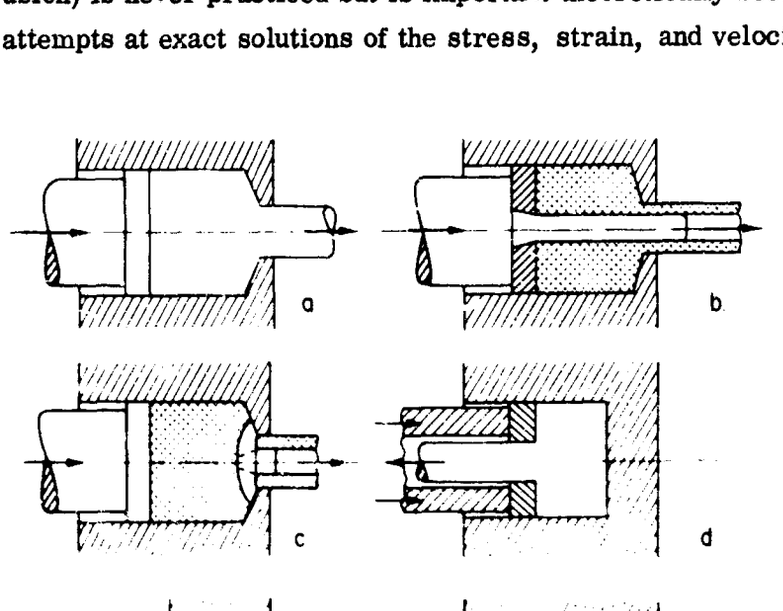


Fig. 2.11. Basic forms of extrusion [73].

fields. Experiments are sometimes performed that purport to be in plane strain; for obvious practical reasons, the width of the container must be limited and the assumption of plane strain becomes valid only if friction on the side walls can be neglected.

2.42 Velocity Distribution

For practical purposes, only two states of sliding may be permitted in extrusion: complete sliding or--primarily for extrusion of aluminum--complete sticking. Intermediate states lead to the development of surface or subsurface defects.

In direct extrusion, sliding along the container wall as well as on the die face is possible in a square die (included angle 180°) only if friction is zero or at least very small (Fig. 2.12a). As soon as friction assumes an appreciable value, sliding may be still maintained along the container wall, but a dead metal zone builds up in the corners of the die and the material shears along this face. In the presence of a lubricant, the material may continue to extrude over this self-generated die surface, but surface and

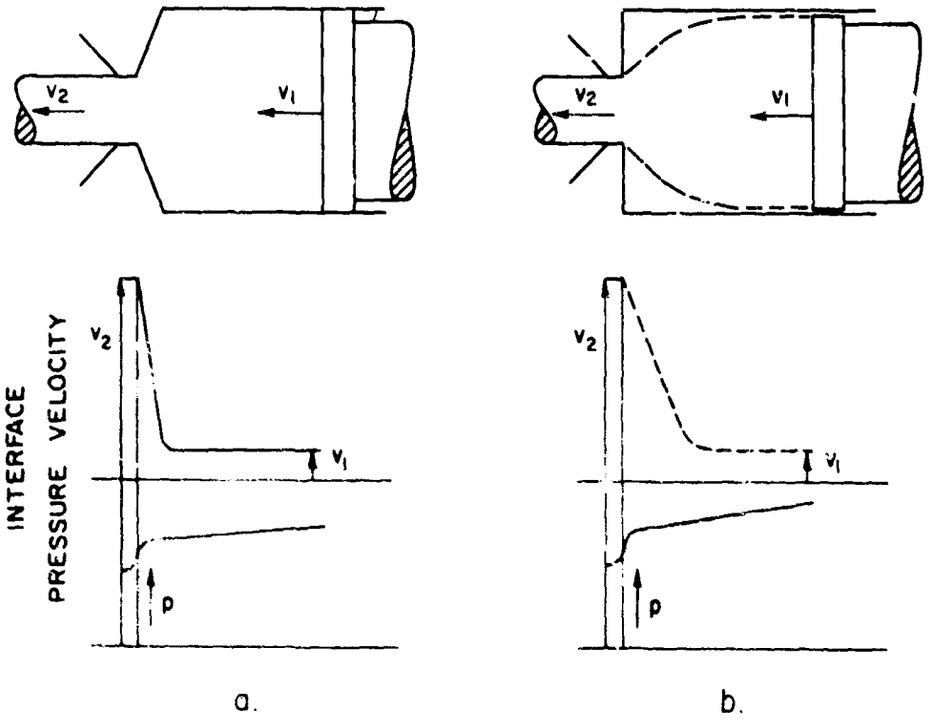


Fig. 2.12. Sliding velocities and interface pressures in direct extrusion with (a) sliding friction and (b) sticking friction [18].

subsurface defects are likely to occur on the extruded product. The effective angle occupied by the dead zone (the complementary angle to the effective die angle) increases with increasing friction and with diminishing reduction; the undesirable side effects of dead zone formation in lubricated metal flow may be avoided if the die is originally made to the appropriate angle. Sliding will then take place over the whole die surface even in the presence of measurable friction. When a glass pad is used as a lubricant in hot extrusion, it gradually melts away to form a die of optimum shape.

As soon as the force required to move the workpiece on the container surface exceeds that of the shear strength of the workpiece material, sticking friction predominates and deformation proceeds by shear in the bulk of the workpiece (Fig. 2.12b). Because sticking is complete on the die and container wall, a dead metal zone of maximum angle forms, and this angle is a function of the reduction ratio. As a reasonable approximation, the included die angle may be taken as 90°; theoretical solutions for the angle of the dead metal zone may be obtained from slip-line fields for plane-strain [41] or from upper bound solutions [2] for axial symmetry.

Because of the typically large extrusion ratios, acceleration of the workpiece material is great and sliding velocities reach a multiple of the ram velocity in the parallel portion of the die (the die land). Ram speeds are typically of the order of a few inches per minute for hot-short light metals and copper-base alloys, and may range up to 1000 ipm on pure metals, steel, and some refractory metal alloys. Extrusion ratios may be as high as 400:1 on light metals but seldom exceed 40:1 on steel; therefore, sliding velocities in the die land (the velocities of the extruded product) are typically of the order of 100 to 1000 fpm but may be restricted to as low as 10 fpm with hot-short materials.

An additional frictional surface is created in tube extrusion between the mandrel and the billet material. The direction of movement and the relative sliding speeds are the same as on the outside surface, at least in the zone of the die land; farther back, relative sliding may very soon decrease and sticking may prevail, especially if the mandrel is fixed to the punch. This could, however, result in severe damage to the mandrel; therefore, sticking is avoided by the application of a lubricant, particularly when extrusion temperatures are high. A special situation arises in extruding hollow products with a bridge (porthole) die (Fig. 2.11c). The hollow is

formed by an insert that is held against the die face with bridges. The billet material is forced to part around these bridges only to be reunited under pressure in the exit zone. Obviously, the presence of any lubricant would prevent rewelding of the workpiece material; therefore, this type of extrusion must always be conducted dry.

Friction along the container wall is eliminated in indirect extrusion, and relative sliding is restricted to the die surface, at least for the geometry shown in Fig. 2.11d. Extrusion of cups and collapsible tubes is also a reverse extrusion process (Fig. 2.11e), but the material replaced by the punch now streams along both the container and punch surfaces. Friction over the large extruded surface could easily limit the process were not precautions taken to minimize friction by reducing the length of the container wall as well as reducing the diameter of the punch after forming a land of minimum practicable length. Contact with the container is completely eliminated in hydrostatic extrusion (Fig. 2.11f), and friction is limited to the interface between the billet and the die. Velocity changes are similar to those experienced in direct extrusion in tapered dies (Fig. 2.12a).

2.43 Stress Distribution

In addition to the general references on metalworking theory, extensive treatments of the extrusion process exist (Johnson and Kudo [41], Bishop [42], Alexander [43], and Pearson and Parkins [44]). Theoretical treatments generally regard extrusion as a steady-state process, although tail effects have been considered [2, 41]. Some analogies with wire drawing may be utilized, if it is duly recognized that the workpiece is now pushed rather than pulled and that an additional contact surface exists along the container wall. Plasticity theory can provide solutions only for plane strain, but a great number of satisfactory technological solutions exist, and conclusions reached from plane-strain solutions may also be applied, at least qualitatively, to axial symmetry. Agreement is often quantitative, especially at higher reductions, if the processes are compared for the same reduction in area, thus allowing for the larger redundant work in axial symmetry. While slip-line field solutions can be derived only for plane-strain, upper bound solutions (recently reviewed by Pierce [45]) also apply to the axially symmetrical practical case, and some attempts have also been made to extend slip-line field solutions to axial symmetry [10].

In considering the forces generated in extrusion, analytical solutions indicated in wire drawing are of only limited applicability because die angles are large, friction has a marked effect on die pressure, and redundant work assumes significant proportions. On the whole, it is greatly preferable to calculate forces and pressures from slip-line field or upper bound solutions. All of them lead to equations that can be represented in a simplified form similar to that found empirically

$$p = \sigma_m (a + b \ln R_E) + c\ell \tag{2.35}$$

In this equation, the parenthetical term includes the forces required to overcome the energy of uniform deformation, redundant work, and die face friction. The constants a and b may be calculated [2] or determined from experiments; reported values cover a rather wide range, from 0.47 to 1.27 for a and from 0.83 to 1.55 for b. One of the favored combinations is a = 0.47 and b = 1.2, suggested by Hirst and Ursell [46] for lubricated hot extrusion with square dies.

Although not immediately obvious from Eq. 2.35, an optimum die angle may be found for extrusion just as for wire drawing. Again, smaller die angles would increase the homogeneity of deformation but increase the frictional force because of the larger contact area. Conversely, a larger die angle reduces the frictional component but redundant work becomes larger and an optimum is found, increasing with increasing friction and extrusion ratio. The effect is significant in cold extrusion but is easily overshadowed by uncontrollable heating and cooling effects in hot extrusion. Numerical solutions for optimum die angles have been reviewed by Pierce [45]. It should be noted, though, that low angles increase the hoop stresses in the dies and also increase the size of the discard, unless the extrusion is pushed through with a deformable follower block (e.g., a graphite block in hot extrusion).

Much more important for this discussion is the contribution of container friction. This must obviously be a function of the billet length and is, therefore, in a general form expressed as $c\ell$ in Eq. 2.35. The effect of container friction may be considered quantitatively [46] by assuming a hydrostatic pressure distribution at all points of a transverse plane marked in Fig. 2.1c. The equilibrium of the horizontal forces acting on the volume element yields

$$dp_\ell \frac{\pi}{4}(D^2 - d^2) = \mu p_\ell \pi (D + d) d\ell \tag{2.36}$$

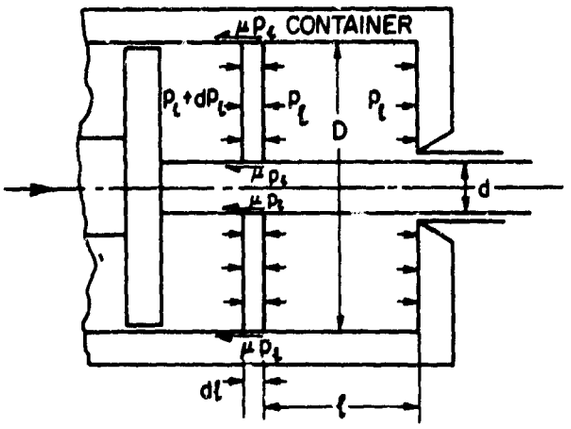


Fig. 2.13. The effect of friction in extrusion [46].

where p_ℓ is the pressure at a distance ℓ from the die face. Rearranging

$$dp_\ell/p_\ell = 4\mu d\ell/(D - d) \tag{2.37}$$

since $p_\ell = p$ at $\ell = 0$, integration yields

$$p_\ell/p = \exp\ 4\mu\ell/(D - d) \tag{2.38}$$

choosing appropriate values for a and b, Eq. 2.35 may be written as

$$p_\ell = \sigma_m(a + b \ln R_E) \exp\ [4\mu\ell/(D - d)] \tag{2.39}$$

If there is no relative motion between the billet and mandrel surface (and also in the extrusion of bars), the (D - d) term reduces to D.

We have already mentioned that because of the large extrusion ratios, interface pressures may be a multiple of the uniaxial yield stress; therefore, the use of a friction coefficient may be rather misleading. It is preferable [2, 47] to adopt the concept of a constant interface shear strength τ_i. Equation 2.39 would then take the following form:

$$p_\ell = \sigma_m(a + b \ln R_E) + 4\tau_i\ell/(D - d) \tag{2.40}$$

For investigations into the effect of friction, it is only necessary to know the extrusion force at two points during the extrusion stroke. This information is readily derived from plots or autographic recordings of extrusion force vs. stroke (Fig. 2.14). With no container friction, the force is constant (broken line) until it begins to rise towards the end of the stroke where the butt is formed. With container friction, an initial high pressure (often called the breakthrough pressure) is registered, which then gradually falls off as the length of the billet is reduced. When the container is colder

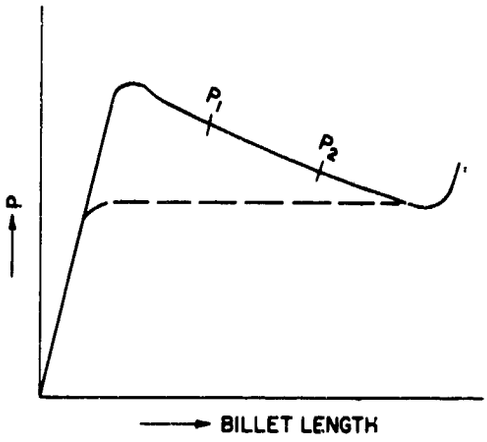


Fig. 2.14. Variation of extrusion force with billet length without (broken line) and with (solid line) container friction.

than the billet in hot extrusion, the extrusion force may rise towards the end of the stroke because of cooling, and the effect of friction cannot be separated. An interpretation in frictional terms would be, clearly, quite meaningless since a zero or even negative coefficient of friction or shear stress would have to be assumed.

2.44 Strain Distribution

We have already pointed out that even though the mechanistic view of extrusion is based on the concept of a steady-state process, this is strictly true only for an interim period. To begin with, the billet is upset until it fills the container (and, unless the nose is preshaped, until the die is filled), then the extruded product begins to form. At this stage, deformation is relatively moderate. Further material flow depends on friction, and a classification of the flow types according to Pearson [44] has become widely accepted (Fig. 2.15). Type A flow is typical of minimum wall friction and of reverse extrusion and results in relatively undistorted grid lines in the extrusion (Fig. 2.15a and d). Increasing container friction in type B flow is evidenced by the distortion of grid lines in the container and by the development of a dead zone (Fig. 2.15b). Type C flow is usually associated with high wall friction and cooling of the outer faces, and is most frequently encountered with heterogeneous materials (Fig. 2.15c).

Since deformation proceeds through shear in the material when sticking friction prevails, the surface of the extruded product will be all new. The

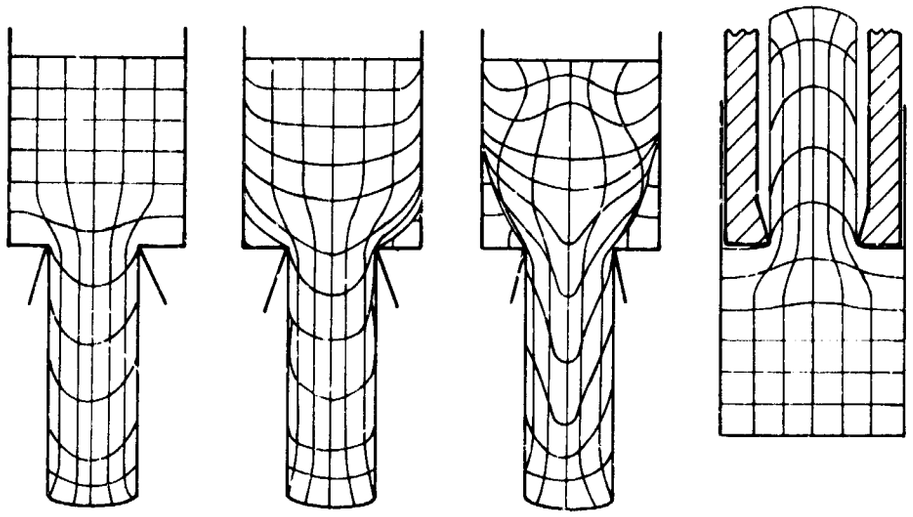


Fig. 2.15. Characteristic types of material flow in extrusion [44, 73].

extrusion surface is partly old, partly new in perfectly lubricated extrusion. While the cross-sectional area of the extrusion decreases as the square of the radius, the surface increases with the first power of the radius. Thus, in the extrusion of a billet to one quarter of its original diameter, the extrusion ratio is 16, the surface increases fourfold, and 3/4 of the final surface is new. From a lubrication point of view, the container and the die present very different problems: the lubricant needs only to protect the original surface of the container, but it must be capable of accommodating the increasing billet surface against the die.

Toward the end of the stroke, the back face of the extrusion develops a crater (pipe) which may collect lubricant, lubricant residues, or oxides. Trimming off this defect entails a loss in valuable material and, thus, in economy. With greater container and die friction, inhomogeneity and material loss incurred also increase, although friction at the back face of the billet counteracts the tendency to pipe formation.

Nonuniform material flow also means that internal stresses acting in the axial direction are set up in the extruded product. The cupping defect (central burst) sometimes observed in the center of cold extruded products is closely related to the same defect in wire drawing and is associated with secondary tensile stresses developed in sections extruded at an extrusion ratio of less than 4:1 [48]. The surface cracking experienced in hot

extrusion (also called speed cracking) is most probably associated with overheating of the surface into the temperature regime of hot-shortness, combined with tensile stresses generated through friction and cooling. The probability of these surface defects occurring is less with increasing homogeneity of deformation. Wilcox and Whitton [49] attribute a defect of similar appearance (fir tree effect) in cold extrusion to the simultaneous occurrence of slip on the die face and sticking in the land. If lubrication is not uniform all around, the extruded section bends toward the poorly lubricated side and may crack on subsequent straightening. Nonuniform friction may also lead to unfilled portions in the extruded section. An exact analysis of these conditions is still lacking, even for simple rounds. Knowledge is even more limited for the extrusion of sections, in which material flow may become very complex and the substantial extension of the original surface may compound lubrication difficulties.

2.45 Heat Generation

Large deformations, often combined with sticking friction, can lead to substantial temperature rise in the extruded product. In consequence, the actual interface temperature may be much higher than the initial state would suggest. A rather sophisticated treatment based on slip-line field analysis has been developed by Bishop [50] which allows for conduction of heat back in the undeformed portion of the billet. An approximation to the bulk temperature rise may be obtained by converting the work done during extrusion into the equivalent heat. Since work done is proportional to the forces as expressed by Eqs. 2.39 and 2.40, greater friction also means more heat generation. This in turn may set a limit to the maximum allowable reduction as discussed below.

2.46 Process Limitations

In principle, any extrusion ratio could be attained since, at extrusion ratios over 4:1, all forces are compressive. In practice, however, the strength of containers, dies, and punches is limited by the capabilities of available engineering materials and by constructional features. Thus, punch pressures seldom exceed 180,000 psi in hot extrusion and a very careful choice of container and die materials and of designs is needed if cold extrusion pressures are to exceed 300,000 psi. A limited extrusion pressure

then means also a limit on the attainable extr... ...io. With increasing friction, the extrusion force rises; consequently, extrusion ratio drops. In this respect, the limiting factor is the peak (breakthrough) pressure registered at the beginning of the stroke (Fig. 2.14).

Another limitation of the process is often noted in hot extrusion. We have already mentioned that extrusion at temperatures that fall within the hot-shortness range of the workpiece material results in circumferential cracks. All factors that tend to raise the temperature of the extruded product represent a limitation in this sense. A minimum starting temperature is usually required to limit the maximum forces and also assure that cold cracking of the material does not occur. The temperature rise due to friction and deformation work must than be kept low enough not to heat the emerging product into the danger zone. Hirst and Ursell [46] derived a formula for the lubricated extrusion of materials, giving the temperature rise $T - T_o$ for adiabatic extrusion (an infinite extrusion speed) as

$$T - T_o = \frac{3.7\sigma_m(0.47 + 1.2 \ln R_E) \exp(\frac{4\mu\ell}{D} - 1)}{\frac{4\mu\ell}{D}\rho c} \qquad (2.41)$$

where ρ is specific gravity and c is specific heat. For a given friction, the maximum allowable reduction ratio may then be determined provided that the yield strength of the material is sufficiently well known for the appropriate temperatures and strain rates, and the increase of forces on breakthrough can be estimated.

2.5 FORGING

Forging, even in its simplest forms, is a batch process both from the mechanical and frictional point of view. Steady-state conditions are never achieved, and the lubricant is always exposed to a pressure-temperature-velocity combination that changes continuously while a given workpiece is being deformed. The roughness of the die surface, determined by thermal-mechanical history, causes localized wear and may provide points of lubricant entrapment. Lubricant residues and wear or pickup products are continually changing, although a semblance of an equilibrium may be obtained through careful control. The absence of a steady-state situation, combined with the generally high forming temperatures, may account for the great

difficulties encountered in a systematic analysis of this process, despite its often deceptive simplicity.

2.51 Definitions

Practical forging operations encompass a great variety of deformation modes. Most frequently, they are subdivided into open-die and closed-die forging processes.

In open-die forging the workpiece is formed between two die faces, and it is free to deform in the other two directions. The simple upsetting of a short cylindrical workpiece (Fig. 2.16) is important both in practice and experiment. The cylinder is compressed on its ends with flat platens that overhang the workpiece throughout the complete deformation process. A variant of this, the upsetting of rings (Fig. 2.17), is of particular significance for investigations of friction. Friction conditions are only slightly different when the upset workpiece is a rectangular slab.

Deformation becomes substantially different if the workpiece overhangs the platens, a group of processes commonly referred to as indentation. The

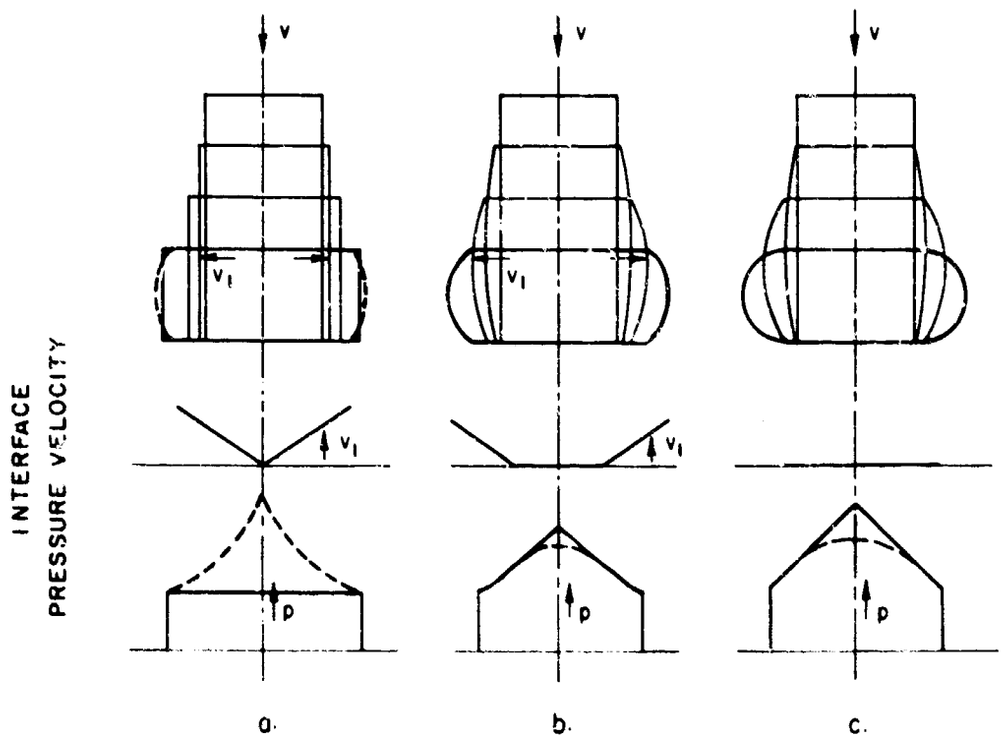


Fig. 2.16. Interface sliding and the friction hill in upsetting a cylindrical workpiece with (a) complete sliding, (b) partial sticking, and (c) full sticking [13].

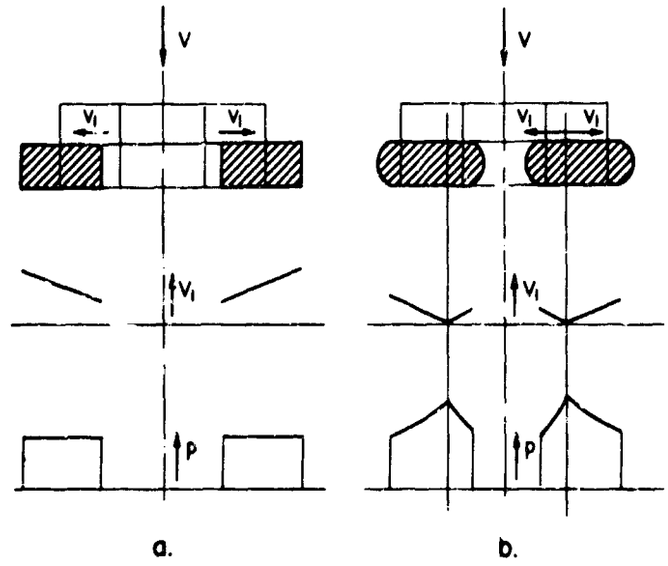


Fig. 2.17. Interface sliding velocities and pressures in ring upsetting with (a) no friction and (b) sliding friction.

industrially very important process of drawing out (cogging) is usually practiced on workpieces of rectangular cross-section, employing narrow anvils that overhang the workpiece only in the lateral direction. The workpiece thickness is reduced in a succession of indentations usually beginning from one end of the billet. From the theoretical and experimental point of view, more tractable is the technique in which the workpiece is indented away from the end, so that symmetrical material flow develops (Fig. 2.18). With anvils and specimens of theoretically infinite width b, the problem reduces to

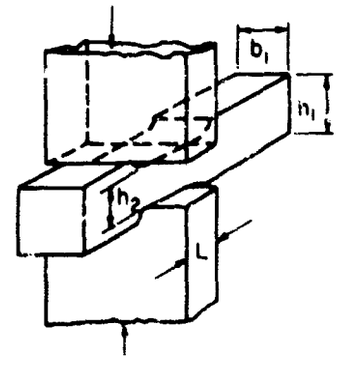


Fig. 2.18. Drawing out (in plane-strain indentation the width b is large compared to height h).

one of plane-strain and becomes amenable to stricter forms of theoretical analysis.

The degree of deformation is defined in the same way as in rolling (Eqs. 2.4 to 2.7).

Free lateral deformation of the workpiece material is prevented in closed-die forging (Fig. 2.19). Excess material is allowed to escape through a flash gutter; the term "closed-die forging" is, therefore, not really applicable—"impression die forging" would be preferable. True closed-die forging is less frequently encountered, and is performed either in a deep die which is closely sealed by the penetration of the other die half prior to the beginning of deformation, or in complex dies activated by multiram presses in which the workpiece material is enclosed in the die before separately activated punches penetrate and deform it. Several comprehensive treatments of closed-die forging are available [51-53].

2.52 Velocity Distribution

Interface sliding is governed by friction and may range from complete sliding to complete sticking. The range of variables is most clearly evident in the upsetting of cylindrical billets (Fig. 2.16). With very low friction, the end face of the cylinder expands and sliding occurs in a radial direction over the entire interface (Fig. 2.16a). In the center of the billet, a neutral point with zero relative sliding develops, somewhat analogous to the neutral line found in rolling (Fig. 2.3). With increasing friction, interface pressures around the center of the end face may reach high enough values to generate frictional stresses equaling that of the shear strength of the workpiece material. At this point, sliding ceases and deformation takes place

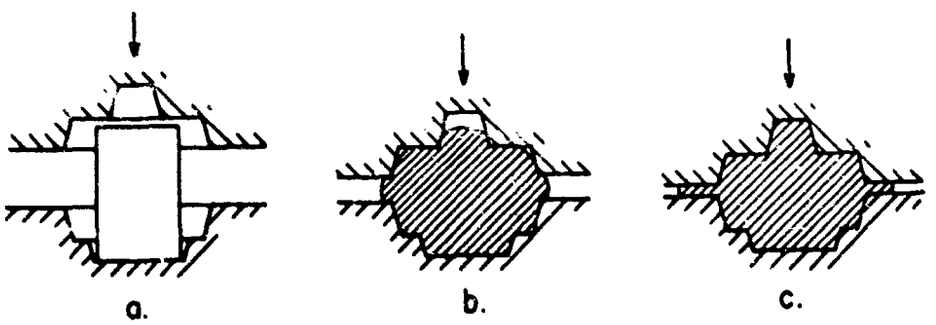


Fig. 2.19. Sequence of die filling in impression die (closed die) forging.

by subsurface shear. Sliding is then restricted to a peripheral (annular) area of the interface (Fig. 2.16b). In the extreme case, complete sticking occurs over the end face and relative sliding velocity is nil (Fig. 2.16c).

When a rectangular slab is upset between flat anvils that overhang the entire slab, the neutral point widens into a neutral line and, in the presence of sticking friction, thickens into a neutral zone. There is, of course, some lateral material flow towards the longer side of the billet too. The same applies to plane-strain indentation, the only difference being that the contact area remains constant and the billet material now extrudes between the approaching anvil surfaces; the similarity of this process to rolling is quite close. The velocity distribution in the direction of the major flow is the same as shown in Fig. 2.16, and the actual velocity exceeds the anvil approach velocity by a factor equal to the ratio of anvil breadth to specimen thickness, L/h, because the volume remains constant.

Ring upsetting is a rather special case. With zero friction at the interfaces, the ring expands as though it were part of a solid disk, and velocities are radially increasing over the entire surface (Fig. 2.17a). With increasing friction, some of the material flow is directed towards the center, the diameter of the hole decreases, and a circular neutral line—a "neutral circle"—develops (Fig. 2.17b). The radius of the neutral circle has been derived from theoretical considerations by a number of authors, including Kunogi [54], Kudo [55], Hawkyard and Johnson [56], Burgdorf [57], Avitzur [2], and Van Sant [58]. Some solutions also allow for changes in friction during compression, such as could be expected if lubricant breakdown occurred (see also Section 5.25).

Closed-die forging, even in its most simple forms, is too complex to permit a detailed analysis. It is known, however, from experimental evidence that sticking occurs very early over most of the die impression surface, and sliding is limited to the surface of the flash land. In a simplified sense, it may be assumed that deformation is limited to a disk-shaped zone the height of which is equal to the flash gap opening. Deformation proceeds by shearing in the bulk of the forging and by interface sliding between the flash land and the flash. The velocity distribution is then the same as in Fig. 2.16b unless friction is sufficiently high on the flash land face to cause deformation to proceed by subsurface shear even in that zone. Under

any circumstances, however, sliding velocities are of the same order of magnitude as in simple upsetting.

Die approach velocities vary over a wide range depending on the forging equipment. Speeds are quite commonly 1 ips in mechanical or hydraulic presses, and may reach as high as 10 ips on the faster units. In contrast, speeds of 20 fps are typical of hammers and may reach three to five times this value in so-called high energy rate units. Interface sliding velocities will, correspondingly, range from zero to up to perhaps ten times the die closing velocity, depending on the location from the neutral line. Whenever sticking friction predominates, interface velocities drop to zero, of course, irrespective of the die closing velocity.

2.53 Stress Distribution

Open-die forging operations, especially upsetting and plane-strain compression, have attracted substantial theoretical effort. Partial reviews of the subject have been given by Vater and Nebe [59] and Lange [60]. Although no strictly valid solutions exist, some of the approximations are close enough to be useful for estimating the effect of friction.

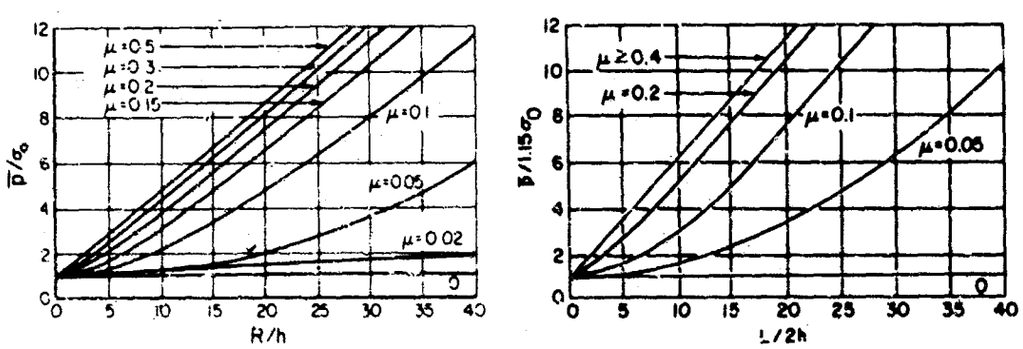
In upsetting, the stress distribution is uniform and the stress is equal to the uniaxial (compressive) yield strength of the workpiece material in the absence of friction (Fig. 2.16a). As soon as friction over the interface reaches a measurable value, the force required to overcome this friction raises the interface pressure, just as it does in rolling. Correspondingly, a friction hill develops which is described by an exponential function and which, therefore, is sharply peaked when sliding friction prevails over the whole surface (broken lines in Fig. 2.16a). When sticking sets in around the neutral point, the interface pressure actually drops and, if the interface shear stress is assumed to be constant, pressure increases along a straight line (solid lines, Fig. 2.16b and c). Direct measurements show a rounding-off of the peak (broken lines in Fig. 2.16b and c), and this would indicate that theoretical analyses which assume the interface shear stress to drop towards the neutral point may be more relevant [5, 12].

Many theoretical solutions exist, most of them based on a similar set of simplifying assumptions. Of several solutions that take into account partial and full sticking at the interface, that due to Schroeder and Webster [61] has been frequently used for studies in friction. While the pressure

distribution may be readily calculated from these analyses, of greater practical importance is the effect of friction on the average interface pressure $\bar{p}$. The results are most readily presented in graphs (Fig. 2.20) which show that the average pressure $\bar{p}$ can easily reach a multiple of the uniaxial or plane-strain yield strength, especially on relatively squat specimens (large R/h or L/h ratio). This accounts for the great difficulties experienced in producing relatively thin webs. A remarkable feature of these curves is that interface pressures may be kept at reasonably low values only with very low friction coefficients. In fact, for a constant R/h or L/h ratio, average die pressures hardly change from $\mu = 0.2$ to full sticking. It is worth remembering, as Bishop [62] pointed out, that the forging load is proportionate to the fifth power of the radius when upsetting a workpiece with complete sticking. Some of this increase comes, of course, from the increasing contact area (which is proportional to the square of the radius), but most of it is attributable to the effect of friction.

Pressure distributions and mean interface pressures can also be calculated for ring compression, as proposed by the authors cited in Section 2.52. However, the main attraction of ring upsetting as a test method is that friction may be determined simply from shape changes; therefore, formulae for forces find little practical use.

In the absence of friction, the interface pressure in plane-strain indentation is equal to the constrained yield strength or 1.15 σ_0 according to the von Mises yield criterion as long as the workpiece thickness h is less than



(a) (b)

Fig. 2.20. Variation of interface pressure with aspect ratio and friction in the upsetting of (a) cylindrical workpieces between overhanging platens [61] and (b) rectangular workpieces in plane strain (after ref. 50).

the breadth of the anvil L. Green [63] has shown from slip-line field solutions that increases in interface pressures up to 4% occur when the ratio of L/h is not an integer, but the effect is small enough to be ignored here. However, of importance is the restraint exerted by the nondeformed portion of the workpiece material whenever the workpiece is thicker than the width of the anvil. Slip-line solutions by Prandtl [64] and Hill [6] both yield the curve shown in Fig. 2.21. Accordingly, interface pressures rise gradually with increasing h/L ratios to a limiting value of 2.57 times the constrained yield stress. It will be recognized that this is the same effect as obtained in rolling or drawing out with a large h/L ratio. In all instances, an increasing ratio of workpiece thickness to contact length represents an increasingly inhomogeneous deformation, caused by the diminishing interpenetration of the deformation zones. The resulting rise in interface pressures is not to be confused with friction effects. The effect of friction becomes important in plane-strain compression only with h/L ratios of less than 1. Alexander [65] produced both a slip-line field and an approximate solution, which lead to the curves shown in Fig. 2.22a for L/h ratios of 3 and 7. The coefficient of friction can then be readily determined from the average interface pressures measured at these L/h ratios (Fig. 2.22b).

Theoretical solutions exist only for the simplest geometries in closed-die forging and, as indicated in Section 2.52, most are based on the assumption of the extrusion of a flash, with shearing taking place in the bulk of the workpiece. Correspondingly, a friction coefficient enters into the solutions of Geleji [5] and Kobayashi and Thomsen [11], but the complexity of the deformation mode makes it unlikely that friction effects could be readily separated from observed forces.

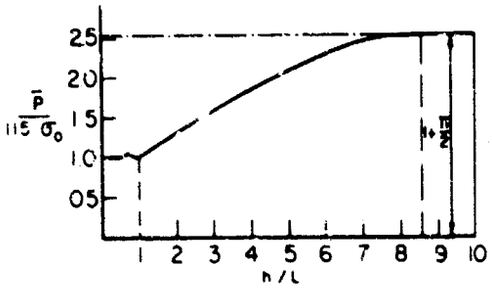


Fig. 2.21. Increase in die pressure caused by the restraint of nondeforming material in plane-strain indentation with a narrow anvil [6].

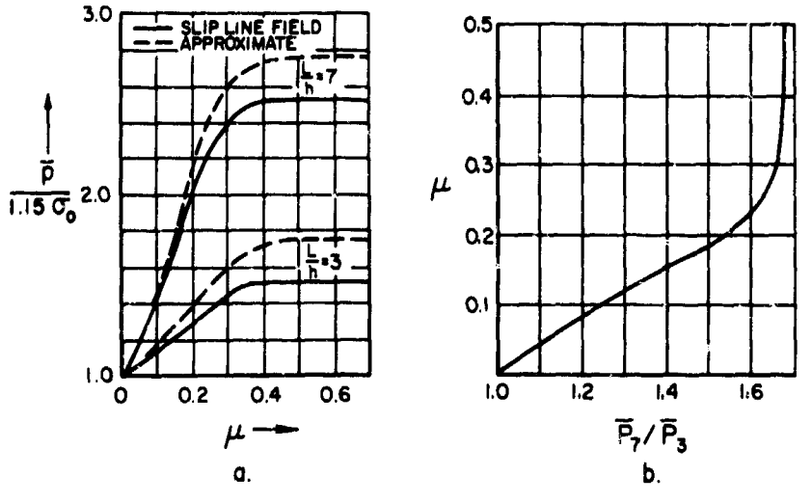


Fig. 2.22. The effect of friction on die pressure in plane-strain compression (a) and determination of a coefficient of friction from indentation with two anvil widths (b) [65].

2.54 Strain Distribution

Uniformity of strain distribution has probably been most exhaustively investigated in the simple upsetting of cylindrical workpieces (Fig. 2.16). In the absence of friction the cylindrical shape is retained, deformation is completely homogeneous, end faces expand, and new surfaces form. In most practical instances, friction is unavoidable and retardation of material flow at the end faces results in a barreling of the specimen. As soon as sticking is attained near the center, expansion of the end face and generation of new surfaces is limited to the annular sliding zone. Complete sticking is most frequently encountered with dry friction, and it has been customary to assume that subsurface flow is responsible for deformation in such instances. This would imply that new surfaces are continually generated by the material that is extruded from the neighborhood of the sticking zone. Experimental evidence indicates, however, that the end faces increase actually by folding over the original side surfaces against the die (Fig. 9.2). Even though the barrel shape thus developed bears a superficial similarity to that obtained with partially sliding friction, deformation becomes highly inhomogeneous, and new surfaces are very small. This also means that the assumptions underlying most theoretical solutions regarding interface pressures lose their validity, and the results cannot be analyzed conveniently. Friction also

affects the deformation pattern in ring upsetting (Fig. 2.17). The outer surface is always convex, but the inner surface may be concave with low friction and convex with high friction.

Material flow tends to be sensitive to friction in plane-strain compression too, with material extruding from the central plane of the workpiece at a greater rate than from near the anvil surface. Again, material flow resembles that found in rolling, and spread in the lateral direction is also observed [18]. Spread assumes significant proportions if the workpiece is too narrow relative to its thickness to assure a close enough approximation to plane-strain conditions. This is typical of drawing out, where the width and height of the workpiece is rather similar. As in rolling, spread increases with increasing friction, but no quantitative work appears to have been done on this subject.

Deformation is highly nonuniform in closed-die forging; as mentioned earlier, most of the material movement is restricted to the zone of flash formation.

2.55 Heat Generation

As in all other bulk deformation processes, the work of forging is transformed into heat, some of which is retained in the workpiece, while some of it is lost to the surrounding atmosphere or to the dies. Friction at the interfaces is a further source of heat. While the expected temperature rise could no doubt be analyzed along similar lines as in extrusion (Section 2.45), detailed examinations of the problem are scarce, probably because the process never attains a steady-state condition.

The absence of theoretical interest may be attributable partly to the fact that a knowledge of temperatures is less critical, because the die surfaces usually have an opportunity to cool between forging successive pieces, and the forging itself is seldom subjected to high enough total strains to cause hot-shortness on account of heat generation, unless the forging temperature range is very narrow. The presence of heat must be recognized, though, because even cold working dies will reach 100° to 200°C and, correspondingly, the lubricants will be subjected to at least these temperatures. While the interface temperature must be higher, it is not likely to exceed or even reach the temperature of the workpiece in hot forging. Isothermal forging, in which the die and workpiece are at the same temperature, is an

exception, of course, but because of the relatively small sliding velocities, it is still unlikely that average interface temperatures would rise considerably beyond the workpiece temperature.

2.56 Process Limitations

We have seen in conjunction with Figure 2.20 that interface pressures rise very rapidly with increasing ratios of workpiece width to workpiece thickness, especially with high friction values. With many workpiece materials, pressures may be high enough to cause indentation of overhanging forging dies, or the total loads may be so high as to make forging uneconomical or impossible on available equipment.

Friction can also limit deformation through its influence on the homogeneity of deformation. Barreling in the upsetting of cylinders generates tangential (circumferential) secondary tensile stresses, which may lead to cracking in materials of moderate ductility. Combined with the temperature rise caused by the work of deformation, cracking may be particularly severe in the hot forging of materials with narrow working temperature ranges. The incidence of cracking may then be avoided by the use of lubricants that effectively lower friction.

The economy of the process is often limited by the rapid deterioration of dies. Although wear is a process distinct from friction, friction can contribute to rapid die wear by opening up and propagating thermal fatigue cracks.

2.6 SHEET METAL WORKING PROCESSES

Most sheet metal working operations are characterized by a gradual development of shape and are, essentially, non-steady-state processes. In common with forging, interface pressures, temperatures, and sliding velocities vary continually. However, a closer approach to an equilibrium lubrication system is more readily attained, mainly because deformation is usually carried out at or close to room temperature.

A great number of publications are available on the practical aspects of sheet metal working, but only a few books [66-68] discuss theory and its implications for practice.

2.61 Definitions

Of the rather bewildering variety of sheet metal working processes, only a few are significantly affected by friction.

Shearing or blanking is one of the most common processes, because it usually precedes other deforming methods. However, lubrication plays a subordinate role because the part is cut by shearing between the die and the punch, and the lubricant does not enter into the process of separation to a marked degree. Theoretical background to indicate possible lubricant effects is missing and lubricants, if applied, serve primarily to reduce wear and die pickup, although the principles applying to metal cutting and discussed in detail by Rowe [69] may well have relevance.

Similarly, bending is a widespread forming method, with friction again playing a rather secondary role. In some instances, friction does control the distribution of stresses and strains; however, theoretical fundamentals are rather limited and usually pertain to situations more typical of deep drawing.

For the purpose of this discussion deep drawing is the most important deformation technique. Emphasis will be on the forming of parts from circular blanks; however, the principles discussed can be applied with some difficulties to other shapes. Relatively thick sheet may be transformed into a cylindrical vessel with a simple cupping operation (Fig. 2.23a). Drawing with a blankholder is more commonly used, especially for the forming of thinner sheet when there is danger of wrinkling in an unsupported, partially drawn flange (Fig. 2.23b). The diameter of the cup can be further reduced and its depth increased by redrawing (Fig. 2.23c) without a significant change in wall thickness, or it may be ironed (Fig. 2.23d) for reducing the walls without changing the initial diameter. Reverse redraw (Fig. 2.23e) is sometimes used for deeper draws.

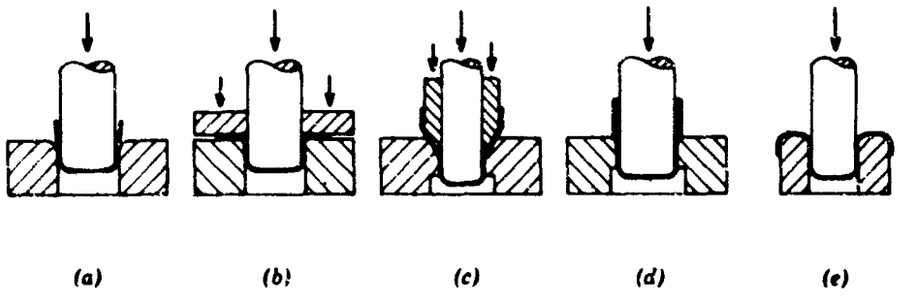


Fig. 2.23. Basic sheet drawing operations [73].

In cupping and in drawing with a blankholder it is usual to refer to a reduction as defined by the reduction between initial blank diameter D and the diameter of the punch d

$$r = (D - d)/D \quad \text{or} \quad r\% = 100\ (D - d)/D \tag{2.42}$$

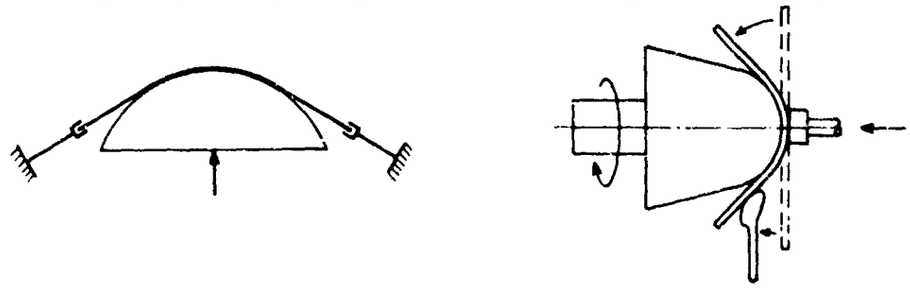
Alternatively, the ratio of blank to punch diameter is expressed as a draw ratio:

$$\text{Draw ratio} = D/d \tag{2.43}$$

The percentage reduction in diameter is usually given for redrawing and the reduction in area (Eq. 2.23 or 2.24) for ironing.

Redrawing and ironing are closely related to the drawing of tubes over a bar, which has been dealt with in Section 2.3. Because of its practical importance, drawing with a blankholder will be discussed in more detail. Drawing with a flat-bottomed punch is probably the most widespread, but drawing performed with a hemispherically ended punch is also of importance for test purposes and, by analogy, in the drawing of curved shapes. In the latter case, the punch first contacts the blank at a single (central) point, and deformation begins by stretching. This situation occurs in many practical drawing tasks—for example, in the production of automobile body panels. The amount of stretch to which the material is subjected depends, among other variables, on the restraint provided by the blankholder. Often it is desirable to increase the restraint by incorporating draw-beads in the mating blankholder and die surfaces, on which the sheet must bend and unbend before it can be pulled into the draw gap.

With the sheet edges completely clamped, pure stretching is obtained; this is the principle of specially built stretch forming machines (Fig. 2.24a).



(a) (b)

Fig. 2.24. Sheet metal deformation by (a) stretching and (b) spinning [73].

The punch is replaced by a fluid in hydraulic bulging. Parts of rotational symmetry may be produced by the process of spinning (Fig. 2.24b), which entails a special form of bending and compression. Although friction is by no means a negligible factor, it has not been subject of a systematic inquiry and will not be considered further here.

2.62 Velocity Distribution

Sliding velocities between the blank and the various parts of the deep drawing tooling are highly variable and a qualitative picture of the variations may be obtained from Fig. 2.25b. Relative sliding over the punch is minimum, since the sheet is essentially folded onto it. The vertical walls of the partly formed cup slide at a speed equal to the draw velocity v over the cylindrical portion of the die surface. Sliding speed gradually diminishes around the draw die radius and in the undeformed part of the flange. While all parts of the flange move in a radial direction towards the center of the punch, the flange circumference is also continuously reduced, leading to a circumferential compressive deformation. Consequently, relative sliding between the blank and the die must gradually decrease towards the edge of the blank. The same sliding velocities are, of course, attained between the blankholder and the upper surface of the blank.

Since drawing is usually performed on hydraulic or mechanical presses, drawing speeds are relatively modest (of the order of 1 to 10 ips); the maximum interface sliding velocities must be of the same order of magnitude.

In drawing with a hemispherical punch, contact with the vertical surfaces of the draw die is established only after the hemispherical punch has penetrated the sheet. Sliding over the punch face is somewhat greater than in drawing with a flat-bottomed punch; however, the velocities are still very small.

2.63 Stress Distribution

Deep drawing with a flat-bottomed punch may be visualized as a sequence of a number of separate events. First, the sheet is bent around the radius of the punch. Adjacent annular zones are then bent around the die radius, and unbent again to form the vertical wall of the cup. Material around the die draw radius and in the undeformed flange is circumferentially compressed. Plastic buckling (wrinkling) of the flange occurs if the blankholder

pressure is not high enough. Obviously friction plays a significant, but quantitatively complex role at all interfaces where relative sliding takes place. Some theoretical approximations of the forces developed in deep drawing are available (for example, by Geleji [5], Chung and Swift [70], and Fukui [71]; reviews of some of the theories may be found in Alexander [72]). While the effect of friction is usually incorporated into theoretical solutions, quantitative treatments have little to offer from our standpoint, because the various components of the friction contribution are difficult to separate. It should suffice here to consider interface friction on a qualitative basis, with reference to Fig. 2.25a.

Initially, the flat end of the punch carries the total drawing load. As the cup begins to form around the punch radius, friction over this interface helps to support the drawing load the same way as it does in drawing a tube over a bar (Eq. 2.33). Because unbending of the previously bent walls occurs between the cylindrical land of the die and the punch, interface pressures may be expected to reach moderately high values at the appropriate places, marked in Fig. 2.25a. Highest pressures are likely to occur around the draw radius. Pressures on the partially formed flange are usually relatively low, as determined by the blankholder pressure; they are likely to increase toward the edge of the flange, because circumferential compression thickens this section and the blankholder load will be concentrated there. From an inspection of part-drawn cups it would appear that the blankholder pressure reaches the yield strength of the sheet material only in the outermost parts of the flange.

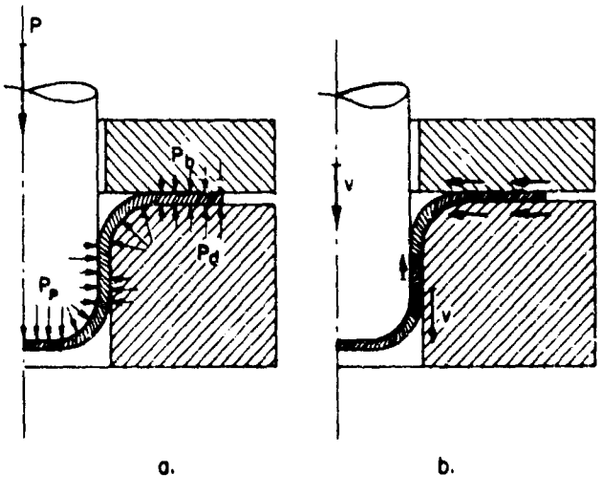


Fig. 2.25. Deep drawing with blankholder: (a) variation of interface pressures and (b) relative sliding velocities.

It is obvious from this qualitative assessment that the drawing force always decreases with decreasing blankholder and die friction. This is of great importance since tensile stresses acting in the cup walls set a limit to drawing.

In drawing with a hemispherical punch, drawing proceeds initially by stretching the sheet in a biaxial stress system. Maximum tensile stresses are produced in the hemispherical part, or at the transition to the cylindrical wall. Interface pressures reach highest values over the punch nose and over the draw radius. Variation of stresses under the blankholder are the same as in drawing with a flat-bottomed punch.

2.64 Strain Distribution

Since the drawing force is initially supported by the base of the cup, tensile stresses are generated in the area around the punch radius and in the initially drawn cup wall. Consequently, thinning of the sheet occurs, and if the uniform elongation of the material is exceeded, necking and finally fracture set in. Friction over the punch surfaces restricts material movement, and helps to support the drawing load. Therefore, thinning is less and fracture may be avoided. A combination of these requirements results in the need for low friction under the blankholder and on the draw die and for high friction on the punch. This has led to the practice of differential lubrication (Section 11.27). Circumferential compression in the outer zones of the blank causes thickening, and the thickness of the cup close to the upper edge may exceed the available draw gap between punch and die. In the final stages of drawing the cup will then be subjected to ironing, and high friction on the punch surfaces coupled with low friction on the die surface will help in obtaining a sound product.

In hydraulic bulging there is, of course, no friction on the "punch" side, although friction may be generated on the female die if one is used at all.

Thinning may be excessive in the bottom of cups drawn with a hemispherical punch and, with zero friction, fracture could occur at the nose of the punch. With increasing punch friction, sliding of the sheet over the punch is hindered, localized thinning is reduced, and a deeper draw is obtained.

2.65 Heat Generation

Even though the total work of deformation is usually considerably less in sheet metal working than in bulk deformation processes, the heat of deformation and of friction combine to give a temperature rise of usually 30-80°C. While bulk temperature increase is relatively modest, it is conceivable that higher flash temperatures are generated in the lightly loaded contact areas, where only asperities contact the die surfaces. This could be important in activating some of the extreme pressure additives, although no evidence of such occurrence is available.

2.66 Process Limitations

The effect of friction is often quite dramatically illustrated in deep drawing. When the drawing force is high enough to cause tensile separation of the part-drawn cup wall, the workpiece becomes scrap. Frequently a very small drop in friction is sufficient to allow drawing of a sound product. The maximum deformation that can be obtained in a simple cupping test is often expressed by the limiting draw ratio (LDR)—that is, the largest ratio of blank diameter to punch diameter that can be drawn without failure. This is, of course, largely a material property, but is also influenced by the sheet thickness relative to the punch diameter and by friction. For a given standard material, the limiting draw ratio may be used as an expression of lubricant quality. It is important, though, that the lubricating conditions be well defined. Thus, for reasons outlined above, greater draws can be achieved with an unlubricated or even roughened punch than with a well-lubricated one. Similarly, in drawing with a hemispherical punch, a dry or roughened punch face helps to distribute the strain and thus give a deeper draw, expressed either as the depth of draw in a part-drawn cup or as the limiting draw ratio in a fully drawn cup.

2.7 SUMMARY

Metalworking processes achieve plastic deformation by applying a force through a suitable tool or die, either in direct contact with the workpiece or through an interposed lubricant film. Friction inevitably arises at the die workpiece interface, and may be expressed from the mechanistic point of view either as a coefficient of friction $\mu = \tau/p$ or as a constant interface shear strength $\tau_i = m \tau_0$.

Friction is, with some significant exceptions, an unwanted factor with a number of undesirable side effects. In general, it raises the forces and the power requirements, subjects the deforming tool to higher pressures, renders deformation less uniform within the workpiece, raises the temperatures at the interface, and may set limits to the maximum obtainable deformation.

Besides the actual magnitude of friction, its distribution is also of major importance. Whenever the product of the coefficient of friction μ and the interface pressure p exceeds the yield strength of the workpiece material in shear k_0, relative sliding between tool and workpiece ceases and sticking friction prevails. Deformation then takes place by subsurface shear in the workpiece material itself. In bulk deformation this could be a desirable situation because peak die pressure and wear of the tool material is often reduced even though frequently at the expense of wear of the workpiece material. In contrast, sliding friction normally entails wear of both die and workpiece material, and may represent a more severe condition, at least for the die material.

The consequences of friction may be most conveniently summarized according to the deformation process:

In rolling, friction causes interface pressures to increase to a maximum at the neutral point, giving rise to the so-called friction hill in the pressure distribution along the arc of contact. The friction hill may be very flat, amounting to only a few percent of the total pressure in well-lubricated rolling, but may double or triple the peak interface pressures in hot rolling or rolling with poor lubrication. The neutral point is close to the exit point with good lubrication and moves toward the center of the contact arc with poor lubrication. It thus determines the amount of forward slip, which in turn affects the amount of frictional heat generated and also controls the surface finish of the rolled product. Too low friction can be undesirable because the strip or slab may not be made to enter the roll gap; too high friction, on the other hand, may cause excessive roll forces, rolling torques, or may limit the minimum thickness to which the material may be rolled with a given roll diameter and tension balance.

Friction increases the drawing force in wire and tube drawing. Interface pressure drops with increasing friction, but this is an effect of minor importance. Friction increases the inhomogeneity of deformation, and is

contributory to the development of residual stresses and also to center bursts. With the exception of the drawing of tubes on a bar, friction also limits the maximum deformation that may be taken in a single draw.

Friction on the face of an extrusion die is significant, because it contributes to the inhomogeneity of deformation and can produce badly distorted material. Friction between the billet and the container wall raises the total extrusion force and may limit the maximum extrusion ratio by generating pressures in excess of those that can be withstood by the tooling. With very low friction it is possible to extrude through a square die (included angle 180°), but the die angle must decrease for higher friction if sliding along the die surface is to be maintained. Otherwise, a dead zone forms at the junction between container wall and die, and extrusion proceeds through this self-created die by shearing through the workpiece material. Although resulting forces are high, the freshly generated surfaces can be of good quality. However, lubricants must be excluded in extrusion with a dead metal zone, otherwise subsurface defects would form.

Friction effects in upsetting are often similar to those found in rolling, although the lubricant does not enter the interface continuously. A friction hill develops in open-die forging operations such as the upsetting of cylinders and in plane-strain compression. Friction must be very low if high interface pressures are to be avoided in forging relatively thin sections. These pressures may exceed the strength of die materials causing indentation of the die. Friction increases the forces also in closed-die (impression die) forging, but the effects are too complex and too little understood to allow generalized conclusions.

Friction is an important variable in sheet metal working operations, particularly in deep drawing. Increasing friction between the sheet and the blankholder and draw die surfaces increases the drawing force and may cause fracture in the part-drawn shape. In contrast, friction between the punch and the sheet may be beneficial in increasing the maximum possible draw with both flat-bottomed and hemispherical punches.

The review presented in this chapter has shown that the theory of metal deformation processes is of value primarily in predicting the effect of friction on forces and power requirements. This allows the design of equipment on a systematic basis; a comprehensive treatise due to Geleji [74] is available on this aspect. Other effects of contact between the tool and workpiece

are often difficult to characterize in the same quantitative fashion. The control of friction and, often more importantly, that of wear is possible only through a suitable choice of process conditions, die materials, and lubricants. Many successful solutions have been found purely empirically; to understand the reasons for these successes and to attempt the development of better solutions, fundamental knowledge relating to the subjects of friction, lubrication, and wear (Chapters 3 and 4) must be considered, which then leads to a more balanced view of the desirable attributes of lubricants (Chapter 5).

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Chapter 3

FRICTION, LUBRICATION, AND WEAR MECHANISMS

Charles H. Riesz

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A wealth of information is available on friction, lubrication, and wear. Most of this material deals with the problems of lowering friction, minimizing or controlling wear, and the effective performance of machinery elements. The sliding or contacting metal surfaces are often found to suffer localized plastic deformation of surface irregularities, and this has led to theories and hypotheses useful in extending knowledge to new areas. Under these conditions the bulk metal is only elastically deformed and, therefore, not permanently affected. On the other hand, in metalworking processes, the workpiece undergoes extensive plastic deformation in contact with a tool or die and concepts must be modified accordingly.

The purpose of this chapter is to survey friction, wear, and lubrication mechanisms in order to highlight those aspects which may have a counterpart in metalworking processes. Attention is directed, wherever possible, toward the ultimate application of this information to a useful understanding of metalworking friction and lubrication. Additional sources are cited to enable the reader to explore a particular subject in depth.

3.1 DEFINITIONS

In the most elementary situation, when one body slides over another, the resistance to motion is called friction. It is found that the frictional force F is proportional to the normal load P and therefore a coefficient of friction μ can be defined:

$$F = \mu P \tag{3.1}$$

This relationship has been recognized for hundreds of years (Section 1.15), and it is still acceptable for many purposes. While early workers assumed a constant coefficient of friction, it is now known that, actually, even the coefficients of dry friction are sensitive to many influences. Furthermore, it should be noted that, in certain instances, sticking friction can occur and μ will have little significance. It was already shown that, for practical purposes, μ is a most useful concept under elastic contact conditions but has only limited value for bulk deformation processes (Section 2.12). Although friction is commonly considered undesirable, it performs a vital function in brake linings, clutch surfaces, and the anti-skid properties of tires. The "bite" or entry friction of the sheet in cold rolling is a pertinent metalworking example (Section 2.26).

The definition of wear that best fits the general situation is given by the OECD (Organization for Economic Cooperation and Development) Group on Wear [1]: "the progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface." Later, we shall see that many effects can contribute to wear including not only mechanical action but also surface fatigue, corrosion, and thermal effects. Only the German literature distinguishes between Abnutzung (wear plus corrosion) and Verschleiss (wear). Although wear may be generally regarded as detrimental, in certain cases it may be beneficial as in "running in" of new machinery elements.

Lubrication aims at the reduction of friction and wear through the use of lubricants between load-bearing surfaces. To suit the situation, lubricants can exist as fluid films, thin films, boundary layers, and often as solid layers formed or deposited by various means. Under appropriate conditions, even gaseous lubrication can be used. Because of the diversity of lubrication requirements, many practical lubricants are viscous fluids containing additives to accomplish specific functions. The cheapest and most widely used viscous fluids are mineral oils, but synthetic organic polymers have more recently been introduced to achieve specialized goals. Vegetable and animal oils and fats not only act as viscous fluids, but the generally high content of free fatty acids also provides boundary lubrication properties. For metalworking operations, the additives also include solids which themselves have lubricating properties (e.g., graphite, molybdenum disulfide, talc). The "soluble oils" are, in reality, concentrated oil-in-water emulsions containing emulsifying agents; they can be readily diluted with water for use, particularly in cold working. A detailed discussion of lubricant components will be found in Chapter 4.

The above survey has introduced a number of concepts that may or may not be familiar; they will be discussed in the following sections.

3.2 FRICTION

3.21 Laws of Friction

Two classical laws describe friction in essentially elastic contact. The first law indicates that frictional resistance is proportional to the load; the second law states that the frictional resistance is independent of the area of

contact. These laws date back to Leonardo da Vinci (1452-1519) and to Amontons (1699). Later, Coulomb (1781) distinguished between static and sliding friction, observing that the force required to maintain sliding was significantly lower than the force required for the initiation of sliding. His observation, or the so-called third law of friction, states that kinetic friction is nearly independent of the speed of sliding. Coulomb also theorized that static friction was due primarily to the interlocking of surface irregularities with adhesion playing a subordinate role. The three laws together provide a quantitative framework for frictional studies.

The laws have been confirmed experimentally under limited conditions, but the origin of friction has remained the subject of considerable study. It should be emphasized that these criteria apply only in the instance of "dry" friction—that is, in the absence of intentionally added lubricants or solids, but in the presence of "normal" amounts of surface oxides, moisture, and possibly the contaminants inherent in industrial atmospheres. The laws also apply to boundary lubricated sliding that will be discussed later (Section 3.45).

3.22 Development of a Theory of Friction

When two "dry" surfaces are pressed together, either statically or in sliding contact, the real contact occurs only at the tips of surface asperities. According to the most generally accepted theory of friction, limited plastic deformation of asperities takes place under intense local stresses and, if surfaces are very clean ("virgin surfaces"), cold welding occurs. The work of shearing these welded junctions upon tangential sliding gives rise to a resisting frictional force, and their deformation and fracture lead to wear and to metal transfer between surfaces. These ideas have been pursued most vigorously by Bowden and Tabor [2, 3]. Variations and refinements have been proposed by many, including Kragelskii [4], Rabinowicz [5], and others. Before discussing the most recent and generally accepted views, it is of value to discuss the general development leading to a theory of friction.

Molecular Theories

Tomlinson [6] proposed a theory based on the molecular forces existing between clean contacting surfaces. He suggested that the field of molecular attraction extends to a distance of several diameters from a surface molecule while a repulsive force field exists at a much shorter distance. Molecules from an opposing surface that come within this repulsive field and

then separate provide a loss of energy which is manifest as friction. An alternation of attraction and repulsion occurs that causes both friction and heating. In his complete theory, an attempt is made to calculate frictional forces from empirical constants derived from elastic moduli.

The molecular attraction theory has been studied in particular by Russian investigators including Deryagin, Epifanov, Adirovich and Blokhintsev, and Kragelskii. These views are summarized by Kragelskii [4] and by Akhmatov [7]. According to this school of thought, the common origin of all kinds of friction must reside in the atomic interactions of the bodies participating in the friction process. The forces originating from the approach of solids have been demonstrated experimentally [8]. These considerations indicate that interactions on an atomic scale produce appreciable forces. Whether these fundamental considerations play a small or major role depends, in large part, upon the presence of absorbed surface layers and surface oxides as well as the nature of the bulk of the material (e.g., whether it is annealed or work-hardened). The molecular concept of friction is of greatest value in relation to degassed surfaces in ultrapure environments such as occur in high vacuum or outer space. With respect to most practical applications, the view is still fundamentally correct, but highly disturbed and contaminated surface layers can so dominate the frictional processes that molecular attraction is reduced to only a small part of the whole picture.

Welding Theory

The best known theory of dry sliding friction is due to Bowden and Tabor [2, 3] and their colleagues at Cambridge. Although originally developed for and generally applied to metallic friction, it has subsequently been extended to many other types of materials. The theory does not require specific reference to atomic interactions; rather, it is based on the fact that even the best surface finish is not flat and smooth on a molecular scale (see Section 5.6). Typically, lapped surfaces have an average roughness of about 0.02 microns (200 Å) and finely ground surfaces can readily be ten times rougher. Therefore, when two apparently flat metal surfaces of apparent area A_a are pressed together by a load normal to their mutual interface, they will touch only at a few relatively isolated regions A_r (Fig. 3.1). Locally, the pressure at these contacts is so high that the asperities of the two metals deform plastically as the local pressure reaches the yield pressure (indentation hardness) p_m of the softer material. As the load is further increased,

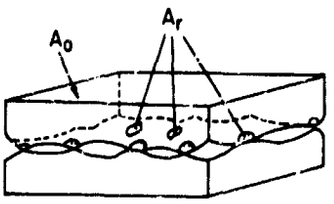

Fig. 3.1. Microscopic representation of two metal surfaces in contact.

the surfaces approach each other more closely, the original areas expand in size, and new contact areas are formed as well. If the projected real area of contact is A_r and the average value of the yield pressure is p_m, then the load P is supported by the sum of all such contact junctions or

$$P = A_r p_m \tag{3.2}$$

With dry, clean metal surfaces, it is postulated that the surfaces cold weld at these contact regions, creating welded junctions with a mean shear strength τ_m; this may reach the shear yield strength τ_0 of the softer metal. The frictional force required to shear these junctions is:

$$F = A_r \tau_m \tag{3.3}$$

The coefficient of friction can then be defined as:

$$\mu = \frac{F}{P} = \frac{A_r \tau_m}{A_r p_m} = \frac{\tau_m}{p_m} \tag{3.4}$$

Inasmuch as shearing usually occurs within the softer of the two metals in contact, the coefficient of friction can be expressed in terms of the material properties of this metal. Since τ_m and p_m are strength properties of the same metal, they vary simultaneously and their ratio for a diverse range of metals is constant, at least to a first approximation. Work hardening causes τ_m and p_m to change, although not necessarily in the same proportion. As will be shown later, surface oxides and films formed by normal atmospheric contamination can also influence observed values of μ.

An important consequence of the cold welding postulate and subsequent derivation of Eq. 3.4 is that it affords a satisfactory explanation of the first two laws of friction—namely, that the frictional force is proportional to the load and is independent of the apparent area of contact. As mentioned before, these laws apply only to contact conditions characterized by plastic

deformation of the asperities of the softer member. If both members of the system deform elastically, the area of contact will be proportional to $P^{2/3}$, according to the analysis of Hertz [9]. Correspondingly, the coefficient of friction should appear to fall with increasing load. However, Archard [10, 11] pointed out that the Hertzian analysis applies only to a single contact; if the surface is regarded as spherical with many small spherical protuberances superimposed on it, the exponent of P will increase and tend toward unity as the size of superimposed spheres is reduced. For large complex surfaces with distributed contacts, both elastic and plastic deformation will produce proportionality between F and P and, thus, a constant coefficient of friction. (A review of the effect of solid areas of contact on friction was given by Jones et al [12]).

If the spherical slider is much harder than the flat surface, a groove will be cut or plowed and additional work will be expended to displace metal. Thus, for such systems, a plowing term should be added to the shearing term to give the total frictional force. Under most practical metalworking conditions, however, the contribution of plowing is small or negligible, except when the tools are rough or adhesion causes well-defined projections to form on one of the contacting surfaces (pickup). Workpiece asperities will, in general, be flattened, and this will require work too.

The concept of cold welding of asperities has proved useful as a simple explanation of the mechanism of dry friction and wear, and it has been confirmed by experiments conducted under controlled conditions. Perhaps the most convincing demonstrations are those in which radioactive sliders leave fragments behind that adhere strongly to the other surface. Direct evidence of adhesion was found for exceptionally clean soft metals in air [13] and for harder metals in vacuum [14]. The subject of adhesion is further discussed in Section 3.25.

Modified Welding Theory

The junction welding theory as presented originally was soon recognized to be oversimplified. A great deal of attention has been directed toward amplification of details of the process and toward the development of more exact theories.

Feng [15] suggested that, under intense locally applied normal and shearing stresses, the interfaces of high spots are roughened as the result

of plastic deformation. Mechanical interlocking and the accompanying strain-hardening causes breakage a certain distance away, and the resulting fragment is welded to the other surface. Thus, welding of a fragment is considered a consequence of friction, whereas the welding theory considers welding as the source of friction.

Kragelskii [4] proposed that the interaction between surfaces is of a dual molecular-mechanical nature, depending on the geometry of the contact (shape of asperities and depth of contact), the specific properties of the bulk material, and the presence and type of films. In contrast, Barwell [16] suggested in a detailed review of the nature of friction that welding or positive adhesion between surfaces is not essential and that plastic deformation of surface regions can account for the observed frictional behavior. It is certainly important to realize that the problem of contact is statistical, and there is real danger in concentrating attention on the behavior of a single junction without regard to the surface as a whole.

Junction Growth Theory

A serious deficiency of the elementary welding theory is that it ignores the interrelationship of the combined action of the shear and normal stresses. Since the metal is deforming plastically at localized regions, both stresses contribute to the yielding. For a two-dimensional single junction, the von Mises yield criterion predicts that plastic flow will occur when

$$p^2 + 3\tau^2 = \text{constant} \tag{3.5}$$

No rigorous treatment exists for a three-dimensional junction, but it can be expected that a similar relationship of the form

$$p^2 + \alpha\tau^2 = \text{constant} = p_m^2 \tag{3.6}$$

should hold [17]. If initially the two surfaces are pressed together by a normal force, the normal stress p active over the real area of contact A_r is equal to the yield pressure (indentation hardness) p_m of the softer material. The total load P is then supported by an area A_r

$$P = A_r p_m \tag{3.2}$$

As soon as the smallest tangential force is applied, a shear stress τ is introduced and the normal pressure must fall to a lower value. This occurs

by the growth of the junction—that is, by increasing the real contact area to A_r' to satisfy the condition $P = A_r' p$. In consequence, the frictional force is no longer proportional to the normal force, and Amontons' law ceases to hold.

Various experimental measurements confirm the growth of junctions according to this model. McFarlane and Tabor [13] evaluated junction growth for steel sliding on indium, and the growth of indium junctions on a glass plate was observed visually by Cocks [18]. Junction growth with harder metals such as copper, platinum, nickel, and silver can also be demonstrated provided the surfaces are thoroughly cleaned [14]. Upon interrupting an experiment, it is found that the normal pull required to separate the contacting material pair can be as high as ten times the original load, giving a direct proof of junction growth occurring under combined normal and shear stresses and explaining the high friction values ($\mu = 1.0$–2.0) measured with clean surfaces. The simple welding theory is particularly inadequate for this situation because with $\tau_0 = \sigma/2$ and $p_m = 3\sigma_0$ the predicted friction coefficient would be only $\mu = 0.16$ from Eq. 3.4. Even if it were assumed that an asperity could be deformed in uniaxial compression, a maximum coefficient of only $\mu = 0.5$ would be predicted. Experiments by Butler [19] and Fogg [20] have shown that the indentation hardness p_m is usually in excess of $2\sigma_0$ (closer to the theoretical $p_m = 3\sigma_0$ cited above), confirming the need for the junction growth theory.

Perhaps the most convincing evidence is found in the work of Courtney-Pratt and Eisner [21], who evaluated directly the effect of tangential force on junction growth in carefully conducted experiments. Junction size was measured by electrical contact resistance, and tangential displacements of only a few microns were determined by multiple-beam optical interferometry. These experiments show that junction growth is indeed a consequence of combined stresses and plastic flow. Even more important is the observation that initially the growth occurs in exactly the same manner for both lubricated and unlubricated contacting surfaces; however, with clean surfaces, the growth can continue indefinitely whereas with a lubricant present, growth ceases at a very early stage for a particular limiting value of shear stress.

These findings permitted Tabor [17] to extend the junction growth model by analyzing the effects of an interfacial layer interposed between the contacting surfaces. This layer could be a contaminant film as well as a

boundary layer of lubricant, presenting an interface of shear strength r_i. As long as the imposed shear stress is below this value, sliding and junction growth occurs as predicted by Eq. 3.6, which may be also written in the form,

$$p^2 + \alpha r^2 = p_m^2 = \alpha r_o^2 \tag{3.7}$$

When shear stresses reach the shear strength of the interfacial film r_i, junction growth will cease and the layer will be sheared at a stress independent of the magnitude of the normal stress. Macroscopic sliding will then ensue, and the area of the junction will have increased to some value A_r'.

The shear strength of the interface may be expressed as some fraction m of the shear strength of the metal r_o

$$r_i = m r_o \tag{2.3}$$

and, for the onset of sliding, Eq. 3.7 can be rewritten

$$p^2 + \alpha r_i^2 = \alpha \left(\frac{r_i}{m}\right)^2 \tag{3.8}$$

Rearranging gives,

$$p^2 = r_i^2 \alpha \left(\frac{1}{m^2} - 1\right) = r_i^2 \alpha \left(\frac{1 - m^2}{m^2}\right) \tag{3.9}$$

The coefficient of friction can then be expressed in terms of only m and α.

$$\mu = \frac{F}{P} = \frac{r_i A_r'}{p A_r'} = \left[\frac{m^2}{\alpha(1 - m^2)}\right]^{1/2} \tag{3.10}$$

This form of the coefficient of friction is very revealing in terms of the frictional mechanism. When m approaches unity, as it would on very clean metal surfaces, μ will attain high values, in agreement with experimental evidence. As soon as m is decreased even slightly, μ will fall to low values typical of practically clean surfaces. For example, if m = 0.95, μ becomes approximately unity (with α taken as 9 from experimental evidence).

If a boundary film is present and is readily sheared in comparison to the metal, a condition is reached that is most important in metalworking lubrication. For values of m less than about 0.2 the term m^2 can, with little error, be eliminated from the denominator of Eq. 3.10, which then simplifies to

$$\mu \approx \left[\frac{m^2}{a}\right]^{1/2} = \left[\frac{m^2 r_o^2}{a r_o^2}\right]^{1/2} = \frac{r_i}{p_m} \qquad (3.11)$$

or

$$\mu = \frac{\text{shear yield strength of interface}}{\text{yield pressure (indentation hardness) of substrate}}$$

The last equation is equivalent to the simple expression of Eq. 3.4. However, the derivation shows that cold welding is not essential to explain the mechanism of friction. Furthermore, the analysis leading to Eq. 3.11 emphasizes the importance of a boundary interfacial layer in determining friction. If the shear strength of the layer is appreciably less than that of the substrate metal (i.e., below about 0.2 r_o), junction growth can be considered negligible and friction is governed by the shear strength of the lubricant film.

We shall see later that in boundary lubrication the surface film interposed between the sliding metal surfaces can be exceedingly thin. There may be local regions where the film will be penetrated and where cold welding can occur. This is often insufficient to influence friction to any degree, but it might initiate adhesion, metal transfer, and wear. In metalworking, pick-up of the workpiece material on the die is liable to interfere with further lubrication and, in this way, seriously impair lubrication.

3.23 Mechanism of Friction in Plastic Deformation

The previously described principles apply primarily to contacts in which the bulk is only elastically deformed. Such conditions exist in bearings, seals, and gears. Even though surface pressures may be high, the contacting material pair is hard enough that the real area of contact is small and only the asperities deform plastically. Radically different conditions are created in deformation processes. The bulk of the workpiece material suffers plastic flow; in consequence, the real area of contact may approach—at least in the absence of a lubricant—the apparent area of contact, and extension of the surface exposes large virgin surfaces.

Once mean interface pressures are large enough to initiate bulk plastic flow, the coefficient of friction cannot be meaningfully described by Eq. 3.4. As discussed in Section 2.12, the interface pressure may range from the uniaxial yield strength σ_o to multiples of this value. The interface shear

strength, on the other hand, cannot exceed the yield stress of the workpiece material in shear τ_0, because the presence of a stronger interface layer will simply cause shear to take place below the surface, in the bulk of the workpiece material (sticking friction, not to be mistaken with static friction). Consequently, the calculated maximum possible friction coefficient decreases with increasing mean interface pressure, as shown in Fig. 2.2. It appears that Shaw et al. [22] were the first to consider this effect in some detail.

The argument is, of course, predicated on the assumption that τ_0 is not affected by the normal pressure, and softening or strain hardening has the same effect on shear strength τ_0 as on the uniaxial yield strength σ_0, and the ratio of the two remains constant at 0.5 (or 0.577, if the von Mises yield criterion is used). There is, indeed, ample evidence to support this assumption, mostly from work conducted under high hydrostatic pressures, and also from experiments aimed at clarifying the effect of subsurface flow on the coefficient of friction.

In the work of Shaw et al. [22], a hardened steel ball was pressed into an SAE 1020 steel surface and then rotated (Fig. 5.9f) and normal load and torque were simultaneously measured. A small centered hole drilled in the plate allowed substantial plastic deformation at high normal pressures. At light loads, a constant friction coefficient of approximately 0.26 was measured, but its value dropped gradually as the normal pressure reached a multiple of the yield strength and approached a value of only 0.10. In a more detailed investigation by Lauterbach et al. [23], totally enclosed test pieces of copper and aluminum were used with similar results. Both investigations also included some lubricated experiments, and agree in that good lubricants prevent the onset of subsurface plastic flow even under high normal pressures, obviously by reducing the effective value of the interface shear strength τ_i. Peterson et al. [24] found that τ_0 increased with normal pressure, but the scatter of their data could obscure this rather inexplicable observation. Peterson and Ling [25] have also suggested that, at very high normal pressures, the workpiece material flows like a viscous fluid. In the absence of other corroborating evidence, the existence of such regimes must be regarded as doubtful at present.

It must be recognized that the contacting surfaces are never smooth and, in most instances, the softer workpiece material is rougher than the tool surface. It is well known from experience that bulk plastic flow can take

place even before the workpiece conforms to all microscopic details of the tool surface, and simple experiments [2, 3] have also confirmed these observations. The asperities on the workpiece material, in general, may be expected to be harder (stronger) than the bulk. However, they are also less easily deformed because of the geometric constraint imposed by the bulk metal. In many ways, the situation is similar to that obtained in the indentation of a large workpiece with a pointed indenter, where the measured indentation pressure could reach $3\sigma_0$ if indentations were spaced far enough apart. A more detailed consideration was given to this problem by Thomsen et al. [26] and Shaw [27]. Both arrive at the reasonable conclusion that sufficient pressure can be transmitted through the asperities to initiate plastic flow in the substrate. However, it should be noted that these treatments are oversimplified; recent experimental work, coupled with a numerical analysis of surface profiles, indicates that asperities depressed into the bulk of the metal cause the valley bottoms to rise and a more rapid conformance of the two surfaces occurs than would be expected from the simple treatment [28-30].

It must be emphasized that all the above considerations apply only if the surfaces are dry. Any liquid lubricant present may be trapped in surface irregularities or carried into the deformation zone by a combination of favorable process conditions; the deforming pressure is then transmitted through this lubricant film. This delays or prevents conformance of the surfaces and may even allow marked roughening of an originally smooth workpiece surface.

A detailed examination of the mechanisms of friction (and lubrication) is possible only after all relevant background information is available and will, therefore, be found in the appropriate sections of later chapters (Sections 6.2, 7.2, 8.2, 9.2, 10.2, and 11.2).

3.24 Stick-Slip

Under certain conditions, the relative sliding of two surfaces occurs in an intermittent fashion. The OECD definition [1] describes stick-slip as a "relaxation oscillation usually associated with a variation of the coefficient of friction with relative velocity or with duration of static contacts." The term stick-slip was first applied to frictional processes of this type by Bowden and Leben [31]. In the stick phase, there is a penetration of

surfaces and a growth of contacts. The duration of such contacts is determined by the relative sliding velocity and by the elastic characteristics of the system. Elastic deformation of the equipment permits relative displacement of the parts supporting the contacting members for a period of time until the lateral force builds up to a point sufficient to cause the sticking surfaces to break away and a rapid motion (slip) ensues. During sliding, penetration of the surfaces increases again and the process is reiterated in a periodic manner. Rabinowicz [5] presents a qualitative description relating the natural frequency and frictional properties of certain systems.

While the difference between low kinetic and high static friction serves to explain the origin of intermittent motion, it is important to recognize that in a perfectly rigid mechanical system stick-slip would not occur. All practical equipment contains elastic elements, one of which is most responsible for stick-slip. In laboratory friction testing apparatus, this is usually the arm carrying a slider. In metalworking practice, the elastic deformation of the long bar supporting the tube drawing mandrel (plug) often causes a troublesome chatter. Generally speaking, the existence of stick-slip in metalworking processes might imply improper process variables (e.g., force, speed, load pressure) for a given lubricant or failure of the lubricant.

3.25 Adhesion

An understanding of the mechanism of adhesion of metals is of fundamental importance in evaluating frictional processes under both local and gross deformation conditions. Adhesion can occur when two metals are pressed together either under a normal load or under combined normal and shear loading, and is evidenced when a measurable tensile force is required to separate the two surfaces. The phenomenon is put to practical use in the processes of solid phase welding; comprehensive treatment of the subject may be found in Tylecote [32].

Adhesion frequently has a less desirable significance in the realm of metalworking since, if it is allowed to become widespread, castastrophic failure could occur. It is adhesion of workpiece metal to tool material that causes severe scoring of the product in extrusion, sticking of the forging in the die in closed die forging, and pickup in drawing. Normally, it is reduced by the presence of absorbed films or oxides that preclude the formation of metallic junctions and, of course, one of the prime functions of a lubricant

is also prevention of such metallic contact. Adverse process conditions can cause breakdown of the surface film, allowing new metal surfaces to come into contact with the tool. Under these conditions, adhesion between tool and workpiece materials will determine the extent of the surface damage that can occur.

Unfortunately, the majority of information that has been generated on adhesion concerns similar alloy pairs, or elemental metals, and relatively little information relevant to industrial adhesion problems is available.

Similar Metals

McFarlane and Tabor [13] made an extensive survey of the adhesion of soft metals. When indium—a soft ductile metal, which does not oxidize readily—is pressed on itself, the force required to separate such a system is approximately equivalent to the static pressing force. Analogous to the coefficient of friction, the ratio of separating force to normal pressing force is called the coefficient of adhesion, which in this case is unity. When an additional tangential stress is applied, adhesion increases markedly as a result of junction growth. Bowden and Rowe [14] demonstrated that a reasonable correlation can be made between the normal adhesion of several nonreactive metals (gold, silver, platinum, and nickel) and the tangential prestressing force. The experiments suggest that asperity bridges of one micron diameter were formed which severed upon stretching by approximately 100 Å, or 1% of the bridge diameter. Such estimates and calculations may involve considerable error but are helpful in providing a picture of the adhesion process under mild sliding friction conditions.

Temperature has a marked effect on adhesion. Bowden and Rowe [14] noted that many metals do not adhere strongly at low temperature because of a lack of ductility of the junctions. Annealing or heating at elevated temperatures produces a marked increase in the adhesion. Because of the effect of annealing, the temperature for the onset of strong adhesion is around the homologous temperature (half the melting point expressed in absolute temperature). The duration of normal pressure application also influences adhesion at a given temperature within the annealing range.

Factors governing adhesion are not well understood even between similar metals. Sikorski [33] conducted an extensive series of twist-compression experiments in which flat ends of two bars (one hollowed out) were pressed and twisted together, and then the force of adhesion was measured. The

data of Fig. 3.2 correlate the coefficient of adhesion so obtained with hardness determined on the faces of samples after separation. The sticking tendency decreased with hardness: hard metals such as cobalt, rhodium, and iridium gave little adhesion, whereas soft metals such as indium, lead, aluminum, and gold adhered strongly. This effect is possibly associated with the recrystallization temperature of the materials, so that if the hard materials were taken to a temperature above that of recrystallization, they too would exhibit high adhesion. Very clean surfaces would adhere even at low temperatures.

Another feature observed is the relationship of crystal structure. The data for both face-centered and body-centered cubic metals follow one law, but the hexagonal close-packed metals with a large c/a ratio follow another law corresponding to much lower adhesion. For these metals there is only one well-developed slip plane (the basal plane), whereas other crystal structures have several. Consequently, when polycrystalline cadmium, zinc, or magnesium slides against itself, shearing of metal at the interface is difficult because of this limitation in deformation mode. This limits the

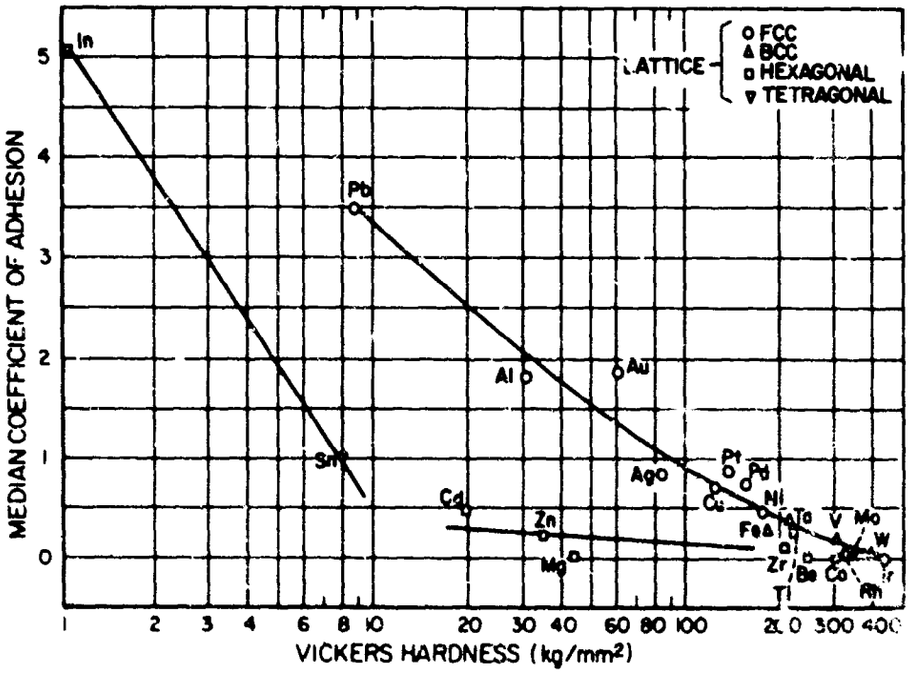

Fig. 3.2. Influence of hardness and lattice structures of elemental metals on adhesion [33].

amount of surface conformation at the interface and also the adhesion. Conversely, because of this easy separation plane, most hexagonal metals (including zinc, titanium, and zirconium) show relatively severe wear damage.

Rabinowicz [5] has demonstrated by several approaches that surface energy is counteracted by volume energy and that W_A/p_m represents a balance between these forms of energy, where p_m is the penetration hardness and W_A represents the work of adhesion, the energy that must be supplied to create an interface of 1 cm^2. Two surfaces, each having an energy γ_A, are created and the interface energy is lost. The data of Sikorski [33] show a good correlation with W_A/p_m. It should be noted, however, that these data are very much dependent upon surface contamination, which can substantially increase the threshold deformation for adhesion in tests such as roll bonding or twist compression.

Dissimilar Metal Pairs

It is well known that wide differences in adhesion characteristics can occur in metalworking processes by changing the material of the deforming tool. A striking example is in the drawing of tantalum wire, which has importance as a surgical material. Tantalum cannot be drawn through steel or tungsten carbide dies with conventional lubricants because pickup occurs and both wire surface and die will be considerably damaged. Dies made of aluminum bronze permit drawing of a sound product, although because of the relatively low hardness of aluminum bronze, a high rate of die wear will have to be accepted. Nevertheless, severe damage to the workpiece material can be eliminated.

With such differences in behavior possible, it is obviously most important to have criteria available which will enable prediction of the adhesion characteristics of dissimilar metal pairs, both for metalworking and for bearing materials. Several theories have been proposed for this purpose, and although their application to metalworking practice is currently rather limited, they represent at least a useful starting point.

Perhaps the best known of these theories is the solubility theory. The criterion of solubility may be set in various forms. In the sliding of unlike metals of similar hardness, Shaw and Leavey [34] noted that if the two metals were immiscible in the liquid state, sliding friction was low, but if the liquids were miscible and they also formed solid solutions or intermetallic compounds in the solid state, then friction was high. Ernst and

Merchant [35] later suggested that solid solubilities should be examined at the sliding temperature. If unlike metals were mutually insoluble at the sliding temperature (room temperature in the work of Ernst and Marchant), low friction would result, while a range of solid solubility would generally indicate high friction and adhesion. Coffin [36] correlated low friction and adhesion with very low solubility of the solid (higher melting point) metal in the liquid (lower melting point) metal. Takeyama and Ono [37] considered the maximum solubility of the lower melting point metal to obtain correlation with adhesion observed in metal cutting.

After Underwood's observation [38] that bearing metals employed with steel were in the B subgroup of the periodic table of elements, Goodzeit et al. [39, 40] tested several metals against iron and mild steel by means of slider-on-disk tests. They found that for low friction the metals should be insoluble both in iron and in the B subgroup. Rabinowicz [41] considers that there is correlation between solubility and atomic size, which in turn determines the position of an element in the periodic table. Therefore, the predictions of Goodzeit et al. [39, 40] are similar to those of other workers who consider only solubility. Goodzeit did find that the concept of position in the periodic table was not relevant if the metal pair investigated did not include iron.

Thus, the concept of solubility may be interpreted in numerous ways but, in general, it provides sound guidelines for the friction and adhesion behavior of dissimilar elemental metal pairs. Further evidence for the solubility theory has been provided by Aynbinder and Pranch [42], Navara [43], Cotfin [44, 45], Hazlett [46], Weiss and Hazlett [47], and Newnham and Schey [48]. It should be remembered that, in all of this work, contamination plays a significant part in determining the observed variations in friction. There is little doubt that with perfectly clean surfaces, friction welding would occur for all metals in the tests employed. However, in some of the tests metal-to-metal contact will occur, even in the presence of contaminant films, because of the severity of the tests. It is here that the solubility theory can give some indication of the relative adhesion tendencies.

Another theory of metal adhesion is concerned with surface energy of adhesion, W_{AB}, where A and B represent two unlike metal surfaces. Machlin and Yankee [49] found that the ratio of work of adhesion to the strength of the weaker component gave an indication of the degree of

adhesion of the metal pair. This is essentially similar to the concept of Rabinowicz [41, 50], who utilizes the ratio of surface energy of adhesion to penetration hardness of the softer material, W_{AB}/p_m. However, Rabinowicz [50] notes that direct measurements of W_{AB} are unreliable, and that indirect estimates are needed. These indirect measurements are provided by measuring the angle of contact, θ, of the lower melting point liquid metal on the other, solid material, since

$$W_{AB} = \gamma_A \ (1 + \cos \theta) \tag{3.12}$$

Measurements of contact angle were suggested by Machlin [51] and by Coffin [52], who inferred that if the angle of contact was less than 90°, then the metals are compatible and friction and adhesion are high. Rabinowicz [50] has used data from wettability measurements, which must still be considered as of rather uncertain accuracy, since precise determination of the contact angle is rarely an easy task. However, using these data, Rabinowicz [50] calculated values of the ratio W_{AB}/p_m and found a general correlation with the average values of friction observed in the sliding experiments of several investigators. He noted that correlation between solubility and friction was poor; however, he used the rather doubtful technique of Shaw and Leavey [34] in assessing solubility data, in which solution in the liquid state is important.

In summary, it is apparent that criteria are needed for the prediction of adhesion and friction phenomena when dissimilar metal pairs are in contact. This has been shown to be important not only in bearing design [53] but also in metalworking [48, 54]. Theories involving surface energy have some relevance in practical observations, as can be seen from the work of Rabinowicz [41, 50], but the measurement of the work of adhesion, or even the angle of contact, presents serious difficulties in practical systems. Solubility theory appears to offer the most promise at the present time although the exact meaning of solubility requires greater definition. The theory has proved moderately successful in predicting the frictional behavior of elemental metals, and there is some indication that the behavior of alloys may also be monitored [55]. However, a comprehensive theory of metallic adhesion is not yet available. Much research needs to be done so that the interaction of materials can be predicted under practical metalworking conditions.

3.3 WEAR

The complex nature of wear has already been suggested by the definition given in Section 3.1. Broadly, the prime practical objective is to devise antifriction systems and lubricants that provide a minimum degree of wear. Laboratory wear experiments are usually designed to give measurable rates of wear under severe operating conditions; the accelerated action is desirable for purposes of rapid evaluation. In metalworking, wear refers primarily to the forming tool, constructed from a relatively hard and stable material, which is used to deform a relatively soft metal often at elevated temperatures. In this context, wear of the tool or die is to be minimized or avoided if at all possible. In the process of deformation, materials may also be worn away from the surface of the workpiece.

The survey given here will show that in machine elements a number of wear mechanisms can be identified, several of which also have importance in metalworking. Various wear mechanisms will be discussed first and their occurrence in deformation processes reviewed in Section 3.35.

3.31 Types of Wear

The types of wear are extremely diverse and not amenable to uniform treatment. The approach used by Burwell [56] is to discern, if possible, the basic mode of wear which then has its own laws. In practical situations, it would not be unexpected that more than one mode of wear would contribute, perhaps with complicating aspects.

Adhesive Wear

Adhesive wear occurs whenever two smooth surfaces slide over each other and—as a consequence of solid-phase welding—fragments are pulled from one surface to the other. Later, these particles can either retransfer or else form loose wear particles.

Abrasive Wear

Abrasive wear (abrasion) occurs when hard protuberances of one surface slide relatively to a second contacting surface and cause displacement or plowing ("two-body wear"); the wear particles formed are generally loose. A second form of abrasive wear is caused in a so-called "three-body" system where an external abrasive grit, loosened scale, or other foreign material is interposed between the surfaces or becomes imbedded in one of them.

Corrosive Wear

When frictional sliding takes place in a corrosive environment, corrosive attack of the exposed metal surface takes place. If a corroded film is originally present, the sliding action wears or breaks the film. Later, we shall see that chemical attack of a contacting suface can be beneficial when it is induced in a controlled fashion to provide a load-supporting E. P. film (Section 3.46).

Surface Fatigue Wear

Repeated sliding or rolling of one metal over another produces repeated loading-unloading cycles that gradually lead to the generation of surface or subsurface cracks; finally, portions of the surface break out. The term spalling is commonly associated with the formation of flake-like particles from rolling element bearings and gear teeth. A similar form of wear is exhibited by brittle, nonmetallic materials in which fracture of the surface leads to wear fragments.

Miscellaneous Forms of Wear

A number of other recognizable forms of wear will be mentioned briefly here. Fretting wear occurs when two contacting surfaces encounter oscillatory rubbing of small amplitude. Fretting corrosion involves fretting, but the separated wear particles may subsequently form oxides or other products which may act either as lubricants or as abrasives. Erosive wear results from the action of a fluid containing solid particles. Cavitative wear may occur in a region of rapidly collapsing vapor bubbles which generate local high temperatures or impact pressures. Oxidative wear results from chemical reaction with air and may be regarded as a form of corrosive wear. Thermal wear refers to the removal of materials due to softening, melting, or evaporation during sliding or rolling.

3.32 Mechanism of Adhesive Wear

It has been indicated in the previous section that wear can originate from many sources or combinations of sources. However, in cases when metallic fraction occurs either locally or over the whole surface, the formation, growth, and shearing of metallic junctions govern wear. Under these conditions adhesion at points of real contacts can occur and the formation of wear particles is a function of interface conditions.

1. The interface between the surfaces is slightly weaker than either of the two sliding materials. Shearing is limited to the interface, and wear is extremely small. The presence of surface or lubricant films will be important in minimizing wear.

2. The interface is stronger than one of the sliding metals and shearing occurs in the softer metal. Fragments of the soft metal adhere to the harder metal.

3. The interface is stronger than one metal and occasionally stronger than the second. Transfer of metal occurs mainly upon the harder metal, but fragments of the harder are also removed.

4. The interface is or becomes harder than either metal. This occurs particularly when identical metals slide on each other; the interface becomes work hardened, and severe damage occurs to both surfaces.

The above outline by no means covers all situations, but experimental evidence indicates that the friction will be substantially the same regardless of the wear mechanism. Whereas all sliding junctions contribute to friction, only a fraction of the formed junctions contribute to observed wear.

Archard [57] proposed a simple wear model in which a probability factor is assigned to represent this fraction. Consider a single circular junction of radius r, it will have an area πr^2 and will support a fraction of the normal load $\Delta P = p_m \pi r^2$ where p_m is the yield pressure of the metal. When this junction is sheared, it produces a wear fragment; on the basis of observation, Archard considered that a hemisphere of volume $\frac{2}{3}\pi r^3$ was representative of the wear debris. The wear fragment is formed during a sliding distance of 2r so that wear volume per unit of sliding distance is:

$$\Delta V = \left(\frac{1}{2r}\right)\left(\frac{2}{3}\pi r^3\right) \quad \text{or} \quad \Delta V = \frac{1}{3}\pi r^2$$

Since $\pi r^2 = \Delta P/p_m$, then $\Delta V = 1/3\ (\Delta P/p_m)$. For a statistical number of junctions, the same relation will apply for each junction. For geometrically similar junctions, the total wear volume V per unit distance of sliding will be given by

$$\frac{V}{\ell} = \frac{P}{3p_m} \tag{3.13}$$

where P is the total normal load.

The above reasoning implies that each junction formed yields a wear particle. If the probability that a wear fragment will actually be produced

from a given junction is expressed by the fraction K, the wear volume produced per unit of sliding distance is expressed as

$$V = \frac{KP}{3p_m} \tag{3.14}$$

To account for the large variations in wear rates, it must be assumed that the value of K varies over wide limits. For fairly clean surfaces, K may be in the range 0.1 to 0.01 whereas for "mild wear," K may be as low as 10^{-6}.

Although the above derivation involves many simplifying assumptions, it agrees with empirical findings which state that wear volume is proportional to load and the distance of sliding, and inversely proportional to the hardness of the surface being worn. Thus, for example, Holm [58] expressed the volume of wear in the following manner:

$$\frac{V}{\ell} = \frac{c\,P\ell}{p_m} \tag{3.15}$$

Here, V = total volume of wear particles formed in distance ℓ, and c is a dimensionless constant determined by experiment. The similarity of the empirical Eq. 3.15 with the derived Eq. 3.14 suggests that the junction areas and the shape and roughness of surfaces, within limits, do not influence adhesive wear.

The nature of the wear fragment has been studied by means of models such as plasticine [59] and of metals [60]. These studies suggest that transferred particles are formed when the plane of the junction is not parallel to the junction. If sliding surfaces, as postulated by Feng [15], become roughened through slip effects, fragment formation might be initiated by this means.

Cocks [61] found experimentally that plastic shearing takes place in a direction slightly inclined to the surface, creating wedges or prows of metals. With flat plates of copper-on-copper and aluminum-on-aluminum, these wedges are self-sustaining. Such prow formation, with a characteristic angle of shearing relative to the surface (Fig. 3.3) is a basic factor in wear even in deformation processes. Indeed, Rowe and Wetton [62] suggested that strip drawing at light reductions may serve as a large-scale model for general wear studies.

Since adhesion between the two contacting surfaces controls the probability of the formation of a wear fragment, adhesion between dissimilar

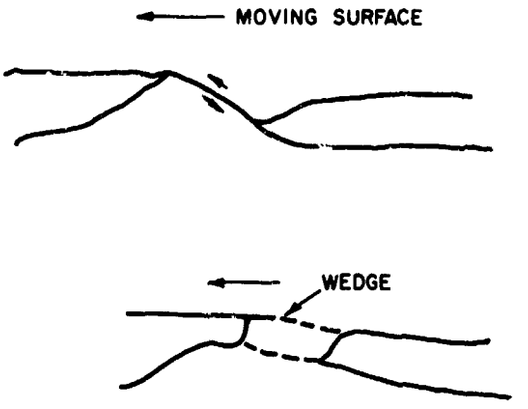

Fig. 3.3. Mechanism of wedge formation between sliding metal surfaces [61].

material pairs (Section 3.25) assumes a governing role. Metal transfer is usually mutual, although it is only to be expected that the wear rate of the softer material is higher. Materials that show marked adhesion wear at a higher rate; thus, in the experiments of Golden and Rowe [63], an aluminum alloy gave steady wear on tungsten carbide irrespective of the surface finish of the carbide, while copper provided a low rate that was governed more by the surface roughness of the carbide. Wear of aluminum was controlled by adhesion, and an abrasive mechanism more like machining was active on copper.

3.33 Abrasive Wear Mechanism

Abrasive wear, as defined in Section 3.31, is frequently encountered in metal finishing operations. Thus, two-body wear is found with files, abrasive papers and cloths, and abrasive wheels; the three-body type of wear is observed in polishing and lapping.

Assuming an asperity of a conical shape the following expression can be derived for the rate of wear [4]:

$$\frac{dV}{d\ell} = P\ell \frac{2\overline{\cot\theta}}{\pi p_m} \tag{3.16}$$

where ℓ is the distance traveled, P is the load, p_m is the penetration hardness of the softer surface, θ is the angle at which the cone cuts the surface, and $\overline{\cot\theta}$ is a weighted average for all individual cones. The expression is similar to the one derived for adhesive wear (Eq. 3.14), but $2\overline{\cot\theta}/\pi$ has

replaced K/3. While real asperities are more likely to resemble truncated cones, the expression also satisfies the empirically derived relation which states that abrasive wear rate is proportional to the load and distance of sliding and is inversely proportional to hardness. Expressions for abrasive wear rates are given by many authors including Rabinowicz [5], Mulhearn and Samuels [64], Goddard and Wilman [65], and Kragelskii [4].

3.34 Corrosive Wear Mechanism

Corrosive wear in machinery elements is normally a mild form of wear, but it can become serious at high temperatures. Under these conditions, it is possible that corrosive constituents of the environment (either present in the gaseous phase or derived from the liquid lubricant) first attack the surface followed by subsequent mechanical action that removes the corrosion products. In other circumstances, the frictional processes first produce a wear debris which is subsequently transformed by corrosion.

Oxidation, which may be regarded as a variant of corrosion, is often beneficial because the oxidized film serves to part the surfaces that otherwise might adhere strongly and cause wear at a high rate or possibly seizure.

3.35 Wear in Metalworking Processes

Wear in metalworking processes is difficult to categorize, partly because more than one mechanism can operate and partly because the deformation processes themselves are so different. In principle, all wear mechanisms may occur, but their importance varies with the workpiece and die material and with the process conditions.

Adhesive wear is, by and large, undesirable because in its more serious forms it is a consequence of lubricant breakdown which leads to pickup of the workpiece material on the die; scoring then accelerates the process and catastrophic failure soon follows. Out of necessity, controlled forms of adhesive wear are sometimes tolerated--for example, in the hot rolling of aluminum, where a coating of aluminum develops on the rolls and, if well controlled, contributes to productivity by allowing heavy reductions without serious impairment of surface quality (Section 6.51). Because large areas of virgin surface are exposed in all processes that result in substantial plastic flow, there is always danger of adhesion, and it is usually one of the prime functions of the lubricant to prevent this by efficient parting of the surfaces.

Once the object of eliminating adhesion is achieved, abrasive wear becomes the predominant mechanism. In the absence of a liquid lubricant, the workpiece material penetrates into minute depressions present in the tool surface. Some of the filled-in portions are then sheared off as the body of the workpiece moves by. If the surface is contaminated, the transferred metal will eventually emerge as loose wear debris, not damaging to the general process. The nature of the surface layers is, however, very important. If the oxide layers are deformable or friable, prevention of metal transfer or pickup is assured; wear is uniform and gradual and results in a slow change in tool shape.

In the presence of a liquid lubricant, trapping in the microdepressions of the tool greatly reduces the possibility of metal transfer and thereby the observed abrasive wear. These conditions, for example, apply to well-lubricated cold rolling. Lubricants may also be trapped in depressions deliberately formed in the workpiece, as by grit-blasting, or in a porous surface film, as by phosphating. As a corollary, exceptionally smooth contacting surfaces can lead to dangerous adhesion and subsequent abrasion or scoring because it becomes difficult to assure that an unbroken lubricant film will intervene between relatively large areas in the close conformity imposed by deformation.

Many metalworking lubricants contain corrosive, "extreme pressure" constituents added to provide a film of lubricating reaction products. If the amount of such additives is too high or the degree of decomposition is excessive, corrosive wear of the workpiece and of the die can occur. For example, chlorinated paraffins may lead to the formation of excessive amounts of hydrochloric acid; since the deformation processes always generate large areas of fresh, reactive surface, appreciable workpiece losses can result in conjunction with high temperatures. The nature of the wear debris or of the product surface provides clues for this type of wear.

Thermal shock, such as the intimate contact of relatively cold forging dies or rolls with hot workpieces, can induce minute cracks or crazing of the die material leading to tool wear. Thermal shock in conjunction with corrosive attack is also a distinct possibility as a mechanism of tool wear.

Fatigue stresses brought about by high cyclic contact stresses lead to surface fatigue wear, which assumes great importance in the rolls of rolling mills. In hot rolling, roll wear may be complicated by thermal fatigue

caused by rapid heating of surface layers in contact with the workpiece, followed by quenching with cooling water or cold lubricant. Minute surface cracks are induced (crazing) followed by spalling of wear particles under the influence of surface fatigue (see also Section 6.29). Similar processes may occur with forging platens and with tube-piercing plugs. The same mechanism probably applies to the ringing type of wear found in drawing (Section 7.26). Occasionally, corrosion accelerates the penetration of fatigue cracks, resulting in a wear mechanism akin to stress corrosion.

In some processes the unfavorable deformation characteristics of the metal require that the tools and lubricants be subjected to the limits of their performance. The tool surface may then be exposed to exceptionally high temperatures sufficient to soften it rapidly; for example, extrusion dies may be "washed out" by rapid erosion and plastic flow or, alternatively, the die opening may close up because of plastic yielding in the die. Then again, very high pressures imposed on a cold extrusion container may cause it to burst after only a few cycles (failure in low cycle fatigue). Such catastrophic tool damage is seldom tolerated, and remedy is often found only in a complete redesign of the process or in a change to a different, less demanding process.

Various aspects of wear encountered in metalworking processes are discussed in Sections 5.5, 6.29, and 7.26.

3.4 LUBRICATION

The preceding discussions of friction and wear have dealt mainly with the sliding of dry surfaces and the role of contacting asperities in developing friction and wear. However, it was also seen that an interfacial film of low shear strength can markedly reduce both friction and wear. The means and mechanisms for interposing lubricant films that will both support the load and prevent damage or wear of the contacting surfaces will now be considered.

The mechanism of lubrication is most readily specified in terms of the thickness of the lubricating film. Qualitatively, the lubricant can provide complete separation and low friction by a thick film of fluid (hydrostatic and hydrodynamic lubrication) or various thinner fluid films (thin film or quasi-hydrodynamic lubrication), molecular layers adsorbed on the metal surfaces (boundary lubrication), surface films formed through a chemical reaction (extreme pressure or E.P. lubrication), as well as solids deliberately interposed to perform a lubricating function. The various kinds and mechanisms

of lubrication will be discussed in succeeding sections below, and their relationship to metal deformation processes will be pointed out.

3.41 Hydrodynamic Lubrication

In general terms, lubrication is defined as any means that causes reduction of friction and wear, as well as other forms of surface degradation, by interposing a lubricant between the interface of two load-bearing surfaces in relative, tangential motion. If the film is thick enough to cause complete separation of the surfaces, relative motion occurs by shearing of the fluid film and the resisting force is that caused by the viscosity of the lubricant. Under these conditions, friction can be very low and wear is negligibly small.

The method of introducing the fluid comprises a further distinction. It is possible to arrange an antifriction system in such a way that the load-carrying members are supported by a pressurized medium. This type of lubrication is known as hydrostatic lubrication. The medium is often a viscous fluid but can also be a gas, such as air. Hydrostatic lubrication is important in metalworking lubrication not only because fluid may be supplied under external pressure as in hydrostatic extrusion, but also because lubricant may be trapped between approaching surfaces, as in rolling. A film of lubricant fluid is trapped between the die and tool surfaces approaching normal to the workpiece and is capable of transmitting the deforming pressure to the workpiece (Sections 9.22 and 9.27). Hydrostatic lubrication is also a vital aspect in any metal deformation process where surface roughness is utilized to trap minute pockets of lubricant; this occurs especially in rolling and drawing operations.

A second method of introducing lubricants makes use of the shape and relative motion of the sliding surfaces to form a liquid film under sufficient pressure to separate the surfaces. Known as hydrodynamic lubrication, this is the system that is most widely used in machinery elements. Hydrodynamic lubrication is highly dependent on an important physical property of the lubricant—viscosity. Hence, as an introduction, it will be useful to review a few basic concepts, followed by an indication of how viscosity is influenced by temperature, pressure, and rate of applying shear stresses as related to metalworking processes.

Viscosity

The concept of viscosity is best illustrated by considering a moving flat plate of unit area that is separated (in the y direction) at a distance h from a flat stationary surface by a film of a viscous fluid. The plate moves at a constant velocity v_{max} under the influence of an applied shear force F, and each layer of fluid within the film is subjected to shearing at the rate of dv/dy. The fluid at the stationary surface has zero velocity while that in contact with the moving plate has a velocity v_{max}. For ideal (Newtonian) fluids, the rate of shear, dv/dy, is linearly proportional to the shear stress. The constant of proportionality is η which is defined as the dynamic viscosity of the fluid:

$$\tau = \eta \frac{dv}{dy} \tag{3.17}$$

Since the shear stress τ is in units of dyne/cm^2 and dv/dy in cm/sec·cm, the c.g.s. unit of dynamic (absolute) viscosity is the "poise" (dyne· sec/cm^2).

In many measurements and calculations, the dynamic viscosity divided by fluid density is more convenient, leading to a second expression of viscosity, defined as the kinematic viscosity ν. If ρ is the density of the fluid, then

$$\nu = \frac{\eta}{\rho} \tag{3.18}$$

In c.g.s. units, the kinematic viscosity is in "stokes" (cm^2/sec). For the low values that occur with normal lubricating oils, the units centipoise (cp) and centistoke (cs) are customary.

A discussion of methods for measuring viscosity is beyond the scope of this book, but brief descriptions will be found in the Appendix, together with a nomograph showing the interrelationship of scientific and industrial units.

Because viscosity is highly dependent on temperature, it is important that the temperature of measurement be specified. Ordinarily, pressure is not indicated since viscosity is customarily determined at atmospheric pressure. Metalworking processes expose the lubricant to relatively high pressures where the viscosity may be orders of magnitude higher than at atmospheric pressure. The effects of temperature and pressure on lubricants are discussed in Sections 4.21 and 4.22.

Shear Characteristics

Lubricating oils approximate Newtonian fluids particularly under the pressures and shear rates encountered in most machine elements. It is only at very high shear rates that the fluids depart from ideality. Porter and Johnson [66] found that noncompounded mineral oils remain Newtonian up to shear rates of at least 10^{-5} - 10^{-6} sec^{-1}

Non-Newtonian behavior may follow various patterns. Fluids or semi-fluids whose viscosity varies with the rate of shear can be characterized by an "apparent viscosity." It can be evaluated in a capillary type viscometer where it is defined as the shear stress at the wall divided by the mean rate of shear computed from the Poiseuille equation for flow,

$$Q = \frac{\pi a r^4}{8 \eta \ell} \tag{3.19}$$

where Q is the volume flow rate through a relatively long, narrow capillary of radius r and length ℓ, a is the applied pressure, and η is the dynamic viscosity of a Newtonian fluid. The shear at the wall is calculated at $ra/2\ell$, and the mean rate of shear is $4Q/\pi r^3$. The apparent viscosity η_a is then,

$$\eta_a = \frac{\pi a r^4}{8 Q \ell} \tag{3.20}$$

The apparent viscosity is expressed in fundamental viscosity units at a given rate of shear.

Certain semisolid materials, typified by greases, soaps, and asphalts, can build up an initial shear yield stress before the material begins to flow. If the flow then continues at a constant slope, $d\tau/(dv/dy)$, there is an analogy to viscosity, and such materials are termed Bingham solids. These materials are frequently characterized by their "consistency"; this is a term describing the degree to which a semisolid material resists deformation. This property is generally expressed in terms of a penetrometer number, particularly in connection with greases (Section 4.25). The study of such materials is further complicated by the fact that consistency is dependent on previous shearing history. Thus, an "unworked" grease has a higher consistency than one which has not been recently subjected to shear. Any semisolid whose consistency temporarily decreases with shear is known as a thixotropic material. The same term is applied to semifluids (e.g., oil paints) which become more fluid when stirred.

Viscoelastic Properties of Fluids

Normally hydrodynamic theory is developed on the assumption that the lubricant is Newtonian. There are circumstances in which shearing strains are applied at such a high rate that a displacement must be considered as a composite of both elastic and viscous components; such fluids are termed Maxwell fluids. The flow properties of the fluid may be expressed in the following way:

$$\frac{dv}{dy} = \frac{dv_e}{dy} + \frac{dv_v}{dy} \tag{3.21}$$

$$= \frac{\tau}{\eta} + \frac{v}{G}\frac{d\tau}{dy} \tag{3.22}$$

where dv_e is the velocity component due to elastic shear, dv_v is the velocity component due to viscous shear, v is the velocity, G is the shear modulus.

The ratio η /G is defined as the relaxation time (in sec) of the fluid. It is also defined as the time required for the stress originating from a suddenly imposed shear strain to fall to 1/e of its initial value (e is the Naperian logarithm base, 2.7183). The relaxation time becomes significant when the transit time of a lubricant fluid in the contact zone is of a comparable magnitude. Typical mineral oils will have relaxation times in the range 10^{-4} - 10^{-8} sec.

In metalworking processes, actual speeds are not excessive, but the strain rate in the lubricant film may reach very high values. Furthermore, pressures attained in many metal deformation operations can readily solidify the lubricant (Section 4.21). Thus, the ratio of η /G can be sufficiently high to be of consequence in detailed calculations.

For further information concerning studies on visco-elastic properties of viscous oils, refer to Milne [67], Barlow and Lamb [68], Dyson [69], and Novak and Winer [70].

Hydrodynamic Theory

Tower [71] made the first experimental observation on the pressure generated by a thin fluid in a bearing. Reynolds [72] derived the classical equations of hydrodynamic flow that have formed the basis for hydrodynamic lubrication theory.

The physical process leading to the generation of a pressure within a converging oil film can be illustrated in terms of a plane wedge or tilting pad

bearing shown in Fig. 3.4 [73]. The tilting pad CD is stationary, and the opposing surface moves at a velocity v. The space between the two surfaces is flooded with a viscous lubricant. Since the pad is stationary, the oil velocity at C is zero but on the moving surface it is v. The average velocity of the oil, assuming a linear velocity profile, is v/2 and for an inlet gap h_i, the oil flow is $(v/2)h_i$ per unit of wedge width. With the same velocity assumption, the flow of oil at the outlet is $(v/2)h_o$. Since $h_i > h_o$, the indicated flow of oil into the gap appears to be larger than that out of the gap. This is, of course, not possible with an essentially incompressible fluid, and pressure builds up in the bearing. The entering oil has to work against a positive pressure gradient, as shown in Fig. 3.4. This distorts the velocity profile so that at the entry point, it is concave rather than linear and the inlet flow is less than $(v/2)h_i$. Similarly, the increased pressure at the outlet increases the outlet flow of lubricating oil and the velocity profile is changed from linear to convex. The velocity distribution distortion at all points between C and D is such that the area under the curve is identical and flow past each point is identical.

Experimental studies and mathematical analyses have indicated that many bearing geometries lead to pressure profiles such as that shown in Fig. 2.4; a maximum value of pressure p_{max} is always found for a particular gap spacing $\bar{h}$. The Reynolds equation in one dimension (since side flow in a wide bearing is negligible) is derived in the following form:

$$\frac{dp}{dx} = 6\eta v \frac{h - \bar{h}}{h^3} \tag{3.23}$$

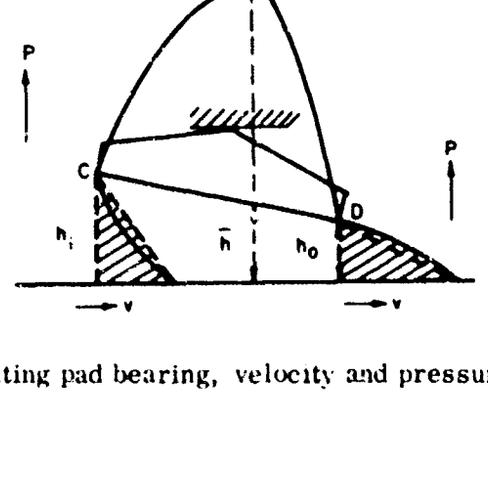

Fig. 3.4. Tilting pad bearing, velocity and pressure profiles [73].

This equation shows the essential feature of hydrodynamic lubrication—namely, that the pressure increases with the velocity v of the moving surface and with lubricant viscosity η. In some metalworking processes, particularly in rolling and wire drawing, the die (roll) and workpiece surface define a narrowing entry zone that may encourage hydrodynamic wedge formation in the same way as in the tilting pad bearing. Most of the time, the viscosities and velocities are not high enough to generate an uninterrupted fluid film with the usual geometries, but die designs have been successfully modified to assure practically full fluid conditions. In wire drawing, if a tube is placed in front of the die with a small clearance between the tube and the wire, sufficient pressure is developed to deform the wire plastically before it enters the die [74]. This aspect is fully reviewed in Section 7.27; the role of hydrodynamic lubrication in other metal deformation processes is amplified in Sections 6.21-6.23, 8.21, 10.23, and 11.21-11.24.

The discussion of hydrodynamic lubrication has been limited here to that in one dimension. The development of the Reynolds equation for two and three dimensions may be found in treatises on the subject by many authorities including Cameron [73], Tipei [75], and Pinkus and Sternlicht [76].

3.42 Elastohydrodynamic Lubrication

In the classical hydrodynamic treatment of lubrication two important assumptions are that the physical properties of the lubricant are not affected by pressure and that contacting surfaces are rigid. However, as the load carried by the bearing surfaces is increased, these assumptions can no longer hold. Pressure can greatly increase lubricant viscosity and, even more important, the mating surfaces can deform elastically. In consequence, effective lubricant films exist under conditions and thicknesses not allowable according to hydrodynamic theory. Modern elastohydrodynamic treatment involves the simultaneous solution of the classical hydrodynamic equation (including a function describing variable viscosity) and the equation for elastic deformation. The study of all these variables is complex but amenable to solution by a digital computer.

Dimensional analysis [77] suggests that h is governed by three dimensionless parameters:

$$\frac{h}{R} = f\left[\frac{w}{E'R}, \frac{\eta_0 v}{E'R}, \alpha_p E'\right] \tag{3.24}$$

The term w is load per unit width, R is radius of curvature, E' is a reduced Young's modulus defined for the two contacting materials as

$$\frac{1}{E'} = \frac{1}{2}\left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right] \tag{3.25}$$

where ν_1 and ν_2 are Poisson's ratios and E_1 and E_2 are Young's moduli for surfaces (1) and (2). In Eq. 3.24, η_0 and α_p are the dynamic viscosity and the pressure coefficient of oil viscosity at entry conditions.

The dimensionless groups of Eq. 3.24 may be replaced for convenience by L (load parameter), U (speed parameter), and M (materials parameter), respectively. On the basis of solutions covering a wide range of conditions, the following relationship indicates the conditions governing the minimum film thickness ratio (H* = h/R).

$$H^* = 1.6\ \frac{M^{0.6}\ U^{0.7}}{L^{0.13}} \tag{3.26}$$

This expression shows that, under elastohydrodynamic conditions, the minimum film thickness is rather insensitive to the applied load, and is governed mainly by the pressure-viscosity characteristics of the lubricant and the elastic properties of the metal. The existence of the elastohydrodynamic regime under conditions usually associated with boundary lubrication has been repeatedly confirmed. Archard and Kirk [78] noted that with mineral oils containing no additives, the load could be increased to values sufficiently high to cause bulk plastic deformation without a breakdown in lubrication. Elastohydrodynamic lubrication in deformation processes is probably limited to the elastic contact zones in the rolling of thin strips.

The basic theory applies to perfectly smooth surfaces, while in practice all surfaces exhibit roughness. Asperities may be expected to penetrate thin films and, indeed, elastohydrodynamic films usually survive only when the average or equivalent film thickness is comparable to the average level of surface roughness. On the more positive side, the roughness of the surface may help to maintain a lubricating film, partly by trapping lubricant within the interface, and partly by the development of localized lubricant wedges on asperities giving hydrodynamic lift. Details of this microelastohydrodynamic action are still debated [79-81].

The importance of surface roughness cannot, however, be overemphasized. Rougher tool surfaces are likely to lead to an earlier penetration of hydrodynamic or elastohydrodynamic films, and the rapid increase of friction with increasing roll surface roughness in cold strip rolling (Section 6.27) provides direct proof. In contrast, beneficial effects are noted when the workpiece surface is purposely roughened either by mechanical (Section 4.52) or chemical (Section 4.4) means. Surface pockets trap lubricants [82] and the lubricant—a viscous fluid or a semisolid—is compelled to enter the critical region between tool and workpiece where the new surfaces are being generated. The lubricant trapped in the pockets assures some measure of hydrodynamic lubrication and functions hydrostatically throughout the metal deforming process.

3.43 Plastohydrodynamic Lubrication

The term covers the application of hydrodynamic theory to conditions where a full-fluid film separates the deforming tool (die) and plastically deforming workpiece. Theoretical treatment requires a solution of the hydrodynamic equation simultaneously with equations describing the variation of viscosity with temperature and pressure as well as equations describing the plastic flow of metal. A few solutions have been produced and will be discussed under rolling (Section 6.21), extrusion (Section 8.21 and 10.23), and wire drawing (Section 7.27). The solutions are rather complex, and experimental verification is available for only a few sets of conditions; the problem deserves much more theoretical and experimental attention.

3.44 Regimes of Lubricating Mechanisms

The basic expression of hydrodynamic lubrication (Eq. 3.23) indicates that film thickness in a bearing is governed by the applied load, the viscosity of the lubricant, and the velocity of sliding. The same factors determine the importance of the measured coefficient of friction and, following Hersey [83], it has become customary to use the nondimensional expression ZN/P where Z is viscosity (denoted by η everywhere else in this book), N the shaft speed in a bearing in rpm, and P the load per unit projected area. Experimental work such as that first conducted by Stribeck [84] may then be described by curves similar to those shown in Fig. 3.5.

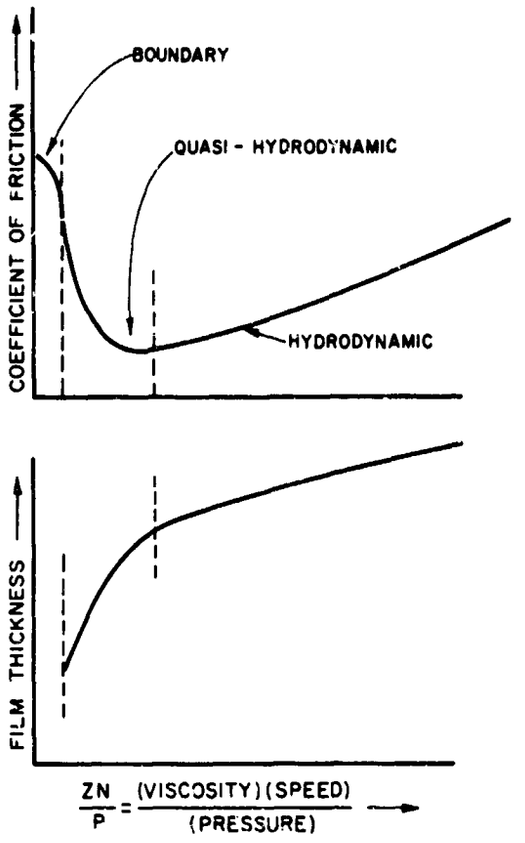

Fig. 3.5. Stribeck curves, describing lubricating regimes.

When viscosity and speed are high enough to maintain a thick film that fully separates the two contacting surfaces, friction is low and reaches a critical minimum value at an optimum ZN/P combination. This is customarily regarded as the low end of the hydrodynamic lubrication regime although it is more likely that, in most practical systems, elastohydrodynamic lubrication prevails around this point. At lower ZN/P ratios the film is too thin to assure complete separation of the surfaces, asperity contact ensues, and the coefficient of friction rises steeply until boundary conditions prevail over the whole surface. Friction is then relatively high and is no longer dependent on the physical properties of the lubricant or on the velocity of sliding. The intermediate regime—variously described as quasihydrodynamic, thin film, or mixed lubrication—is of particular importance in metalworking lubrication because true hydrodynamic lubrication is seldom achieved, and purely boundary lubrication is often objectionable because of the relatively high friction. The existence of mixed or quasihydrodynamic lubrication has been repeatedly deduced from observations in metalworking experiments.

"Hydrodynamic pockets" (caused by entrapment of the fluid) and a dropping coefficient of friction with increasing speed suggest a hydrodynamic mechanism while the surface damage and high friction evident in the absence of suitable boundary lubricants indicate that at least some of the surface is exposed to conditions that lead to boundary contact (Section 6.21 and 7.23).

There is no strict treatment of the mixed friction regime available. Vogelpol [85] suggested that friction in the mixed regime can be defined as

$$\mu_{mix} = \beta\mu_B + (1 - \beta)\,\mu_H \tag{3.27}$$

where β = the fraction of surface area in boundary contact; μ_B = the boundary coefficient of friction; μ_H = the hydrodynamic coefficient of friction.

However, this formula is no more than a restatement of the definition of mixed lubrication and is of no particular practical value since β is unknown.

The importance of the ZN/P concept is that, in the hydrodynamic regime, equivalent processes can be compared despite fairly wide differences in viscosity, speed, and specific loading. Also, an estimate can be made of the approach of boundary lubrication as the variables are changed, provided that identical physical units are maintained.

The ZN/P parameter gained widespread acceptance because of its usefulness in practical bearing applications. However, Sommerfeld [86] had earlier obtained a solution for wide cylindrical bearings. This solution shows that the performance of geometrically similar bearings can be described in terms of a nondimensional parameter,

$$\left(\frac{P}{\eta V}\right)\left(\frac{C}{R}\right)^2$$

It will be noted that the "Sommerfeld number," widely used in bearing theory and studies, is inverse to the ZN/P parameter but carries in addition, the dimensionless "shape" term, $(C/R)^2$, where C is the radial clearance and R is radius. In the operation of a journal bearing, this ratio defines an eccentricity of the bearing that in turn produces a convergence of surfaces and generates a pressure wedge that is characteristic of hydrodynamic lubrication. This was illustrated previously in terms of a tilted pad bearing in which a converging wedge is created. Occasionally, and rather loosely, qualitative features of lubrication regimes are discussed with reference to the

"Sommerfeld number." In metalworking lubrication, this is taken in the reciprocal form and is essentially used to denote the group ZN/P.

3.45 Boundary Lubrication

The previous discussion has emphasized that as the lubricating film is made extremely thin—for example, by high local loads or by the extension of surfaces—an exceedingly thin layer of perhaps molecular dimensions can remain to separate the contacting surfaces. This type of lubrication was first examined by Hardy [87], who termed it boundary lubrication. It is generally found that bulk properties of the lubricant (such as viscosity), are of little importance, but that the chemical constitution of the lubricant and that of the underlying metal assume great significance. In metalworking processes, bulk deformation of the workpiece produces chemically reactive, new (virgin) surfaces. These must be lubricated to avoid adhesion; an effective way of accomplishing this objective is to interpose boundary lubricants in the vital interface between tool and workpiece. Extremely thin boundary films prevent the disastrous consequence of metal-to-metal contact, and efficient metal deformation can ensue.

The following discussion will indicate the mechanism of boundary lubrication as distinct from extreme pressure and solid film lubrication, both of which also provide thin separating films but operate through mechanisms clearly different from boundary lubrication.

Experimental Observations

Boundary lubrication has been studied extensively, and the results of experimental studies are useful for descriptive purposes. The most pertinent comments may be summarized as follows:

1. Boundary lubrication depends on the chemical nature of the underlying metal as well as that of the lubricant.

2. Layers only a few molecules thick can provide effective boundary lubrication.

3. The bulk viscosity of the lubricant has no significant effect upon its boundary frictional behavior.

4. Coefficients of friction of effective boundary lubricants lie in the range 0.01-0.1 (as compared to $\mu \simeq 0.005$ in hydrodynamic journal bearings).

5. The frictional force is independent of the speed of sliding; however, an increase in bulk temperature could desorb or destroy the boundary lubricant.

6. Friction and surface damage depend upon the chemical nature of the lubricant and the products of reaction between the surface and the lubricant.

7. The boundary frictional behavior will be influenced by the surface factors involving temperature, presence of moisture, oxygen, or various surface contaminants; in general, these factors are evaluated in terms of altering the chemistry of the boundary lubricant-metal surface reaction.

8. Roughness may influence boundary lubrication indirectly. In metalworking processes, the lubricant may initially function hydrodynamically, but eventually the trapped lubricant functions hydrostatically to support the load. Further plastic deformation of the workpiece then utilizes the lubricant as a thin boundary layer to maintain tool-workpiece separation.

Test Methods

Since boundary lubrication predominates at high local loading and low speeds, experimental test arrangements frequently use a loaded hemispherical slider of a few millimeters radius sliding over a flat plate (Fig. 5.9a). With a few kilograms of load, a well-defined track is impressed on the plate. While details of design may vary, the testing apparatus always includes means for measuring the frictional force and, from the known load and frictional force, a coefficient of friction may be calculated. This, together with an assessment of the surface damage observed in the track, provides a good measure of lubricant performance. Machines built with springs as the force-measuring devices are prone to develop stick-slip (Section 3.24) that may also be used as a qualitative indicator of lubricant performance.

Boundary lubrication studies are frequently conducted with test machines of related configuration; these include pin-on-ring, pin-on-disk, hemispherical slider-on-disk, and crossed-cylinder models. For lubricant evaluation, industry tends to use machines primarily designed to show E. P. effects. Descriptions of these machines and a more extended discussion are included in Section 5.27.

Nature of Boundary Films

The strength of attachment of boundary films covers a wide range and is a function of the chemistry of the lubricant-metal system. Mineral oils, extensively used as lubricating fluids, are comprised of hydrocarbons that are mainly paraffinic and naphthenic in character but also contain some aromatic hydrocarbons. As products of refining processes starting with various crude oils, they may vary widely in composition and their nature is further discussed in Section 4.21. Highly refined mineral oils, as well as synthetic hydrocarbons, are mainly nonpolar.

Industrially used mineral oils contain small amounts of naturally occurring polar constituents as well as polar compounds (usually fatty oil derivatives) added for specific purposes including boundary lubrication. These polar molecules contain a permanent imbalance of electrical fields and hence a significant dipole moment. When such polar substances are adsorbed, a mirror image of charges is induced in the metal surface that assists in strong attachment. Layers subsequent to the initial surface layer are held by weaker forces.

The strongest attachment of surface layers occurs by chemical reaction. Practical metal surfaces are covered with surface oxides, or hydrated oxide films. Thus, stearic acid, for example, reacts with the surface oxide and a chemisorbed layer is attached, as shown schematically in Fig. 3.6 [88]. Additional layers are held by weaker molecular forces, such as association and hydrogen bonding.

Boundary lubrication can be effected then by thin layers of lubricant, but the effectiveness in lubrication will be influenced by the degree of attachment to the surface. As will be shown later, boundary film attachment is indicated by the maximum temperature (transition temperature) at which effective lubrication may still be expected.

Formation of Boundary Lubricant Films

As the load between two sliding surfaces is increased, the lubricant film becomes thinner and thinner, but low friction will persist as long as even one monolayer of a good boundary lubricant is present to separate the surfaces. This can be demonstrated by an experiment with stearic acid ($C_{17}H_{35}COOH$). A small amount of this material is spread, either in molten form (m.p. 69°C) or in solution (e.g., ether), upon the surface of grease-free water in a trough containing a movable side (Langmuir trough). A

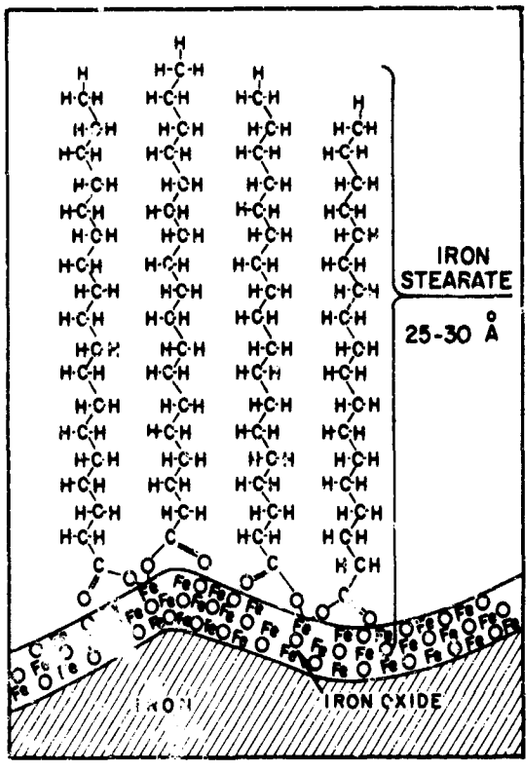

Fig. 3.6. Stearic acid adsorbed on an iron surface [88].

uniform, monolayer film of parallel aligned molecules is formed with the polar ends (-COOH) adjacent to the water surface and the hydrocarbon tail ($C_{17}H_{35}$-) extending normal to the water. By bringing a metal specimen through such a film, known numbers of molecular layers of acid can be deposited on the surface. The friction of a monolayer is initially the same as that of multilayer films (Fig. 3.7); however, repeated traverses over the same path demonstrate that multilayer films are more durable and resistant to wear [2].

The study of boundary lubrication was pioneered by Hardy [87] during the period 1918-1932; Langmuir [89] was the first to demonstrate that a monomolecular film of a fatty acid on glass could decrease friction to low values. Many investigations have since proven that monolayers of not only fatty acids, but also fatty alcohols, amines, esters, metal soaps, and other compounds provide boundary lubrication.

The importance of chain length was first demonstrated by Hardy [87], who found that the longer carbon chain compounds give lower friction. Even paraffinic hydrocarbons can provide lubrication, but lower members of the

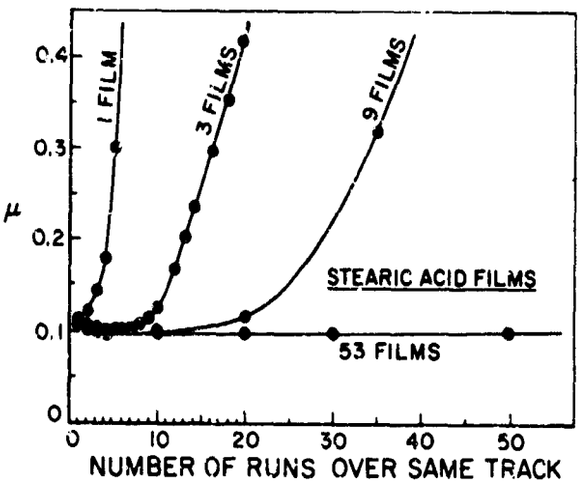

Fig. 3.7. Wear of stearic acid films deposited on stainless steel [2].

series which are liquid tend to allow stick-slip motion to occur whereas higher, solid members (paraffin wax) give smooth sliding. The very short chain fatty acids also give stick-slip sliding, but transition to smooth sliding occurs with solid members of the series even on unreactive surfaces such as glass or platinum. In general, it is found that both solid paraffins and solid fatty acids provide less effective lubrication when their melting points are exceeded

On reactive surfaces, such as copper, fatty acids will lubricate at temperatures above the melting point of the acid (Fig. 3.8). Thus, a 1% solution of lauric acid ($C_{11}H_{23}COOH$) in a hydrocarbon liquid carrier can be used to deposit a film that is effective not only up to 44°C, the melting point of lauric acid, but up to 110°C, which is the melting point of the metal soap, copper laurate. Thus the effective boundary lubricant is a film which has formed by reaction with the surface or alternatively could be supplied in the reacted form as a metal soap. This can be confirmed by the use of copper laurate on an unreactive surface; copper laurate thus lubricates platinum up to a temperature of 110°C. Boundary lubrication action is most effective if solid films of low shear strength are interposed between the sliding surfaces or if solid films are formed by reaction In the latter case, chemical

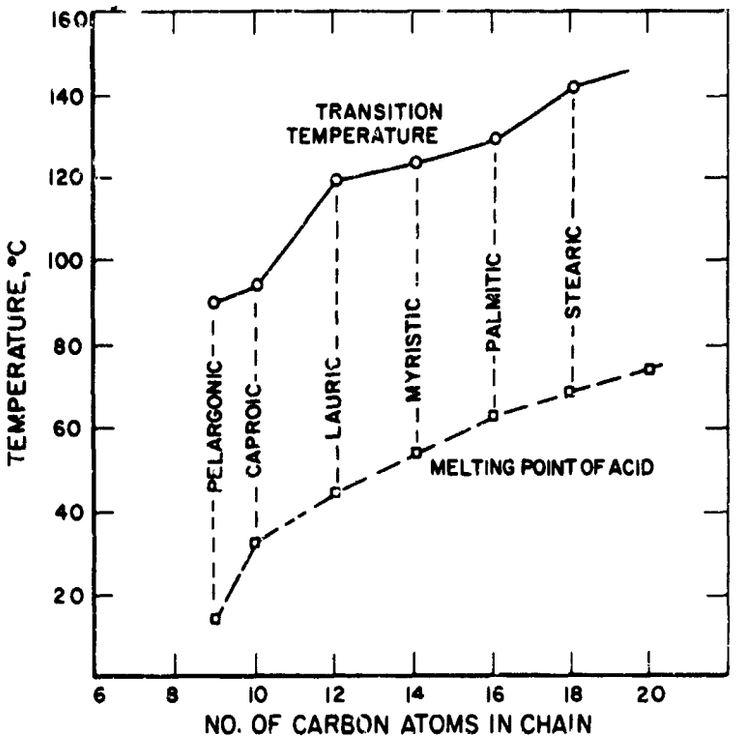

Fig. 3.8. Role of temperature on the lubrication of copper by various fatty acids [2].

reactivity of the surface becomes an important factor. This is shown in the experiments conducted by Rowe [90]. While seizure of clean, outgassed copper was prevented by admission of caproic acid ($C_5H_{11}COOH$) vapors, friction still remained high. Admission of oxygen and/or water vapor, greatly speeded the formation of a metal soap film and markedly reduced friction. Since most metals exposed to the atmosphere normally have surface films containing both oxides and moisture, the formation of boundary layers is generally quite rapid.

Menter and Tabor [91] showed by electron diffraction that there is a short-order regularity of fatty acid monolayer that is reduced with increasing temperature; at a critical transition region, characterized by steeply rising friction, the orientation becomes random. On nonreactive metals, this transition temperature is close to the bulk melting point of the acid whereas on reactive metals it is near to the melting point of the appropriate metal soap. Further studies by Chapman and Tabor [92] indicated that the hydrocarbon chains are more closely packed on reactive metals than on nonreactive metals. The increased lateral cohesion on reactive metals thus

partially accounts for the improved boundary performance of such layers. Conversely, when the soap layers become completely disoriented upon melting, lateral cohesion is again lost.

The preceding discussion depicts boundary lubrication in terms of idealized monolayers. In practical applications, the boundary lubricant is supplied at rather low concentrations (typically 0.5-5%) in essentially non-polar mineral oil carriers. This has two consequences: first, the boundary film absorbed at the surface is formed by co-deposition of the carrier fluid (Zisman [93]); second, a partially aligned (oriented) surface film of 10^3-10^5 Å thickness is formed that has a much higher viscosity than the bulk of the lubricant and, near the surface, behaves like a plastic solid [94, 95]. There is a particularly steep rise in viscosity when the chain length of the boundary additive and the carrier are exactly matched [96]. These observations afford at least a partial explanation of the surprisingly high efficiencies frequently attained by practical lubricants containing boundary additives or additive mixtures.

Above the melting point of soap films formed on reactive metals, friction is high but some evidence of boundary lubrication persists until the temperature becomes high enough to desorb the lubricant. Metallic friction is then observed.

Mechanism of Boundary Lubricated Sliding

The mechanism of boundary lubrication of perfectly smooth surfaces is readily depicted in terms of shearing taking place within the boundary films.

It has been possible experimentally to prepare surfaces with no asperities by careful cleavage of a mica sheet so that flat areas may extend over several square millimeters. These surfaces will, after exposure to air and upon pressing together, exhibit a tangential shear strength comparable to that of the original solid. By interposing a monolayer of boundary lubricant, Bailey and Courtney-Pratt [97] were able to determine the shear strength of calcium stearate, a metal soap commonly used as a boundary lubricant. The observed monolayer shear strength was 250 g/mm^2. A comparison of this value with the bulk shear strengths of metals (e.g., 16 kg/mm^2 for copper) indicates the potential effectiveness of uninterrupted boundary lubricant films. Cameron [98] estimated the shear strength of boundary organic films from the van der Waals forces due to the interaction of

external hydrogen atoms. His estimates of shear strength are of sufficient magnitude to account for observed friction forces.

Real surfaces are never ideally smooth; the boundary film may be penetrated by metallic asperities, and metal-to-metal contact may contribute appreciably to friction. If the applied load is supported over a contact area A_r and metallic junctions form over a fraction m of this area, the force required to shear the interface will be the sum of two shear terms, one due to the shear strength of the metal τ_o and one due to that of the lubricant τ_ℓ :

$$F = A_r \left[m \tau_o + (1 - m) \tau_\ell \right] \tag{3.28}$$

The contribution of metallic junctions to boundary friction can only be estimated approximately but appears to be rather small. It is much more important that the lubricant inhibit junction growth (Section 3.22) and thus reduce friction to the practically observed, relatively low values.

Other Theories of Boundary Lubrication

There is no universal agreement on the simple boundary lubrication mechanism given above. In general, Russian investigators frequently describe boundary friction in much more detail based on considerations of friction as a combined molecular-mechanical process. Akhmatov [7] has summarized much of the detailed molecular viewpoint of boundary lubrication.

Boundary lubrication theory based on the Rehbinder effect is particularly different from the adsorption theory. It relies on the observation that the resistance of single crystal metals to deformation and fracture in tension is lowered in a surface-active environment. Typical experiments include tensile tests with tin, lead, and copper single crystals submersed in low concentrations (e.g., 0.2%) of fatty acids and alcohols (e.g., oleic acid, cetyl alcohol). Originally, the effect was attributed to a penetration of the surface-active molecules into microcracks of the surface and, more recently, it was suggested that the surface free energy is lowered. In polycrystalline metals and alloys, Rehbinder effects are also possible, but the evidence is much less striking [99-101].

The interpretation of the Rehbinder effect has been a matter of controversy over the years. Recent work by Kramer and Haehner [102] indicate that dissolution of strain-hardened free layers by the surface-active medium leads to a reduction of dislocations and thus to a lowering of tensile yield strength. This view has been corroborated by Barlow [103], who found that

carbon tetrachloride changed the strain-hardening characteristics of copper in orthogonal metal-cutting experiments.

The applicability of the Rehbinder effect to metal deformation processes is not clear. Except for sheet metalworking, all processes involve compressive deformation, for which no comparable reduction in yield stress has been noted. Nevertheless, Veiler and Likhtman [104] suggest that "plasticization" of the metal surface occurs in the presence of surface-active compounds and causes a reduction in deformation forces. The nature of the postulated plasticization is not specified. It would seem that the more usual boundary lubrication theory adequately explains the measured force reduction.

3.46 Extreme Pressure Lubrication

Boundary lubricants and their reaction products fail to give adequate surface protection at elevated temperatures since the surface film melts or decomposes. In order to protect sliding metal surfaces at higher temperatures, certain compounds containing active chemical groups are included in the lubricant. Although originally developed to meet sliding situations where high and localized pressures were known to exist, the actual function of these "extreme pressure" additives is to lubricate at relatively high temperatures, typically up to 300-400°C.

The most commonly used E.P. additives are organic compounds containing chlorine or sulfur. These are not normally reactive, but they decompose at hot spots induced by friction and react with the metal to form chlorides or sulfides. The properties of a film deposited on a steel surface are those of iron chloride or iron sulfide. The relative actions of a boundary additive (5% oleic acid) and a chlorinated paraffin (40% chlorine content) contained in a mineral oil are illustrated in Fig. 3.9 [105]. It is evident that the boundary lubricant gives low friction below about 140°C. Reaction of the chlorinated additive with the metal surface begins at about 200°C to cause a decrease in friction which persists up to about 300°C. Commercially compounded oils contain appropriate boundary and E.P. additives that lubricate metal surfaces over a wide temperature range. It is also not uncommon for a given E.P. additive to contain several reactive groups with apparently different functions.

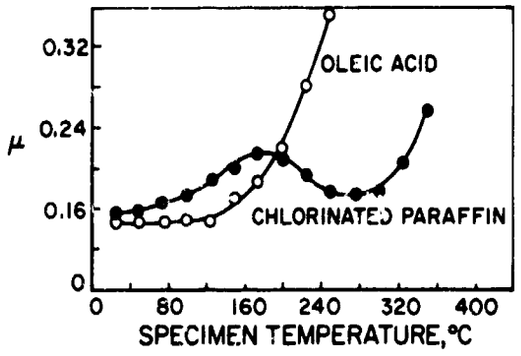

Fig. 3.9. Influence of temperature upon boundary and E. P. Lubrication [105].

On steel surfaces, it is found that the maximum temperature is higher for sulfur-containing E. P. compounds than for chlorine-containing compounds. This action can be interpreted in terms of the behavior of iron chloride and iron sulfide films deposited on steel surfaces in a vacuum [106]. In common with other lamellar crystals, iron chloride exhibits low friction; therefore, a chloride film gives low friction up to about 300°C when iron chloride sublimes. Iron sulfide is stable up to about 750°C, but its friction is somewhat higher. In air, the relative usefulness of these compounds may change since the sulfide films can readily oxidize.

Other E. P. additives are known including phosphorus-, boron-, and iodine-containing compounds. In general, all form some type of metal surface film that exhibits a high resistance to penetration, a low shear strength, and a low friction interface that in metalworking processes effectively separates the die and workpiece. Further discussion of E. P. compounds and specific mechanisms of action may be found in Section 4.23.

It is evident from this qualitative picture that the performance of E. P. additives requires an extremely delicate balance of chemical reactions. On the one hand, the formation of a surface reaction film is required at temperatures where welding and adhesion might otherwise occur. On the other hand, the reaction of the additive must not be so great as to cause excessive corrosion. As a chemical reaction, this process is time-dependent. In metalworking lubrication, this action must occur in a particularly short

time since new and reactive surface is generated at high rates and it is important to prevent metal pickup by the tool. It is also necessary to recognize that, in most instances, only one passage or contact between work and tool occurs in contrast to multiple contacts in machine elements. Thus, an excessive amount of E. P. additive may not lead to the desired lubrication effect because of low reactivity yet may result in subsequent corrosion or surface damage of the product upon storage.

The kind and concentrations of E. P. additives are usually dictated by specific process conditions and metals. For lubrication at relative low temperatures, boundary lubricants will be most effective; but as the temperature of the interface increases, E. P. action becomes necessary to avoid metal-to-metal contact. Some metals, including titanium and stainless steels, do not react readily with boundary lubricants, so pickup occurs; thus, the use of E. P. additives is indicated as a possible solution. The subject is exceedingly complex, but the basis for lubricant formulations described under specific metalworking processes can be interpreted within the framework of the above mechanisms.

3.47 Solid-Film Friction and Lubrication

The lubrication of sliding metal surfaces can be accomplished, as we have seen, by thick films under hydrodynamic conditions, thin surface films under boundary conditions, and by solid films formed at slightly elevated temperature by chemical reaction with the metal substrate in E. P. lubrication. Surfaces can also be lubricated effectively by various solids of relatively low shear strength interposed between sliding surfaces. These solid films can be oxides or various other solid substances and, in particular, solids with a lamellar structure, the most important of which are graphite and molybdenum disulfide. In this section, only the mechanism for the action of thin solid films is presented. A more detailed discussion of various solid lubricants and their mode of action will be found in Sections 4.24-4.28.

Lubrication by thin solid films can be visualized in terms of a simple forging operation, that of the axial upsetting of a cylinder (Fig. 2.16). If a cylinder of a hard material, such as steel, is upset between flat platens with two thin layers of a soft, ductile material such as copper acting as a film of lubricant, the decrease in thickness will be accompanied by an increase in

contact area. The resulting outward surface flow will induce shear stress in the thin copper film. As shown by Fig. 2.16a, a friction hill develops and the coefficient of friction may be readily obtained from Fig. 2.20a. If friction is very low, plastic flow can be expected to occur when the interface pressure p reaches σ_o, the uniaxial yield stress of the steel workpiece material. The thin copper sheet is sumultaneously subjected to a shear stress τ, and plastic flow will occur when it reaches the shear yield stress τ_o. In any element of interfacial area ΔA, the normal force ΔP will be $p \cdot \Delta A$ and the tangential shearing for ΔF is $\tau \cdot \Delta A$. By definition (Eq. 2.1), the ratio of these forces gives the coefficient of friction simply as

$$\mu = \frac{\Delta F}{\Delta P} = \frac{\tau \cdot \Delta A}{p \cdot \Delta A} \tag{3.29}$$

$$\mu = \frac{\tau_o \text{ (copper)}}{\sigma_o \text{ (steel)}} \tag{3.30}$$

Since τ_o (copper) and σ_o (steel) are known material constants, μ is also constant and readily evaluated (for example, with typical values of 20,000 and 100,000 psi, respectively, μ is approximately 0.2).

Rowe [105] analyzed a model comprising a loaded hard ball sliding over a plate lubricated by a soft metal film. Again, the coefficient of friction is found to be a function of material properties, but this time the indentation hardness, $p_m = 3\sigma_o$, appears in the denominator because the restraining effect of the substrate restricts plastic deformation:

$$\mu \approx \frac{\tau_o \text{ (copper)}}{3\sigma_o \text{ (steel)}} \tag{3.31}$$

This model conforms to the geometry commonly used in sliding friction experiments (Fig. 5.9a). The forging model more nearly relates to metalworking lubrication.

From the foregoing discussion, it is evident that, in principle, any solid material of lower shear strength than the workpiece metal can be used as a lubricant in metalworking. Thus, lead has been found effective in cold tube-drawing; solid polymers and waxes are often used as are the solid soaps, such as sodium or calcium stearate. While the latter may also show boundary attachment, they are effective even on nonreactive materials under favorable circumstances by forming films of low shear strength. Selected crystalline

solids, particularly graphite and molybdenum disulfide, exhibit low friction up to relatively high temperatures; and solids such as lime, talc, mica, and vermiculite have also found application.

Discussion of the various classes of lubricants and special mechanisms, where applicable, is presented in Chapter 4: lamellar solids (Section 4.24), soft metals (Section 4.26), polymeric solids (Section 4.27), and oxides and miscellaneous lubricants (Section 4.28). Other pertinent topics include surface preparation (Section 4.5) and conversion coatings (Section 4.4). The last procedure forms a surface film that does not lower friction by itself, but provides a firm key for superimposed, reacted, or infiltrated lubricants.

3.48 Free Rolling

Rolling is an important basic mechanism for certain machine elements characterized by remarkably low friction. The most familiar examples, ball and roller bearings, are widely used in industry. The tangential interactions between contacting surfaces are small, and lubricants have practically no effect upon friction. This mechanism has been termed free rolling by Bowden and Tabor [3]. Since superficially it might appear that free rolling and rolling of metal strip are parallel operations, a few comments are presented here.

Early theories of rolling friction attributed friction to interfacial slip between the rolling element and the surface. Thus, Reynolds [107] observed that a metal cylinder rolling over a flat rubber surface traverses a distance less than its circumference because the rubber is stretched; since the stretch is not uniform, slip is assumed to occur. Eldredge and Tabor [108] showed that even under heavy loading conditions, this type of slip can make only a minor contribution to frictional losses; it is negligible for metals. For example, in the initial passage of a hard steel ball between flat parallel surfaces of a softer metal, there is a marked plastic displacement of metal ahead of the ball. Repeated traversals over the track result in a slow increase in groove width and gradual decrease in resistance to rolling. Further studies showed that, regardless of whether the rolling produces either elastic or plastic deformation, boundary lubricants had no appreciable effect [109]. After an equilibrium state is reached because of work hardening of the metal, a major contribution to rolling resistance is the energy lost in elastic deformation of the ball or roll.

Free rolling, as described above, and rolling in the metalworking sense are obviously quite different processes. In the former, elastic deformation is the dominant feature; in the latter, extensive plastic deformation is inherent in the process. Because of the elongation of the strip, relative slip develops between the workpiece and roll surfaces (Section 2.22), and lubricants are very effective in reducing friction. In "free-rolling" devices such as ball or roller bearings, however, lubricants are used primarily for wear reduction purposes.

3.49 Temperature Effects

In metallic friction, we have seen that interfacial contact between two elastically deforming sliding bodies is quite often limited to asperities and that plastic deformation of these very localized regions occurs. As a consequence, localized high temperatures can be expected. This has been demonstrated experimentally by Bowden and Thomas [110], who determined on an oscilloscope the thermoelectric voltages generated by a pair of dissimilar metals. Instantaneous temperatures of 500°C or more can be observed, but the duration is short (milliseconds or less). At very high speeds, surface layers can be melted, particularly when thermal diffusivity is low [111]. In Section 4.27, it will be shown that for polymeric substances the formation of thermally softened layers is an important factor in reducing sliding friction.

Bowden and Tabor [2] have shown by a simplified mathematical treatment that for a single junction, the temperature rise ΔT is given by

$$\Delta T = \frac{\mu P g v}{4 r J} \cdot \frac{1}{k_1 + k_2} \tag{3.32}$$

where g is the gravitational constant, r is the radius of the individual asperity, J is the mechanical equivalent of heat, and k_1 and k_2 are the thermal conductivities of the surfaces in contact. In practical terms, this indicates that the temperature rise of a given junction is directly proportional to the energy generated by sliding contact as characterized by high values of μ, load, and velocity; it is inversely proportional to the dimension and thermal conductivities of the contact. The distribution of temperature flashes or transients varies over a wide range so that, statistically, only a small number of the total junctions reach relatively high levels [112].

In metalworking, two factors act to minimize the importance of surface thermal transients. First, there is essentially complete contact of the sliding surfaces so that the junction model used in the derivation of Eq. 3.32 does not apply. Second, if the metalworking lubricant is effective, the proportion of localized metallic junctions is small and the high thermal conductivity and mass of the workpiece tend to prevent high surface temperatures.

It would appear, therefore, that even though the frictional energy may be quite large, surface temperature increases due to sliding friction must be relatively minor in metalworking. However, heat generated by general plastic deformation of the workpiece can be substantial (Chapter 2), and general temperature increases of 200-300°C may be possible in cold working. Temperature rises of this magnitude will impair the effectiveness of boundary lubricants and may even lead to a decomposition of organic components, but it may be beneficial in activating E.P. additives. The effects of temperature are, however, minimized by the usually very brief time of exposure. An assessment of the useful and harmful aspects of temperature rise is more logically deferred to the discussion of individual deformation processes.

3.5 SUMMARY

The literature available on friction, wear, and lubrication is monumental and is growing at a fast rate. The survey presented in this chapter is based primarily on evidence gained in experiments in which the bulk of the contacting materials does not suffer plastic flow. The validity of such information is necessarily limited for deformation processing; nevertheless, a qualitative picture of the mechanism of friction, wear, and lubrication may be obtained by an extension of the generalized concepts.

If deformation proceeds without an intentionally applied lubricant (dry friction), contact is made initially between asperities of the tool and workpiece material surfaces. Welding of the asperities governed by junction growth will be only a minor factor in determining the magnitude of friction, the amount of metal transfer (pickup), and the degree of wear and surface damage to the tool and workpiece. The major contribution to these events will be due to the contact of freshly generated deforming metal with the die, influenced by factors that limit the mutual adhesion, particularly the presence of surface films of adsorbed gases, contaminants, or oxides.

In the presence of an appreciable surface film, whether it be a natural oxide existing on the workpiece or a specifically applied lubricant, lubricating mechanisms discussed in this chapter may become active. Dry films such as oxides, lamellar solids, or coherent films of metals or plastics may completely separate the die and workpiece surface if they present sufficient resistance to penetration and are capable of following the extension of the surfaces. When the film thickness is small compared to the roughness of the tool surface, total conformity with the tool surface is possible and friction may be high. The situation is rather similar when only surface films formed by extreme pressure additives or monolayers of a boundary lubricant are present. In most instances, however, excess lubricant either of a carrier or of the liquid boundary or E. P. lubricant itself is available, and becomes trapped in pockets between asperities or larger scale surface features of the die and workpiece surface. A mixed film lubrication mechanism is then likely to prevail; boundary contact occurs only over a relatively small area of the interface, and the coefficient of friction may be low because the trapped hydrodynamic film presents little resistance to sliding.

Fully hydrodynamic films may also develop when the deformation process geometry is favorable—that is, converging surfaces are presented, interface velocity is high, and a lubricant of sufficient viscosity is used. A film of substantial thickness may also be built up in some processes where the die and tool surfaces approach at high velocities; such squeeze films will be discussed in conjunction with forging (Section 9.22). Continuous, thick films are provided also by controlled melting of a suitable phase-change lubricant (Section 8.34).

The concepts discussed in this chapter have been drawn upon repeatedly for appraisals of friction and lubrication in metalworking [113-115], and will be extensively used in Chapters 6 to 11 to rationalize observations in experimental and industrial deformation processes. The validity of generalizations is often limited, however, by two basic features of metalworking: the bulk plastic flow of the workpiece material and the consequent generation of new surfaces. Fundamental experiments in which these conditions are observed will, no doubt, significantly improve our understanding of basic friction, wear, and lubrication mechanisms in deformation processes.

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Chapter 4

LUBRICANTS

Charles H. Riesz

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4.1 INTRODUCTION

In all frictional processes, the relationship between the lubricant and its environment is very complex, and frequently solutions to lubrication problems are arrived at empirically. For a given process, the lubricant may be tailored—by selection, compounding, and mode of application—to meet more severe performance requirements. Most practical lubricants have been developed in this empirical fashion, but the greatest progress has been possible when specific mechanisms could be discerned and applied in a logical manner. A vast body of information is now available for lubricants used in systems typified by essentially elastic contact. It is beyond the scope of this chapter to review or even categorize this information. However, it has become increasingly clear that specific mechanisms operative with various lubricant classes are relevant also to the performance of lubricants designed for bulk deformation in metalworking.

Information presented in this chapter is limited to selected functional aspects of basic lubricants and to their modes of application. The classifications used are somewhat arbitrary but are generally based on the type of the lubricants and the mechanism of their performance which appears most pertinent and descriptive. Emphasis placed on new and recent developments is deliberate and is designed to direct attention toward areas considered of greatest value for potential use and development in metalworking lubricants.

One feature common to modern lubricants is their complex nature; the diversity of properties desired for a given application is obtained by the varied contributions of a number of constituents or additives. Discussion of composite lubricants for metalworking applications is deferred to the appropriate metalworking process and, more specifically, to deformation

processing of a given metal or alloy class (Chapters 6 to 11). However, generalized topics pertinent to lubricant dispersion, disposal, surface preparation, and selected problems peculiar to metalworking lubricants will be included in this chapter.

4.2 LUBRICANT TYPES

Lubricants can be crudely divided into liquids, solids, and semi-liquids (greases, emulsions, and dispersions). Further, according to their mode of performance, lubricants can be classed as hydrodynamic, boundary, extreme pressure, and solid. The latter classification is, however, more suited to conventional bearing and machinery elements than to metalworking lubricants.

Despite obvious overlaps and possible contradictions in detail, the groupings used here follow the general rule that liquid lubricants provide a fluid-film lubricating effect and might also assist in preventing metal pick-up under thin-film, quasi-hydrodynamic conditions; thus, materials that are normally liquid are included under the category of hydrodynamic lubricants. For application to generally more severe boundary lubrication situations, substances are classified under the headings of boundary lubricants, extreme pressure lubricants, lattice-layer compounds, soft metals, and inorganic compounds. This section will discuss the categories of lubricants in the order given above. Later sections give individual attention to emulsions, coatings, and polymeric materials, and then treat the important lubricant-related topics of surface preparation, lubricant removal, waste treatment, and health problems.

4.21 Hydrodynamic Lubricants

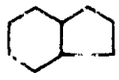
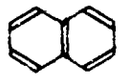
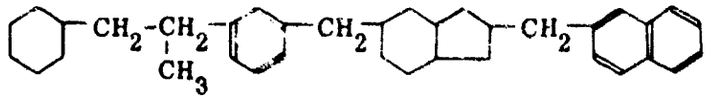
Historically, lubricants fulfilled only a minor role until the Industrial Revolution. Most needs were then supplied by various oils and greases derived from animal, vegetable, and fish oils. In the latter part of the nineteenth century, the merit of mineral oil based lubricants, with respect to superior temperature and oxidation resistance, was recognized and their use became wide-spread. After about 1920, the rapidly growing automotive and electrical industries led to the development of modern lubricants. During and following World War II, a rapid evolution of aviation lubricants was triggered and within a decade, space-oriented lubricants became necessary.

Mineral Oils

Crude oil is a complex mixture, predominantly hydrocarbon in nature, which can be separated into gas and liquid fractions and asphaltlike residues by distillation and other processes. The lubricating oil fraction comprises complex hydrocarbon molecules ranging from 20 to about 70 or more carbon atoms per molecule. This fraction as well as lighter fractions containing as little as 10 carbon atoms (heavy gasoline) per molecule may be used in metalworking lubricant compositions. Table 4.1 indicates simple hydrocarbon structures.

TABLE 4.1

Typical Hydrocarbons

$CH_3-CH_2-\ldots-(CH_2)_x-\ldots-CH_2-CH_3$	Straight-chain paraffin
$CH_3-\underset{\displaystyle CH_3}{\underset{\vert}{CH}}-\ldots-(CH_2)_x-\ldots-CHCH_3$	Branched-chain paraffin (isoparaffin)
	Naphthene (5-carbon ring)
	Naphthene (6-carbon ring)
	Fused naphthene
	Aromatic (benzene)
	Fused aromatic (naphthalene)
	Mixed system hydrocarbon

The relative distribution of paraffinic, aromatic, and naphthenic components in lubricating oils has a significant effect on practical physical properties including viscosity, viscosity-temperature-pressure relationships, and performance characteristics.

For a given molecular size, the paraffins have relatively low viscosity and density and higher freezing points than other types. Characteristically, their viscosity decreases less rapidly with temperature than does that of the naphthenes or the aromatics. Paraffinic oils may have low oxidation resistance, unless inhibited by anti-oxidant additives; this property is significant mainly in the lubrication of engines of all types. In general, paraffinic lubricating oils tend to be more expensive than naphthenic-base oils.

Aromatics inherently have a higher degree of oxidation stability, but tend to form insoluble black sludges in high-temperature engine service. These oils are also characterized by high densities and by a relatively rapid decrease in viscosity with temperature.

Naphthenic oils are characterized by a low pour point, low order of oxidation stability, and other properties generally intermediate between those of the paraffins and aromatics. In practice, most so-called paraffinic oils are actually composed of paraffinic and naphthenic structures, with only a minor proportion of aromatic hydrocarbons. When stabilized with an oxidation inhibitor, naphthenes afford nonsludging oils of good service performance.

Excellent means are now available to determine the proportions of structural types present. These methods include adsorption and other separational techniques in combination with measurements of density, refractive index, molecular weight, and spectrographic data [1]. Table 4.2 presents typical inspection data for a mineral oil used as a rolling lubricant [2]. This oil has not been highly refined and contains a relatively high proportion of aromatics. The detailed hydrocarbon type analysis given in Table 4.3 shows that there is an appreciable amount of naphthenes in the saturated portion. There are additional naphthene structures fused to aromatic rings (e.g., indans, acenaphthalenes). Sulfur is present in chemical combination, for example, as complex thiophene-type compounds. The polar constituents (2.3%) were not resolved but would certainly add boundary properties to the oil.

Ordinarily, such detailed hydrocarbon analyses are not available for metalworking lubricants. However, with the rapid pace of analytical

TABLE 4.2

Typical Inspection of a Mineral Oil ("Coray 37") Used as a Rolling Lubricant [2]

Gravity, °API	25.9
Specific Gravity at 15.6°C	0.8990
Density 20/4°C	0.8953
Viscosity, SUS at 37.8°C	84.0
SUS at 98.9°C	36.8
Flash, open cup, °C	166
Fire Point, °C	191
ASTM Distillation at 10 mm (corrected to 760 mm), °C	
5%	321
10%	332
20%	341
50%	359
80%	384
90%	392
95%	399
Final Boiling Point, °C	418
Neutralization Number, mg KOH/100 ml	0.0
Sulfur, wt%	0.06
Aniline Point, °C	73.9
Refractive Index, n_D at 67°C	1.4655
n_D at 20°C	1.4930
Silica Gel Separation, wt%	
Saturates	67.7
Aromatics	30.0
Polar	2.3

progress, it is conceivable that such knowledge can be usefully applied in advancing the state-of-art of metalworking lubricants. In the following subsections, an attempt is made to relate relevant lubricant properties to broad classes of mineral oils.

Viscosity-Temperature Relationship. The variation of the viscosity of oils with temperature is an important practical aspect, shown for various

TABLE 4.3

Typical Composition of Mineral Oil ("Coray 37") Used as a Rolling Lubricant [2]

Constituent		wt %
Saturates		
Paraffins		2.7
Noncondensed naphthenes		23.4
2-Ring naphthenes		15.9
3-Ring naphthenes		12.8
4-Ring naphthenes		8.7
5-Ring naphthenes		1.5
6-Ring naphthenes		2.7
	Total	67.7
Aromatics		
1-Ring benzenes		4.9
Indans		4.1
Indenes		5.6
2-Ring naphthalenes		1.3
Acenaphthalenes		2.6
3-Ring acenaphthalenes		5.2
Phenanthrenes		3.2
Chrysenes		0.9
Benzothiophenes		0.3
Dibenzothiophenes		1.8
	Total	29.9
Polar Constituents		2.3

commercial products in Fig. 4.1 [3]. It will be noted that some oils are identified by the SAE (Society of Automotive Engineers) classification which specifies the oils in terms of arbitrary standards for practical application rather than in scientific terms. The data are plotted on a semi-empirical chart (ASTM D341) that has the special advantage that the straight line defined by the viscosities at any two temperatures permits an estimation of

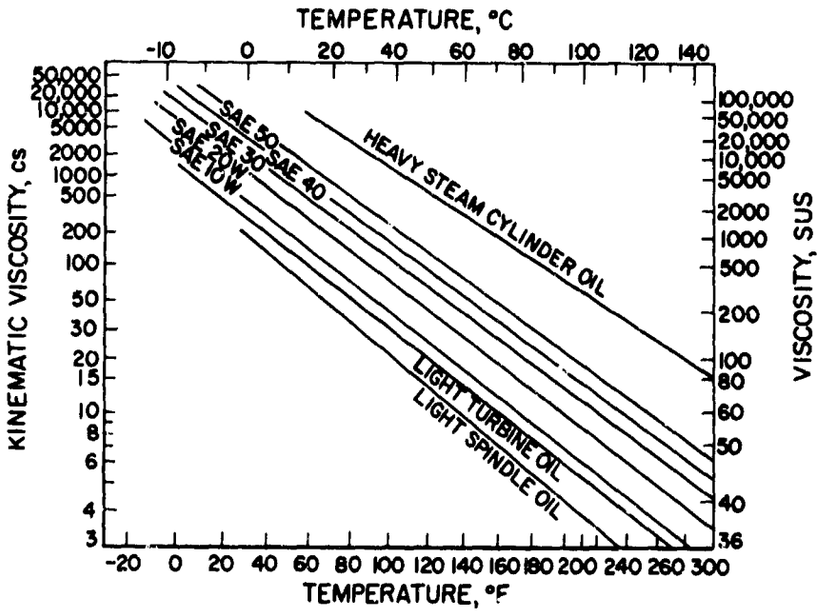


Fig. 4.1. Variation of viscosity with temperature for various oils [3].

viscosity at any other temperature, down to just above the cloud point, the temperature at which a solid phase separates upon cooling.

In the past, the most commonly used means of describing the decrease in viscosity of petroleum oils with temperature was the viscosity index (V.I.). This index was based on the observation that among the commercial oils, the decrease was least with paraffinic oils and highest with a naphthenic type. A series of paraffinic Pennsylvania oils was selected and arbitrarily assigned a viscosity index of 100; similarly, a series of naphthenic Gulf Coastal oils was assigned a viscosity index of zero. Normally, oils with a high V.I. (e.g., above 80-90) are considered desirable as lubricants, but the significance of the index in the very high or very low ranges is questionable. However, the concept is readily grasped and has gained widespread acceptance as a means of characterizing the viscosity-temperature relation of mineral oils.

Viscosity-Pressure Relation. The effect of high pressures on viscosity has importance in conventional applications when a continuous film of lubricant is needed to prevent metal-to-metal contact under high local loads. In metalworking lubrication, this variable assumes an even greater significance. Figure 4.2 presents data showing the increase in viscosity caused by

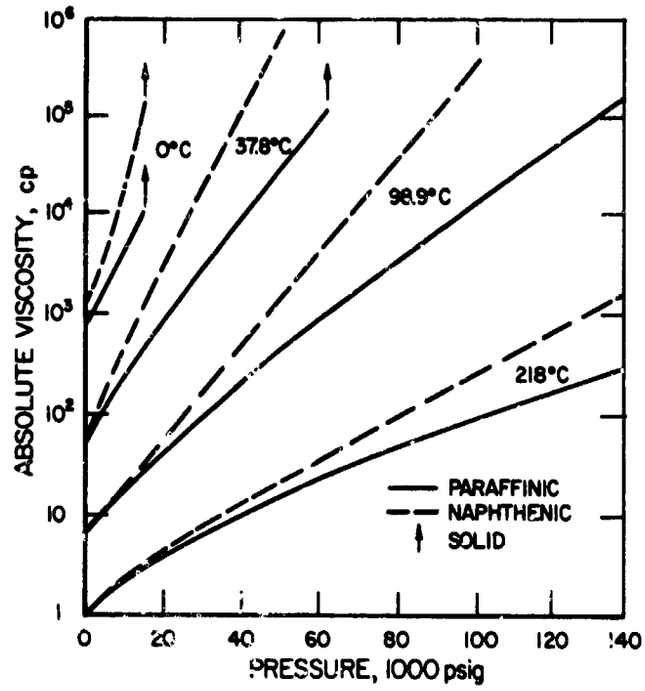


Fig. 4.2. Viscosity-pressure relationships for typical mineral oils (selected data from ref. [4]).

pressure changes with two types of mineral oils. The increase is exponential, and the pressure-viscosity properties can be expressed as follows:

$$\eta_p = \eta_o \exp B_p \tag{4.1}$$

where η_o is the absolute viscosity at atmospheric pressure

η_p is the viscosity at elevated pressure p

B_p is a constant for a given oil.

On a logarithmic basis

$$\log \frac{\eta_p}{\eta_o} = \frac{B_p}{2.3} \tag{4.2}$$

Values of B_p for several petroleum oils are given in Table 4.4. These data on many mineral oils as well as on synthetic oils may be found in an ASME study [4], the most comprehensive and reliable compilation available. A survey of this work was presented by Hersey and Hopkins [5]. Cameron [6]

TABLE 4.4

Viscosity-Pressure Coefficients for Several Petroleum Oils [3]

Nominal Viscosity, SUS	Viscosity at 1 atm, cp		Viscosity Index	Molecular Weight	Average Values of $B_p \times 10^4$				
	37.8°C	98.9°C			0°C	25°C	37.8°C	98.9°C	218°C
				Paraffinic Oils					
250	48.0	5.94	96	450	1.99	1.45	1.29	0.87	0.57
700	144.3	12.62	99	576	1.97	1.47	1.36	0.95	0.64
2500	523	27.6	91	700	2.65	1.84	1.61	1.09	0.67
				Naphthenic Oils					
250	49.9	5.07	23	349	2.92	2.14	1.87	1.11	0.59
700	131.4	8.32	8	383	3.4	2.58	2.18	1.31	0.71
2500	485.0	15.49	-42	400	4.8	3.23	2.83	1.54	0.81

has derived empirical correlations for both naphthenic and paraffinic oils based on the ASME data; these are stated to be somewhat more accurate than the simple one given above.

In general, it may be noted that at a given temperature, naphthenic oils suffer greater viscosity increase with pressure than the paraffinic oils; at the lower temperatures (0°C and 37.8°C), the viscosity rises sharply and the paraffinic oils tend to solidify (Fig. 4.2). Because of the high pressures (100-250 kpsi) normally encountered in metalworking processes, this property may be extremely important; it explains, at least partially, why such high pressures can be transmitted through an oil film.

Viscosity-Temperature-Pressure Relation. In cold metal deformation processes, significant increases in temperature arise from the friction at the sliding tool/work interface and from the heating due to the plastic deformation of the metal. These changes markedly decrease the viscosity of the fluid lubricant. Counteracting this change is the increase in viscosity with pressure due to the high loads developed. The relationship of these changes can be related by the very approximate empirical equation:

$$\left[\frac{\partial (\ln \eta)}{\partial (1/T)}\right]_p = D \left[\frac{\partial (\ln \eta)}{\partial p}\right]_T \qquad (4.3)$$

where D is 2.0×10^5 when temperatures (T) are expressed in °K and p in atmospheres [7]. An approximate rule-of-thumb is that a 38 atm increase in pressure offsets a 1°C increase in temperature (500 psi for 2°F) [8]. A quantitative but still empirical relationship between oil composition and viscosity-temperature-pressure was developed by Roelands, Vlugter, and Waterman [9].

In the simplest terms of chemical structure, any complication of the lubricant molecule leads to a greater increase in viscosity with pressure. Bridgman [10] concluded that the relative pressure effect was greater when (a) a complicated molecule was substituted for hydrogen, (b) when the constitution was of the branched or iso-type, and (c) when a heavy atom was substituted as in the halogenated hydrocarbons. For a detailed discussion on the role of hydrocarbon structure in viscosity-temperature-pressure relationships, refer to standard texts (e.g., refs. 1, 9).

The emphasis of the above discussion on molecular structure of lubricants should not obscure the fact that a particular oil may solidify under the high pressures incident to metal deformation processes. When an oil

solidifies (for example, during passage through a drawing die), the lubrication behavior is greatly modified and improved. The occurrence of solidification is not adequately documented. The ASME study [4] is one of the few comprehensive sources available. Other sources of information include Hersey and Shore [11], Boyd and Robertson [12], Bridgman [13], Boelhouwer and Toneman [14], Galvin, Naylor, and Wilson [15] and Rowe [16].

Synthetic Lubricants

Demand for new lubricants and hydraulic fluids designed to meet high performance specifications has led to the development of synthetic lubricants. These new materials are of quite diverse chemical types; they have found application chiefly in aircraft purposes and military defense systems, as well as in highly specialized areas in the chemical, nuclear, and other industries. Figure 4.3 shows the viscosity-temperature characteristics of some synthetic lubricants; a typical petroleum oil is included for comparison [3]. A brief discussion of some of the distinguishing characteristics will be presented here. More detailed discussions are given by Gunderson and Hart [17], Bowers and Murphy [18], and Goddard [19]. A brief commentary on

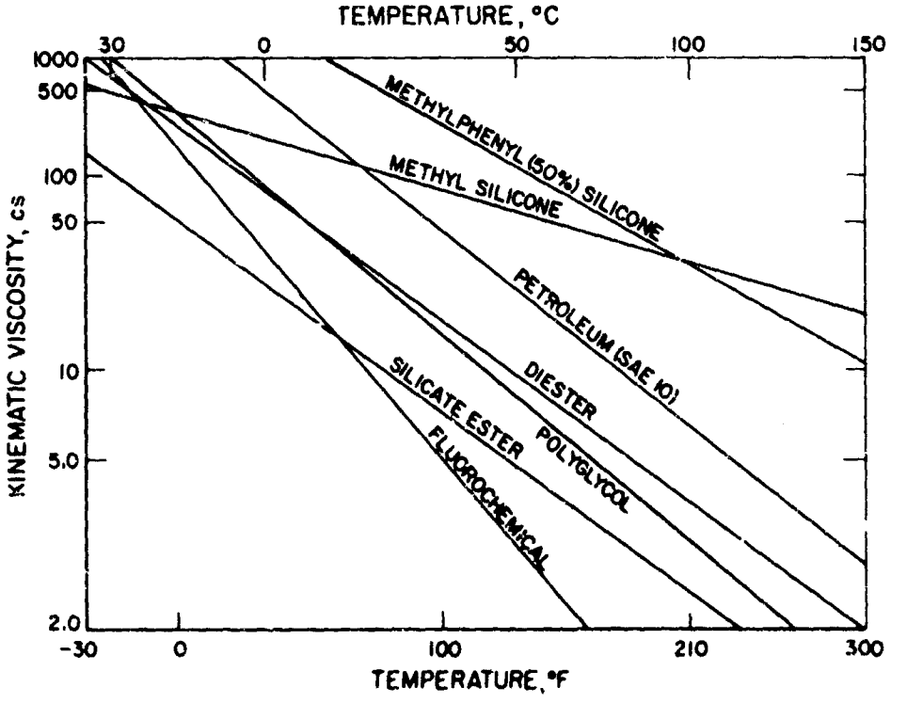


Fig. 4.3. Viscosity-temperature characteristics of synthetic lubricants [3].

the potential application of these lubricants to metalworking applications then follows.

Polyisobutylenes. The possibilities of producing lubricants by the polymerization of olefins has been studied for many years. Of these, polyisobutylene oils have achieved commercial importance since the raw material, isobutylene, $(CH_3)_2C=CH_2$, is readily available in large quantities as a by-product from petroleum cracking plants. The chemical formula of the oils is simply C_nH_{2n}, and polyisobutylenes used as lubricants range in molecular size from about 20 to more than 100 carbon atoms. These olefins in many ways are comparable to mineral lubricating oils and have excellent viscosity-temperature characteristics.

Polyisobutylenes have found extensive application as high-temperature lubricants primarily because they decompose and oxidize to volatile products leaving no carbon residue, in contrast to comparable mineral oils. This property, in particular, has spurred research studies for their application as metalworking lubricants especially where nonstaining is desirable, as in rolling of sheet. The viscosities of polyisobutylenes used for this purpose range from 4 to 45 cs at 37.8°C.

Dibasic Acid Esters. Esters are the class of compounds formed by the combination of an organic acid (with a COOH end group) with an alcohol (with an OH end group):

$$R\text{-}\overset{\overset{O}{\|}}{C}\text{-}OH + HO\text{-}\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}\text{-}R_1 \longrightarrow R\text{-}\overset{\overset{O}{\|}}{C}\text{-}O\text{-}\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{C}}\text{-}R_1 + H_2O$$

where R and R_1 are any alkyl group (monovalent alkyl radicals, derived from paraffins) such as CH_3-, CH_3CH_2-, $C_{17}H_{35}$-, etc. It is also possible to form esters from alcohols and dibasic acids. Dibasic acids contain two carboxyl

$$\overset{\overset{O}{\|}}{(-C\text{-}O-)}$$

functional groups. For lubricant synthesis, the most important dibasic acids used are the following:

sebacic $\quad HO\text{-}\overset{\overset{O}{\|}}{C}\text{-}(CH_2)_8\text{-}\overset{\overset{O}{\|}}{C}\text{-}OH$

azelaic $HO-\overset{O}{\overset{\|}{C}}-(CH_2)_7-\overset{O}{\overset{\|}{C}}-OH$

adipic $HO-\overset{O}{\overset{\|}{C}}-(CH_2)_4-\overset{O}{\overset{\|}{C}}-OH$

Branched-chain primary alcohols, such as 2-ethyl hexanol, as well as commercially available C_8-, C_9-, and C_{10}-alcohols, are reacted to form dibasic acid ester fluids.

Typical dibasic acid esters used as lubricants are: di(2-ethyl hexyl) sebacate(dioctyl sebacate); di(3, 5, 5-trimethyl hexyl)sebacate (dinonyl sebacate); di-iso-octyl azelate. The general structure may be regarded as:

$$R-O-\overset{O}{\overset{\|}{C}}-R_1-\overset{O}{\overset{\|}{C}}-O-R_2-O-\overset{O}{\overset{\|}{C}}-R_3$$

where R, R_1, R_2, and R_3 may be any alkyl group. Thus, the composition of these materials can be varied readily for specific purposes.

A large market has been developed for their use in aircraft turbine engines. These lubricants flow freely at low temperatures and maintain viscosity and load-carrying ability to temperatures of 250-290°C.

Polyglycols. Polyglycol lubricants are based on polymers having the following general structure.

$$RO-\left[CH_2-\underset{R_1}{CH}-O\right]_n-R_2$$

where R, R_1, and R_2 can be any alkyl group and/or hydrogen. If R, R_1, and R_2 are all hydrogen atoms, a series of polyethylene glycols is formed of increasing molecular size determined by n. If R_1 is a methyl (CH_3-) group, polypropylene glycols are formed. Introduction of alkyl groups for R and R_2 will give polyethers ($-\overset{|}{C}-O-\overset{|}{C}-$). Compositions of polymers based on esters, ethers, polyethylene glycols and mixtures can be produced. By control of the structure, it is possible to prepare water-insoluble fluids with good temperature-viscosity characteristics and having application up to 230°C. The products of oxidation are either volatile or soluble in the fluid, thus showing little tendency for formation of solid deposits upon decomposition.

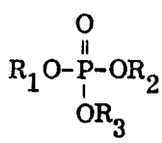
The water-soluble polyglycols have been developed mainly for use as fire-resistant hydraulic fluids. They have been suggested as a component of metalworking lubricants [17].

Chlorofluorocarbons. The chlorofluorocarbons are linear polymers in which all hydrogen atoms have been replaced by chlorine and fluorine. The most important products are low molecular weight polymers of chlorotrifluoroethylene,

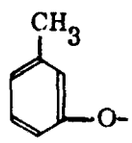
The products have outstanding oxidation resistance and thermal stability. They can be heated in air at 300°C without decomposition. The liquids have a high density (1.8-2.0 g/cc) and a relatively high viscosity-temperature coefficient. They are quite inert chemically and are useful in lubricating compressors designed for halogens or oxygen, and can be used for lubricating equipment handling chlorates and perchlorates. The chlorofluorocarbons have been repeatedly used for metalworking lubrication. At sufficiently high temperatures (e.g., 800°C), the vapors decompose and show E.P. characteristics.

Phosphate Esters. The esters of phosphoric acid have become important as lubricants and as performance-improving additives for other lubricants, both mineral oil and synthetic. The discussion here will be limited to their use as lubricants.

The orthophosphate structures may be represented generally by:



where at least one R group represents an alkyl group while the others may be either additional organic groups or hydrogen. The best known phosphate is one in which the R_1, R_2, and R_3 groups are replaced by the aryl (aromatic) cresyl group, e.g.,



The product is tricresyl phosphate, the properties of which will be discussed in Section 4.23. The properties of the phosphate esters can be varied over wide limits by suitable variation of the radicals R_1, R_2, R_3. The esters range from water-soluble, low-boiling liquids to water-insoluble, viscous, high-boiling liquids and even high-melting-point solids. They have been used as synthetic lubricants with properties comparable to high-quality, petroleum-based oils.

In addition to the neutral, tertiary phosphate esters, one or more of the R-groups can be hydrogen. These compounds, called organo-substituted phosphoric acids, are partial esters of phosphoric acid, and have found use as additives for various purposes.

Sulfur analogs of the above compounds are well known in which at least one single-bonded oxygen atom is replaced by sulfur. The general class is called thiophosphates, the prefix thio indicating the presence of sulfur. The thiophosphates and their derivatives have been used as lubricating additives for antiwear, extreme pressure, corrosion inhibition, and many other purposes.

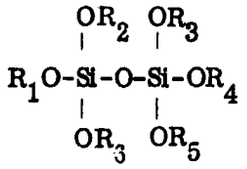
An important application of phosphate esters is as fire-resistant hydraulic fluids in aircraft. The fluids have high oxidative resistance, low volatility, good hydrolytic stability, and excellent thermal stability up to about 400°C. By appropriate choice of esters, useful lubricants with good viscosity-temperature characteristics comparable to that of a high V. I. mineral oil can be obtained. The esters, in general, react with metal surfaces and exhibit some boundary lubrication ability.

Silicate Esters and Siloxanes. The silicate esters comprise compounds based on the orthosilicate structure:

$$\begin{array}{c} OR_2 \\ | \\ R_1O\text{-}Si\text{-}OR_3 \\ | \\ OR_4 \end{array}$$

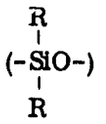
where R_1, R_2, R_3, and R_4 are organic groups which may or may not be identical. The best known types are the tetraalkyl, the tetraaryl, and the mixed alkyl-aryl orthosilicates. The presence of the $-\overset{|}{Si}-O-\overset{|}{C}-$ bonding distinguishes the silicate esters from the silanes and silicones.

A second class of compounds is important, the dimer silicates or, more commonly, the siloxanes, represented by the general formula

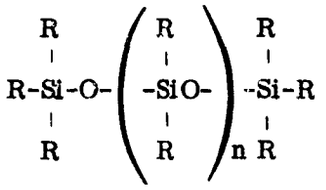


These fluids offer good thermal stability (275-450°C decomposition temperature), useful viscosity-temperature properties, wide liquid ranges, and low volatility. A serious disadvantage is their relatively poor hydrolytic stability (although this can be moderated by structure changes) and poor boundary lubrication properties. Many products have been developed for use as high-temperature hydraulic fluids and for heat-transfer fluids.

Silicones. Silicone lubricants comprise a structure with repetitive



units as the inorganic backbone of the polymer chain. The general formula is



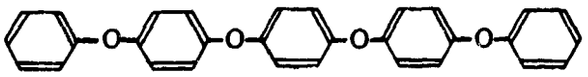
where R may be the same or different organic groups, but most frequently methyl or a mixture of methyl ($-CH_3$) and phenyl ($-C_6H_5$) groups. The polymers vary from highly mobile, low-boiling fluids to viscous fluids and to gums. Under hydrodynamic conditions, they withstand extremely high rates of shear and have very small viscosity-temperature coefficients (see Fig. 4.3). They are chemically inert and thermally stable to about 360°C. Because of these favorable physical and chemical properties, the silicones fulfill most of the requirements for an ideal lubricant with one important exception—boundary lubrication.

With respect to boundary lubrication, the chemical inertness is a disadvantage and steel-on-steel combinations are particularly difficult to lubricate. It is possible, however, to incorporate chlorine into the phenyl

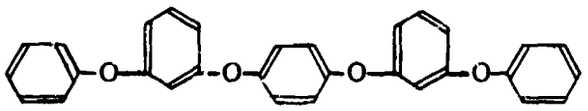
groups of a phenylmethyl silicone fluid. Chlorophenylmethyl fluids have achieved some importance as lubricants, particularly for aircraft turbine use. Fluorine may also be substituted in the molecule.

Silicones have found little use in metalworking applications because of their generally poor boundary properties as well as their very high cost.

Polyphenyl Ethers. The polyphenyl ethers are structures comprising three or more benzene rings linked in a linear chain through oxygen:



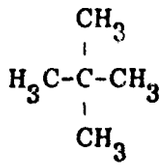
Various lengths are possible, and alkyl, halogen, and other substituents may be attached to the phenyl groups. In addition, the point of attachment may be varied.



The viscosity-temperature characteristics of the polyphenyl ethers are good. Although the polymers are stable to about 400°C, they are susceptible to oxidative degradation. The materials are in a development stage.

Fluoroesters. Certain esters derived from organic carboxylic acids and fluoroalcohols are suitable for lubricants, have a reasonable hydrolytic stability, and are thermally stable up to about 310°C. The fluorinated products are more viscous and have a larger temperature viscosity coefficient than their unfluorinated analogs. The products are largely experimental.

Neopentyl Polyol Esters. The neopentyl polyol esters are a group of organic esters with excellent thermal and oxidative stability up to 210°C. These esters may be considered as derivatives of the hydrocarbon neopentane:



All of these polyols can be esterified with selected acids to produce long-chain ester combinations—for example,

$$\begin{array}{c} CH_2OOC\text{-}C_8H_{17} \\ | \\ CH_3\text{-}CH_2\text{-}C\text{-}OOC\text{-}C_8H_{17} \\ | \\ CH_2OOC\text{-}C_8H_{17} \end{array}$$

Because of their stability, lubricating ability, and nonstaining qualities, these esters have been used as additives in the rolling of metal foil [17]. These materials may be considered experimental at present.

Experimental Synthetic Oils. Most of the synthetic oils mentioned above have achieved some degree of commercialization. Many other products are still quite experimental [17, 18]. A comprehensive review of advanced lubricants by Adamczak, Benzing, and Schwenker [20] indicates that of the organic materials, the polyaromatics are the most stable to heat (425-465°C). Of the inorganic fluids, phosphonitrilic chloride polymer is stable up to 535°C and fluid down to below -18°C; this type of material, however, has poor compatibility with metals.

Synthetic Metalworking Lubricants. The above presentation serves to emphasize that synthetic lubricants have found little application as metalworking lubricants. In large part, this is due to their high cost compared to lubricants based on mineral oils. Other than the economic factor, the use of synthetics may be expected to expand if certain outstanding properties can be utilized. Many of the synthetics have viscosity and viscosity-temperature characteristics that qualify them for consideration (Fig. 4.3). The dimethyl silicones are outstanding in this respect, but are not usable because of their minimal boundary lubricating ability; modified silicones are now available that have improved boundary properties.

Perhaps the most interesting feature of many synthetic lubricants is their high thermal and oxidation resistance. Unfortunately, the properties of synthetics have been rated in terms of conventional bearing applications so that a listing, such as that in Table 4.5, must be considered qualitative and tentative. Some synthetic lubricants, such as the polyphenyl ethers and polyaromatics, are exceptionally stable; their resistance to oxidation is listed as good since no effective representation of this factor is currently available. High stability may, however, be undesirable when lubricant

TABLE 4.5

Stabilities of Selected Synthetic Lubricant Classes

Class	Approx. Limit of Thermal Stability, °C	Oxidative Stability
Phosphonitritic chloride	500-535	Good
Polyphenyl ethers	430-480	Good
Polyaromatics	425-465	Good
Chloro- or fluorosilicones	330-360	Fair
Silicones	330-360	Poor
Fluoroesters	330-360	Good to ~320°C
Chlorinated hydrocarbons	330-360	Good
Neopentyl polyol esters	300-350	Fair
Chlorofluorocarbon polymers	290-320	Good to ~300°C
Dibasic acid esters	200-250	Poor
Silicate esters, disiloxanes	200-250	Poor
Polyglycols	200-250	Poor
Phosphate esters	150-400	Good
Polyisobutylenes	150-300	Fair
Mineral oils	150-300	Fair

residues must be evaporated at low annealing temperatures. Thus polyisobutylenes, which are otherwise comparable to mineral oils, have exceptional nonstaining properties.

Synthetics that contain chlorine and fluorine would be expected to exhibit E. P. behavior at elevated temperatures. Synthetic oils containing silicon might produce undesirable residues, and the evolution of silicon dioxide aerosols would be a distinct health hazard. The polyglycols have good hydrodynamic properties, are soluble in both water and mineral oils, and leave no residue upon oxidative decomposition. The last property is especially useful in metalworking lubrication. The properties of the phosphate esters can be varied over wide ranges by structure, but inherently good lubricating properties are the general rule, in addition to good oxidative stability.

Mineral oils are listed at the bottom of Table 4.5. This does not mean that they are inferior or will be replaced by synthetic lubricants. If anything, the discussion has indicated the difficulty of replacing mineral oils despite the singular advantages of many synthetics.

Glasses

Under appropriate high-temperature conditions, molten glasses have been found that wet metals and act as liquid lubricants, primarily in extrusion. The glass coating serves not only as a lubricant but also protects the metal surface from oxidation and reduces heat loss to the tool.

Glass is defined as a supercooled liquid, or a solid that gradually softens to form a high-viscosity liquid upon raising the temperature. Upon cooling, no discontinuous change occurs, but the liquid becomes rigid through progressive increases in viscosity. The high viscosity of glassy liquids and the possibility of controlling viscosity by chemical composition within convenient temperature ranges make many inorganic glasses useful as metalworking lubricants. The property of forming a glass is possessed particularly by silica (SiO_2) and boron trioxide (B_2O_3), and by mixtures of one or both of these substances with oxides of the alkali or alkaline-earth metals or lead. While SiO_2 is, by far, the most important glass-forming system, B_2O_3, P_2O_3, P_2O_5, GeO_2, and S also form the basis of some specialty glasses; in all, sixty-six glass-forming systems are known, most of which are metal oxides [21].

On prolonged heating at fairly high temperatures, glasses may undergo devitrification whereby crystals will separate from the supercooled liquid. It may be mentioned that organic substances, such as glycerol or glucose, also form glasses but have found only limited, experimental use as lubricants.

For metalworking applications, commercial glasses or frits (glasses quenched by rapid cooling in air or water) are used. Glasses of widely varying compositions are listed in Table 4.6; even more varied compositions are available from frit producers. The properties of such glasses are optimized for glass-forming techniques and chemical durability, but many are suitable metalworking lubricants. Colored glasses are available in a wide range of compositions.

TABLE 4.6

Composition of Some Special Glasses [21]
(Data by Corning Glass Co.)

Corning No.	Glass Type	Approximate Composition, %	Suggested Extrusion Temp. Range, °C
8363	Lead borate	10 B_2O_3, 82 PbO, 5 SiO_2, 3 Al_2O_3	530
9772	Borate	--	870
8871	Potash lead	35 SiO_2, 7.2 K_2O, 58 PbO	870-1090
0010	Potash-soda-lead	63 SiO_2, 7.6 Na_2O, 6 K_2O, 0.3 CaO, 3.6 MgO, 21 PbO, 1 Al_2O_3	1090-1430
7052	Borosilicate	70 SiO_2, 0.5 K_2O, 1.2 PbO, 28 B_2O_3, 1.1 Al_2O_3	1260-1730
1720	Alumino-silicate	57 SiO_2, 1.0 Na_2O, 5.5 CaO, 12 MgO, 4 B_2O_3, 20.5 Al_2O_3	1650
7740	Borosilicate	81 SiO_2, 4 Na_2O, 0.5 K_2O, 13 B_2O_3, 2 Al_2O_3	1540-2100
7810	Silica	96 SiO_2, 2.9 B_2O_3, 0.4 Al_2O_3	1930-2040
7900	Silica	96 SiO_2	2210

Viscosity. The viscosity of the glass-formers and particularly of the liquid silicates is orders of magnitude higher than for most other liquids. Water, metals, and salts all have viscosities of about 1 centipoise at the liquidus temperature. The better glass-formers have viscosities of about 10^3 poises at the liquidus temperature. Silicates with viscosities of less than 10^2 poises at the liquidus temperature ordinarily cannot be quenched to glasses. The viscosities of the glasses of Table 4.6 are shown in Fig. 4.4 Relationships of glass composition and viscosity will be found in Morey [22].

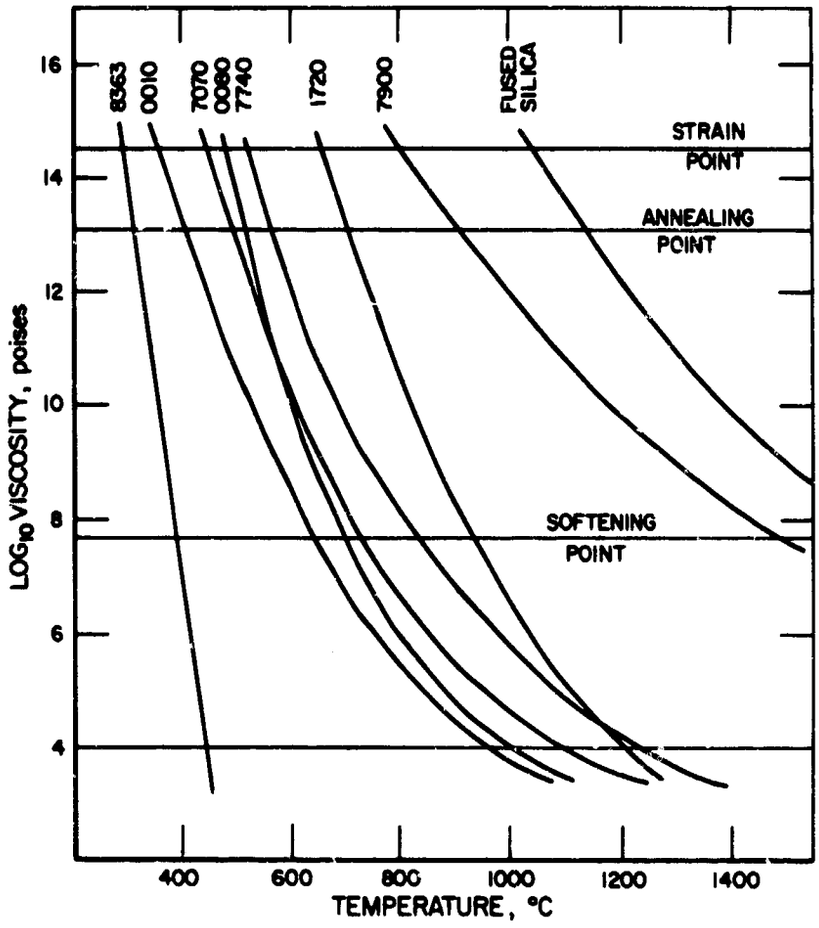


Fig. 4.4. Viscosities of some glasses [21].

Effect of Pressure on Viscosity. The viscosity of glass lubricants is believed to be relevant to hot working processes, but data on the important effect of pressure are quite fragmentary. Dane and Birch [23] studied the viscosity of glassy B_2O_3 at two temperatures (359°C and 516°C) and at relatively low pressures (up to 28,400 psi); the following equation was found to fit the data:

$$\eta = \eta_0 \exp(aP) \tag{4.4}$$

where η_0 is the viscosity at atmospheric pressure and a was 1.05×10^{-4} in^2/lb at 359°C and 0.32×10^{-4} in^2/lb at 516°C. It appears that glasses used in metalworking applications are not sensitive to pressure (see Section 8.34).

Surface Energy. Surface energies of glasses vary in the broad range of 80-400 ergs/cm^2. It is not known to what extent surface energy or wettability determines lubricating performance. Nevertheless, good wetting is important when the glass is also expected to protect the workpiece surface during heating and when a preapplied glass film of controlled thickness is relied upon for lubrication.

Glass as a Metalworking Lubricant. The general subject of glasses and their properties has been discussed in greater detail by Hutchins and Harrington [21], Morey [22], Kingery [24], Stanworth [25], Shand [26], and Volf [27].

For specific applications of glasses as metalworking lubricants, refer to Section 8.34 (Hot Extrusion) and 9.33 (Hot Forging).

4.22 Boundary Lubricants

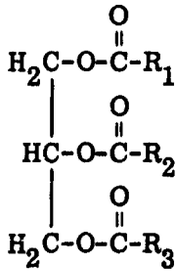
In Chapter 3, it was shown that as the load is increased, the lubricant can be squeezed out and may be reduced to a thin film. Ultimately even one molecular layer can give protection to sliding metal surfaces. The best protection was realized when the boundary lubricant was solid or could react with the metal surface to form a solid film. The long-chain fatty acids possess to the highest degree the physical and chemical characteristics necessary to form solid surface layers as boundary lubricants. This section will discuss the nature of fatty oils and the derived fatty acids and related compounds, such as the alcohols and amines prepared from the fatty acids. These materials constitute the most important boundary lubricants normally used in metalworking applications.

Natural Oils and Fats

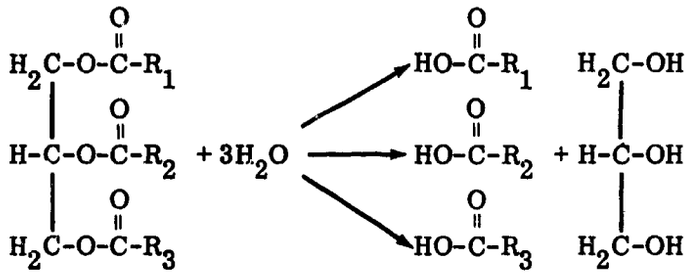
It is important to understand the nature of natural oils and fats since these materials are widely used in the neat form and are also the source of the fatty acids, the effective boundary lubricant components of commercial metalworking lubricant formulations. At the temperatures normally encountered in metalworking processes, the fatty oils decompose releasing some of the constituent fatty acids. Further, many of the commercial oils used will already have suffered partial degradation which produces varying contents of free fatty acids.

Natural oils consist of water-insoluble fats and oils derived from plant and animal sources; the major components are glyceryl esters of fatty acids.

Glycerine is a trifunctional alcohol, $CH_2OHCOHCH_2OH$, and the derived fats and oils are triglycerides,



To a first approximation, the alkyl substituents R_1, R_2, and R_3 may be considered to be identical. In fact, however, minor variations in these substituents are probable and mixed triglycerides are generally present. The oils are described in terms of the fatty acids released when the triglyceride is hydrolyzed.



(4.5)

In Eq. 4.5, if $R_1 = R_2 = R_3$ is $(-C_{17}H_{35})$, stearic acid is released in the free state. However, it is possible that R_1, R_2, and R_3 can provide many variations of fatty acid structure; for example, the fatty acid can be unsaturated, as in the case of oleic acid. Since these component acids constitute approximately 95% of the total oil or fat triglyceride, the natural oils and fats can be classified in terms of the relative proportions and compositions of these fatty acids. Many natural oils (for example, palm oils) show considerable variation in free acids and in the distribution of all acids dependent on source.

The nonglyceride components of natural oils and fats are complex; however, since crude natural oils and fats usually contain less than 5% and refined oils less than 2% of these constituents, their contribution to the lubricant properties is minor.

The term "fat" is ordinarily applied to triglycerides that are solid or, more correctly, semisolid, at ordinary temperatures; "oil" is applied to

triglycerides which are normally liquid. The distinction is arbitrary and there are many other specific terms applied according to origin, such as tallow, lard, vegetable butters, and neatsfoot oil (rendered from the feet of cattle).

One further distinction is necessary to identify the natural waxes. These differ from fats in that they are esters of certain higher monohydric alcohols rather than of glycerol (Section 4.25).

The various natural oils and fats can be classified in terms of the relative proportions of the different fatty acids. Table 4.7 lists the fatty acid composition of materials often contained in metalworking lubricants. The data show that coconut oil and palm oil contain relatively high amounts of saturated acids. Palm oil, obtained from the pulp of the palm fruit, is more important as a metalworking lubricant than kernel oil and contains saturated and unsaturated (olefinic) fatty acids in approximately equal amounts. Both palm oil and the animal tallows and greases are characteristically high in free fatty acids (3-30%); this property makes these oils especially useful as boundary lubricants. Inedible lard oil, the residue after crystallizing and pressing of lard, normally contains 15-25% of free fatty acids. Rapeseed or ravison oil, as well as mustard oils, contains erucic acid:

$$CH_3(CH_2)_7CH{=}CH(CH_2)_{11}COOH$$

This acid contains 22 carbon atoms as well as one double bond. Another acid, present in smaller amounts, is eicosenoic acid (20 carbon atoms, 1 double bond).

Castor oil should also be mentioned. It is markedly different from other oils because of its high content (85-90%) of ricinoleic acid containing a hydroxyl group attached to the carbon chain:

$$CH_3(CH_2)_5CHOHCH_2CH{=}CH(CH_2)_7COOH$$

Fats of land animals contain unsaturated acids, principally oleic (one double bond) and linoleic acids (two double bonds). Marine oils are distinguished by the presence of extremely unsaturated fatty acids (four or more double bonds), considerable variations in carbon chain length, and also a relatively large proportion (as much as 25%) of saturated acids. In addition, the glyceride esters amount to only 25-35% while 65-75% are esters of normally higher monohydric alcohols. The most important marine oils are whale, california sardine (pilchard), menhaden, and herring oils.

TABLE 4.7

Fatty Acid Composition of Various Fats and Oils

No. of Carbon Atoms	Name of Acid	Coconut (Copra) Oil	Palm Kernel Oil	Palm Oil	Tallow (Beef)	Tallow (Mutton)	Lard	Cotton-seed Oil	Rape-seed Oil
				Saturated Acids					
12	Lauric	44-52	40-52	—	tr-0.2	tr-0.2	—	—	—
14	Myristic	13-19	14-17	0.5-6	2-8	4-10	1-4	1	—
16	Palmitic	8-11	7-9	32-45	24-37	24-38	20-28	26-31	3-5
18	Stearic	1-3	1-3	2-7	14-29	15-30	5-14	3-5	1-3
	Total (typical)	92	81	40-50	50-55	52-57	35-40	28-35	6-10
				Unsaturated Acids					
Monounsaturated									
16	Hexadecanoic	—	—	0.8-1.8	1.9-2.7	1-2	—	—	—
18	Oleic	5-8	13-19	38-52	40-50	38-48	41-51	22-26	14-18
Diunsaturated									
18	Linoleic	tr-2.5	0.5-2	5-11	1-5	—	2-15	37-43	20-24
Triunsaturated									
18	Linolenic	—	—	—	—	—	0.1-0.2	—	8-12
	Total (typical)	8	19	50-60	44-52	40-50	60-65	60-70	60-80*

tr = trace; values in wt %

*Contains erucic (35-40%) and eicosenoic (3-5%) acids.

The unsaturation of the various oils is one means of characterizing them and has some, occasionally debated effect on their lubricating properties. High unsaturation of an oil, however, may indicate instability in storage or in use, resulting in polymerization and oxidation to gummy residues.

The technology of fats and oils is a specialized subject and reference for specific information should be made to standard texts including Bailey [28], Eckey [29], Hilditch [30,31], and Kirschenbauer [32]. Bailey [33] and Norris [34] present a useful introduction to the subject.

An important physical property of fats and oils used as metalworking lubricants is viscosity. Table 4.8 [35] indicates that at atmospheric pressure most of the natural products have quite similar viscosities with the exceptions of rapeseed oil and castor oil. Rapeseed oils contain esters of longer chain acids that contribute to somewhat higher viscosities. Castor oils, characterized by a high content of ricinoleic acid esters, have appreciably higher viscosities.

TABLE 4.8

Viscosity of Fats and Oils [35]

Oil	Acid Number	Specific Gravity (20°/4°C)	Kinematic Viscosity, cs		Saybolt Viscosity, sec	
			37.7°C	98.7°C	37.7°C	93.7°C
Olive	—	0.9158	46.68	9.09	216	55.2
Rapeseed	0.34	0.9114	50.64	10.32	234	59.4
Cottonseed	14.24	0.9187	35.88	8.39	181	52.7
Soybean	3.50	0.9228	28.49	7.60	134	50.1
Linseed	3.42	0.9297	29.60	7.33	139	49.2
Castor	0.81	0.9619	293.4	20.08	1368	97.7
Coconut	0.01	0.9226	29.79	6.06	140	45.2
Palm kernel	9.0	0.9190	30.92	6.50	145	46.5
Lard	3.39	0.9138	44.41	8.81	206	54.2
Neatsfoot	13.35	0.9158	43.15	8.50	200	53.1
Refined whale	0.75	0.9227	31.47	7.48	147	49.7
Sperm	0.80	0.8829	22.99	5.70	110	44.1

However, the most important aspect of the viscosity of natural oils and fats is the marked increase with pressure and early solidification in comparison with mineral oils. Elevation of temperature has a countereffect, so that in metalworking lubrication both variables must be taken into account. Figure 4.5 is a plot of the viscosity increase caused by pressure relative to viscosity measured at atmospheric pressure. It is evident that solidification occurs at much lower pressure for the fatty oils than for the mineral oils. An elevation of temperature from 25 to 40°C does not appreciably lower the slope of the viscos. -pressure relationship, but solidification pressures are markedly increased (Fig. 4.6). The relationship of temperature to apparent solidification point is given in Fig. 4.7 for lard oil and sperm oil [5]. Very little reliable information is available on the solidification characteristics of natural oils although this property could well be the most important one for metalworking lubrication.

For broad generalizations on the effect of pressure on the viscosity of liquid natural oils, reference may be made to Cameron [6].

Fatty Acids

The saturated fatty acids derived from natural fats, oils, and waxes contain, with few exceptions, an even number of carbon atoms. In addition,

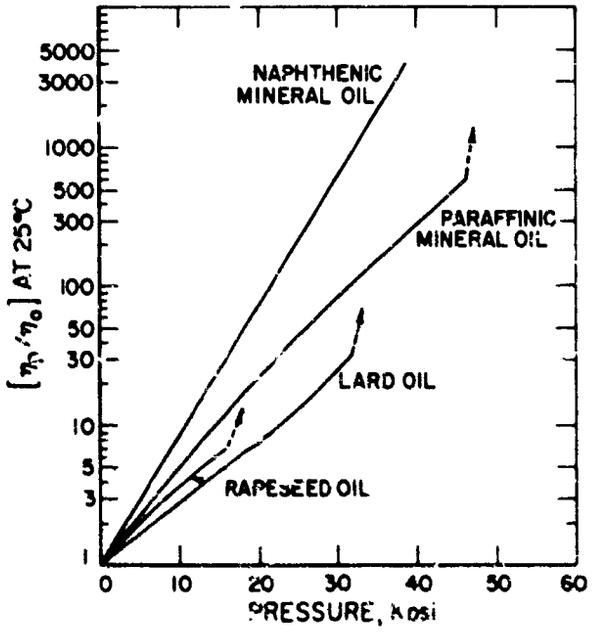


Fig. 4.5. Relative effects of pressure on the viscosity of mineral and natural oils at 25°C.

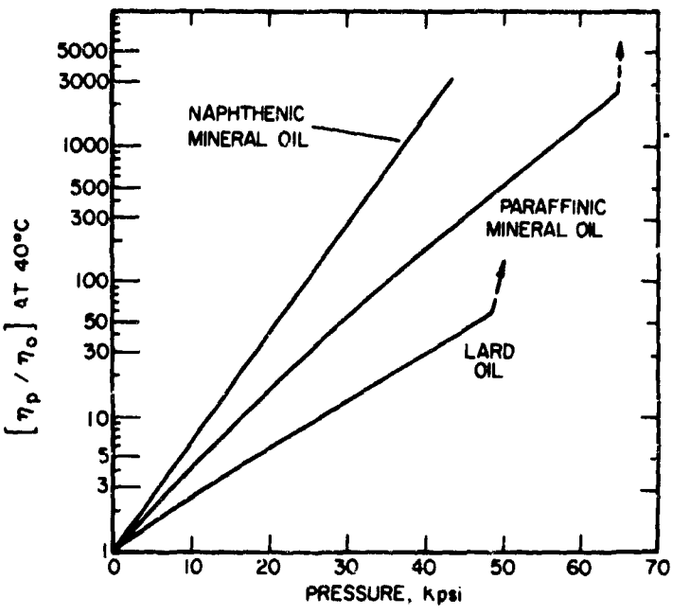


Fig. 4.6. Relative effects of pressure on the viscosity of mineral and natural oils at 40°C.

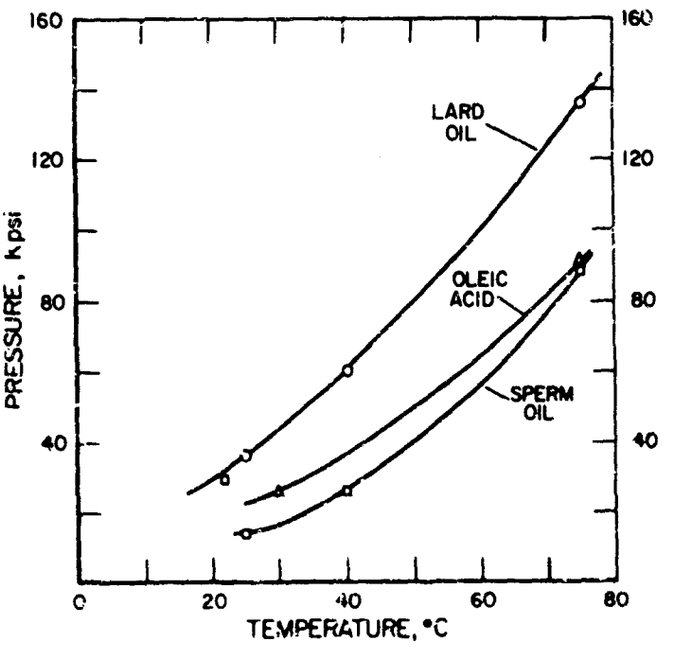


Fig. 4.7. Apparent solidification of fatty oils [5].

the acids may contain one, two, or more double bonds. In the natural vegetable oils and in fats from land animals, the double bonds are separated by at least one carbon atom. The isolated olefinic bonds are not highly reactive, and at low temperatures the molecule resembles the saturated acid. For example, oleic acid (one double bond) is almost as stable as stearic acid. However, if an acid contains two or more separated double bonds (as in linoleic acid), there is a probability that, upon heating or on contact with hot metal surfaces, the double bonds will tend to migrate until they are adjacent (conjugated). Conjugation greatly enhances chemical reactivity, and the compounds will both oxidize and polymerize quite readily into high molecular weight solid polymers. Acids, particularly those derived from highly unsaturated oils, such as fish oils, can produce undesirable metal staining.

Commercial acids are derived from fats and oils by hydrolysis. Typical acid compositions [36] of saturated and unsaturated commercial products are listed in Tables 4.9 and 4.10. It is evident that wide ranges of products are available.

The viscosities of the saturated fatty acids and their variation with temperature are depicted in Fig. 4.8 [37]. It is apparent that an increase in chain length causes a marked increase in viscosity at a given temperature.

TABLE 4.9

Approximate Composition (wt %) of Commercial Saturated Acids [36]

Acids	Saturated Acids							Unsaturated Acid
	C_6	C_8	C_{10}	C_{12}	C_{14}	C_{16}	C_{18}	
Caprylic	5	92	3					
Capric		1	97	2				
Lauric			1	97	2			
Myristic				1	96	3		
Palmitic (90%)					1	94	5	
Stearic								
Eutectic					1	70	28	1
Single pressed					2	50	38	8
Hydrogenated tallow					4	30	63	1

TABLE 4.10

Approximate Composition (wt %) of Commercial Unsaturated Acids [36]

Designation	Saturated Acids				Unsaturated Acids			
Carbon Number of Acid:	C_{14}	C_{16}	C_{17}	C_{18}	C_{16}	C_{18}	C_{18}	C_{18}
Number of Double Bonds:	0	0	0	0	1	1	2	3
Low polyunsaturated oleic	3	4	1		10	77	4	1
Oleic, white	3	4	1		8	73	8	1
Oleic, red oil	3	5	1	1	7	71	8	1
Linoleic	1	4			1	33	60	

The solidification of oleic acid under high pressure has been presented previously in Fig. 4.7.

Fatty Alcohols

Fatty alcohols are prepared from fatty acids, such as tallow acids, by hydrogenation:

$$RCOOH + 4H_2 \rightarrow RCH_2OH + H_2O \qquad (4.6)$$

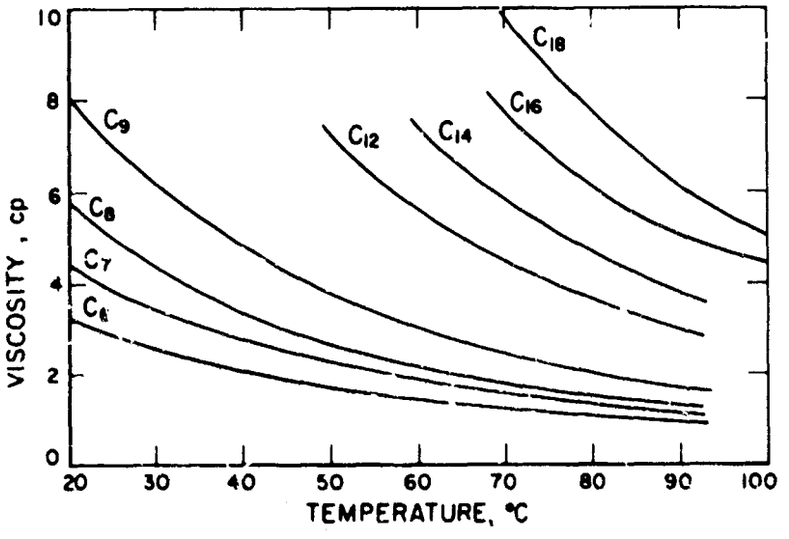


Fig. 4.8. Temperature-viscosity relationships for the saturated fatty acids [37].

The conversion is on the order of 90%. Other methods of producing alcohols utilize hydrogenolysis of the glyceride ester or reduction with sodium. The most extensively used raw materials are coconut oil and tallow, the latter being somewhat less pure and less expensive. The important commercial alcohols are generally saturated as shown by typical products given in Table 4.11 [38].

The alcohols below C_{12} are colorless oily liquids. Above C_{12}, the physical form of the alcohol progresses from soft, crystalline platelets to crystalline solid waxes. The viscosity-temperature characteristics of C_8-, C_{12}-, and C_{18}- alcohols are shown in Fig. 4.9 [38].

Other Fatty Acid Derivatives

Other derivatives of possible use in boundary lubrication are the fatty amines and amides. Fatty acids are converted to amines by the intermediate formation of nitrile:

$$RCOOH + NH_3 \longrightarrow RCN + 2H_2O \quad (4.7)$$

$$RCN + 2H_2 \longrightarrow RCH_2NH_2 \quad (4.8)$$

TABLE 4.11

Composition of Commercial Fatty Alcohol Mixtures [38]

Common Name	Approximate Composition, wt % (100% Alcohol Basis)						
	C_6	C_8	C_{10}	C_{12}	C_{14}	C_{16}	C_{18}
Octyl alcohol	1	98	1				
Decyl alcohol		2	98	trace			
Lauryl alcohol			2	96	2		
			1	71	26	2	
			1	65	25	9	
Myristyl alcohol				2	95	3	
Myristyl-cetyl alcohol				4	44	24	28
Cetyl alcohol					1	97	2
Cetyl-stearyl alcohol					3	64	33
Cetyl-oleyl alcohol						50	50*
Stearyl alcohol						5	95

*Oleyl alcohol

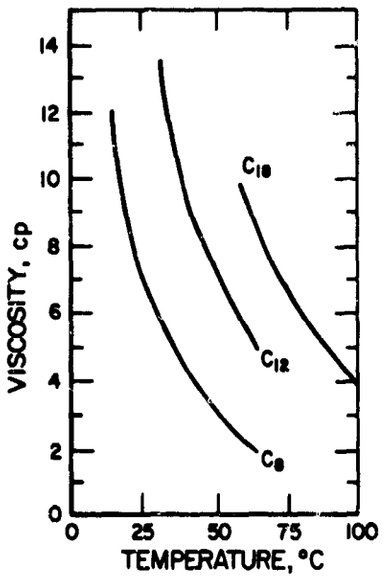


Fig. 4.9. Viscosity of fatty alcohols [38].

Such products are derived commercially from coconut oil acids, tallow acids, and cottonseed oil acids.

The fatty acid amides are prepared by reacting ammonia under pressure with a fatty acid:

$$RCOOH + NH_3 \longrightarrow RCONH_2 + H_2O \tag{4.9}$$

Hydrogenation of Natural Oils and Fats

It is possible to modify the degree of unsaturation by addition of hydrogen in the presence of nickel catalysts. Thus, highly unsaturated fish oils can be partially hydrogenated; less saturated oils such as cottonseed oil can also be hardened. The process consists chemically in the direct addition of one molecule of hydrogen to each double bond:

$$\cdots\ \begin{array}{c} H\ H\ H\ H \\ |\ \ |\ \ |\ \ | \\ -C-C=C-C- \\ |\ \ \ \ \ \ \ \ | \\ H\ \ \ \ \ \ \ \ H \end{array}\ \cdots + H_2 \longrightarrow \cdots\ \begin{array}{c} H\ H\ H\ H \\ |\ \ |\ \ |\ \ | \\ -C-C-C-C- \\ |\ \ |\ \ |\ \ | \\ H\ H\ H\ H \end{array}\ \cdots \tag{4.10}$$

Other than saturation, the main result is to form generally higher melting products compared to the starting material.

Soaps

The formation of solid soap layers was shown in Chapter 3 to provide effective boundary lubrication of metal surfaces. Metal soaps are commonly used in metalworking operations for the purpose of boundary lubrication and sometimes also for thick film lubrication. Soaps (e.g., sodium stearate $NaO \cdot COC_{17}H_{35}$) are the reaction products of the higher fatty acids with a metal hydroxide. The alkali soaps are soluble in water whereas other metal soaps are generally insoluble. Other reaction products are possible: (1) acid salts which have the general structure $RCOOM \cdot RCOOH$ (R = alkyl group, M = metal) and are formed by sodium, potassium, and ammonium ions and (2) basic salts of multivalent metals (aluminum, beryllium, and lead as well as a few others) as typified by $Al(OH)(RCOO)_2$. The soaps and associated salts are important in grease manufacture, which is discussed in Section 4.25.

Since the melting point of soap-film layers is associated with the transition temperature limiting the most effective boundary performance of a particular fatty acid, melting points of some fatty acid metal soaps are given in Table 4.12 [39].

4.23 Extreme Pressure Compounds

A wide variety of materials have been employed to improve the load-carrying capacity of lubricants under severe load conditions. These extreme pressure (E. P.) additives function at elevated temperatures by reacting irreversibly with metal surfaces to form inorganic films which prevent adhesion between the contacting metal. In principle, it is possible (Section 3.46) to combine suitable boundary and E. P. additives in a mineral oil fluid to obtain good lubrication over a wide temperature range, the E. P. additive becoming active at temperatures where the boundary lubricants fail. Such additions and combinations have become an important part of lubrication technology.

The most common E. P. compounds contain chlorine, sulfur, or phosphorus, either alone or in combinations. These agents decompose, and the reaction products form metal surface films based on chlorides, sulfides, or phosphates. The classical view of the action of E. P. compounds is summarized by Bowden and Tabor [40], and a brief account is presented in Section 3.46. The nature of the E. P. film is, of course, highly dependent on the environment, including oxygen and water. Because the film formation

TABLE 4.12

Melting Points of Fatty Acid Soaps [39]

Cation	Melting Point of Salt, °C							
	Enanthate (C_7)	Caprylate (C_8)	Pelargonate (C_9)	Laurate (C_{12})	Myristate (C_{14})	Palmitate (C_{16})	Stearate (C_{18})	Oleate (C_{18})
Ammonium (neutral)	112	114	115	75	75-90	—	—	—
Ammonium (acid)	45	54	—	77	84	89	93	78(dec.)
Potassium (acid)	—	80-140	—	80-150	95-160	100-160	100-160	95
Lithium	—	—	—	229.2-229.8	223.6-224.2	224-225	220.5-221.5	—
Barium	238-239	—	—	>260	—	dec.		100(dec.)
Calcium	—	—	216	182-133	—	153-156	150-154	83-84
Magnesium	—	—	—	150.4	131.6	121-122	132	—
Lead	85	100	95-100	104.6-104.8	108.6-108.8	112.2-112.4	115.6-115.8	≈50
Silver	—	—	—	211-213	211	209	205	—
Zinc	131-132	135-136	131-132	128	—	129	130	70
Copper (ic)	—	264-266	260	111-113	—	115-120	125	100
Nickel (ic)	—	—	—	44	—	80	80-86	18-20
Cobalt (ic)	—	—	—	—	—	70-75	73-75	—

dec. = decomposes

involves chemical reaction, the metal surface must not corrode excessively before the high temperature levels are reached where the film takes effect against incipient seizure or high friction.

The role of E. P. additives in lubricants is particularly complex and highly dependent upon the precise service conditions. Thus, reaction time may be a controlling parameter because, if the decomposition and reaction do not occur within the time interval needed for lubrication, friction may not be improved and corrosion may be the only consequence. In metalworking lubrication, it may be preferable to seek a highly reactive compound even if the compound decomposes prior to entry into the high-temperature zone. The bulk of the published information on E. P. additives refers to their role in machinery elements; reviews such as those by Molyneaux [41] and by Stewart and Stuart [42] are directed toward application in gears, engines, bearings, and related machinery uses. In this section attention will be directed toward the mechanism of action of specific chemical groups in promoting E. P. action. This knowledge will be useful in understanding or predicting lubricant action in metalworking processes.

Chlorine Compounds

Various chlorinated hydrocarbons (mostly paraffins) are available commercially for use as E. P. agents. Generally the chlorine content is 30-50%. Sanin et al. [43] showed, in a systematic study, that effectiveness decreased with decreasing chlorine content, the monochloro fraction (one chlorine atom per molecule) showing no E. P. characteristics. They concluded that the mechanism involved evolution of HCl at elevated temperatures and subsequent formation of an iron chloride surface film. Other workers have suggested that HCl is released by hydrolysis with trace amounts of water, indicative of a corrosive mechanism. No doubt both types of action occur.

Chloride films may reduce friction more than sulfide films but suffer the disadvantage that they fail at a lower temperature; iron chloride ($FeCl_3$) ceases to lubricate when it sublimes at about 300°C in vacuo [40]. In the presence of air and moisture, chloride films may fail by oxidation or sometimes by hydrolysis.

Sulfur Compounds

Numerous sulfur compounds have been patented as E. P. additives. The sulfur compounds must be of the appropriate reactivity for practical use.

Compounds which have been used successfully include mercaptans, thio acids, sulfonic acids, thiadiazoles, benzothiazole derivatives, and sulfurized hydrocarbons and animal oils [42].

Commercial E. P. lubricating oil additives are usually a combination of sulfur, chlorine, or phosphorus compounds either as mixtures or in the same molecule; zinc or lead soaps and salts are frequently included. Sulfide films are less easily sheared than chloride films, but are hydrolytically stable and effective up to about 750°C in vacuo. Friction is usually reduced by including an appropriate friction-r. cing additive such as a fatty acid or soap (frequently lead soaps).

The mechanism of the action of organosulfur compounds has been the subject of many investigations reviewed by Allum and Forbes [44].

Phosphorus Compounds

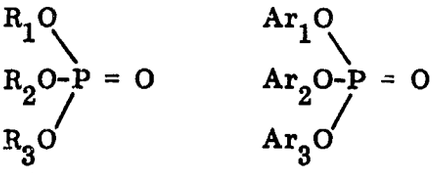
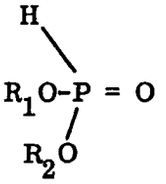
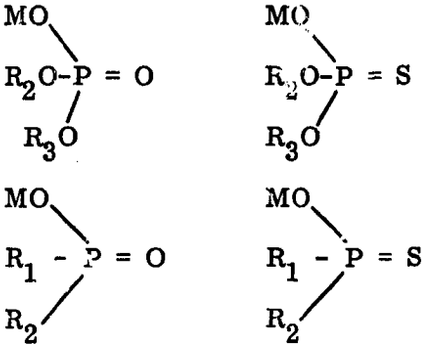
Effective E. P. action can be obtained from a large number of compounds but especially the aliphatic and aromatic phosphate esters, acid phosphate esters, and metal salts derived from phosphoric, thiophosphoric, phosphinic, and thiophosphinic acids. Some of these are listed in Table 4.13. The possible modifications by structure changes are extremely numerous. Sanin et al. [43] show that in certain tests the thiophosphites were superior to the thiophosphates and that effectiveness increased with shortening of an alkyl side chain. It is evident that the chemist can make useful structure changes to meet specific purposes for a given additive class. For metalworking lubricants, it is probable that such sophisticated changes may not be necessary.

In a comparison of the reaction of phosphorus- and sulfur-containing E. P. additives, the phosphorus component was shown to predominate over the sulfur [45]. The surface condition is also important: Furey [46] showed that surface roughness was an important factor; prior phosphating of the surface was also shown to be useful [47].

The action of phosphorus E. P. lubricants has been studied in some detail and with a diversity of interpretations. An early study by Beeck, Givens, and Williams [48] attributed the lubricating mechanism of tricresyl phosphate (TCP), a widely used E. P. compound, to the polishing action produced through formation of an iron-iron phosphide eutectic. This early view was initially supported by the observation of phosphides in static, high-temperature experiments [49].

TABLE 4.13

Phosphorus Extreme Pressure Compounds

Class	Formula
Aliphatic and aromatic phosphate esters	
Hydrogen phosphoric acid esters	
Metal salts derived from phosphoric, thiophosphoric, phosphinic and thiophosphinic acids	

R_1, R_2, R_3 = alkyl; Ar_1, Ar_2, Ar_3 = aromatic; M = metal

The present view is that the most polar ingredients in TCP act as the effective antiwear additive and that TCP serves as a reservoir from which the active form of impurity is generated by oxidation, hydrolysis, or thermally induced surface reactions. Extremely low levels (0.3%) of polar impurities can induce the mechanism [50, 51].

Iodine Compounds

It can be assumed that members of the halogen series—fluorine, chlorine, bromine, and iodine—will form metal halide films at high temperatures on metal surfaces. Thus, each will have merit as E.P. lubricants. The use of chlorine-containing lubricants has been mentioned; these are important because of their relatively low cost. Bromine and fluorine compounds are noted briefly in the next section. Iodine, the highest member of the halogen

series (molecular weight 126.91), provides some unusual E. P. properties deserving of special mention.

Rowe [52] found that titanium iodide (TiI_2), formed as a reaction product by heating titanium in iodine vapor, gave low friction. The possibility that iodine and iodine compounds have E. P. activity was confirmed by Roberts and Owens [53] and by Furey [54].

Owens et al. [55, 56] suggest that charge-transfer complexes formed by reacting iodine with aromatic compounds function by producing a low-shear-strength metal iodide layer. Furey [54] observed that iodine dissolved in hydrocarbons markedly reduced friction, while bromine or chlorine were ineffective. Since sliding contact studies with aluminum, gold, and glass surfaces all showed similar results, Furey suggested that the formation of a diiodide surface film was not essential.

While its mechanism of action is still debated, iodine is unique in its scientific development since it attained substantial confirmation of its performance in laboratory experiments; widespread industrial application has yet to follow, particularly with respect to metalworking lubricant uses. Compounds listed in Table 4.14 are the known lamellar metal iodides [57]; these data may be considered in seeking new E. P. systems.

TABLE 4.14

Lamellar Metal Iodides [57]

Compound	Melting Point, °C	Compound	Melting Point, °C
AsI_3	147	MgI_2	700
BiI_3	437	MnI_2	n.a.
CaI_2	575	NiI_2	797
CdI_2	390	PbI_2	380
CoI_2	515	SbI_3	178
FeI_2	593	TiI_2	480*
GeI_2	n.a.	VI_2	n.a.
HgI_2	259	YbI_2	n.a.

n.a. = not available

*Decomposition temperature.

Bromine and Fluorine Compounds

The E. P. action of bromine- and/or fluorine-containing agents is suggested by the experiments of Johnson, Swikert, and Buckley [58] on cobalt- and nickel-base alloys lubricated at temperatures up to 650°C with several reactive gas lubricants (CF_2Br plus 1% SF_6; CF_2Br_2 and 1:1 mixture of CF_3Br and CF_2Br_2). An E. P. film was formed comprised of $CoBr_2$ and $NiBr_2$, respectively; both compounds have low shear strength. In these experiments, no evidence was found to indicate that the carbon-fluorine bond was ruptured. Since oxygen competes for metal surface sites, its presence may be detrimental [59]. However, at 10 mm pressure, Baldwin and Rowe [60] found that decomposition of CCl_2F_2 vapors produced a lubricating film on stainless steel that persisted up to a higher temperature (800-900°C) than the film prepared from chlorine alone; it was concluded that a mixed chloride-fluoride film was formed, but this was not confirmed by X-ray evidence.

Borate Compounds

Kreuz, Fein, and Dundy [61] investigated the use of borate lubricants, generally 3% tribenzylborate $(C_6H_5CH_2O)_3B$ in a light solvent neutral oil. Films of a few thousand angstroms in thickness contained boron, ferrous iron, and organic compounds. They were gray and were appreciably harder than the steel substrate. The inorganic component of the film is comparable to that derived from a mixture of boric and ferrous oxides.

The results indicate that at least one other E. P. lubricating mechanism is possible and that additional E. P. lubricants might be developed with potential for metalworking application. It is even possible that the apparent E. P. action is essentially a result of reduced adhesion between the contacting members and, in this respect, the treatment could be a variant of boronizing discussed in Section 3.25.

4.24 Lamellar Solids

Of the solid lubricants, the most widely used are graphite and molybdenum disulfide (MoS_2). Both are highly anisotropic and lamellar in crystal structure. Many additional compounds—including certain metallic iodides, chlorides, and sulfides—have been investigated for solid lubrication, but these remain relatively less important. In this section, attention will be directed toward the nature of lamellar solid lubricants.

Graphite

Graphite has been recognized since ancient times as a material occurring naturally in volcanic rock, metamorphic strata, and sedimentary formations. The graphite-bearing ore usually contains associated silicate minerals which vary in kind and percentage depending on source. Graphite itself is hydrophobic (water-hating) and is electroconductive.

The classification of natural graphites is quite varied, but three physically distinct common varieties are customarily distinguished: flake, amorphous, and lump. Flake is classified according to purity, with high grades containing 95-96% carbon. Amorphous graphite is specified according to locality and carbon content (seldom higher than 85%). Lump is frequently a mixture of flake and amorphous and is not encountered in lubricant applications. Bastian [62] indicates that the fine-flake types used in hot metalworking lubricants have 5 to 10% ash whereas amorphous grades may have from 15 to 40% ash; the low-ash product is presumed to be better to avoid abrasive ash buildup in heated dies.

The theoretical graphite crystallite is comprised of parallel layers of planar hexagonal carbon rings as shown in Fig. 4.10. Each carbon atom is joined to three neighboring carbon atoms at 120° angles to form a layer. The C-C distance is 1.415 Å, and the width of each "benzene" ring is 2.456 Å. The atoms are joined between layers at a distance of 3.354 Å at room temperature (d-spacing). Graphite from various sources will differ both in details of crystallographic structure and in associated impurities. It is

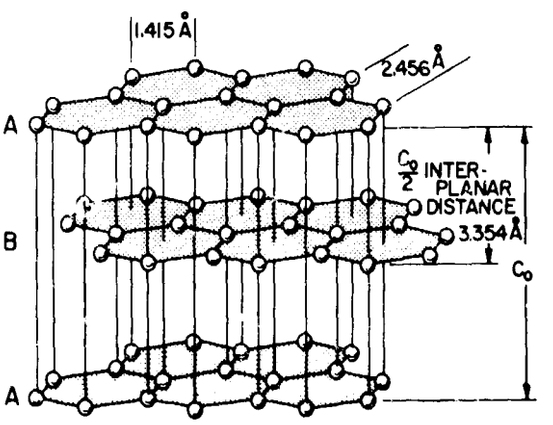


Fig. 4.10. Structure of hexagonal graphite.

therefore necessary to rely on the supplier to furnish uniform products for specific applications, such as lubrication.

The physical properties of graphite vary greatly with source, purifying procedures, and, in the case of artificial graphites, with manufacturing procedure. Anisotropy is a characteristic property. Thus, thermal conductivity is approximately 50% higher in the planar direction than in the perpendicular direction. Similarly, tensile strength may be 50-90% higher parallel to the planes than in the C_o-direction.

Colloidal graphite used for lubrication is a permanent suspension of finely ground natural or manufactured graphite dispersed in a liquid carrier, such as water, oil, or alcohols. Dispersions obtained as concentrates are diluted for use. With respect to particle size, fine particles serve to aid suspension; particles larger than 1 or 2 μ cannot be permanently suspended in water or liquids less viscous than water. However, the particles cannot be too fine, since when ground to under 0.1 μ, the graphite structure becomes turbostratic, not suitable for lubrication. The dispersive properties of graphites can be controlled by the manufacturer; for example, the oxygen content and hydrophilic nature of graphite is markedly increased by milling [63].

The frictional characteristics of graphite in sliding under elastic deformation depend apparently upon the crystal structure and also upon the presence of adsorbed gases or vapors. The friction between graphite and metals may be increased if solid solutions are formed at the interface. This is shown in data cited by Mordike [64] in Fig. 4.11 where the low friction of graphite persists until solid-solution phases are formed. These experiments were performed out of contact with air (in vacuo) and with relatively long waiting periods between tests. In contact with materials stable at high temperatures, graphite apparently shows an inherently low friction at very high temperatures (i.e., above 1500°C and up to 2000°C) independent of the presence of vapors. The influence of these factors in metalworking is not known.

The above discussion on graphite covers only a small portion of the large amount of material available on the lubricating properties of graphite. Further details will be found in the literature [40, 63, 65].

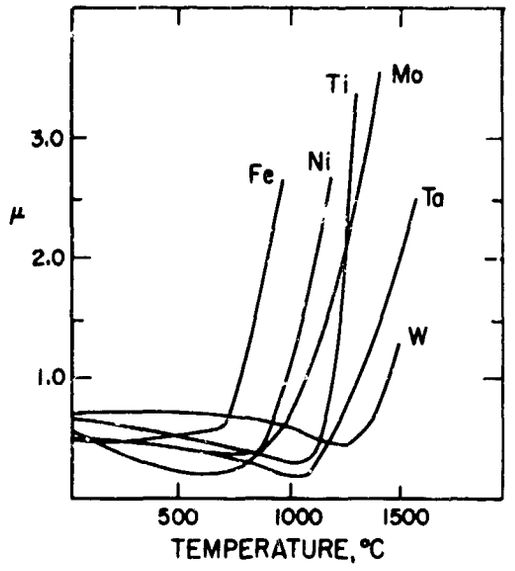


Fig. 4.11. Friction of graphite on various metals [64].

Molybdenum Disulfide

Molybdenum disulfide has long been known as a lubricant, often being mistaken for graphite because of its similar physical appearance and behavior. However, the two materials are quite different in their performance as solid film lubricants especially with respect to environmental conditions.

The material used as a lubricant is derived from the mineral ore molybdenite, MoS_2. The lubricant grade is derived after considerable processing and purification. Dickinson and Pauling [66] suggested that the easy cleavage of molybdenite (MoS_2) was a consequence of its crystal structure. The structure is shown in Fig. 4.12. Each molybdenum atom is surrounded by equidistant (2.41 Å) sulfur atoms. The arrangement leads to relatively close-packed layer-lattices of MoS_2, which are three atom layers thick and are held together by strong covalent bonding. The adjacent layer is separated at a distance of 3.49 Å. The bonding between these layers is of the weak van der Waals type, and shearing takes place between the layers of opposing sulfur atoms; hence low friction may be an intrinsic property of the molybdenite structure. This contrasts with high electron bonding in graphite.

Also in contrast to the observed behavior of graphite, oxygen and water vapor cause decomposition of MoS_2 with a consequent rise in friction.

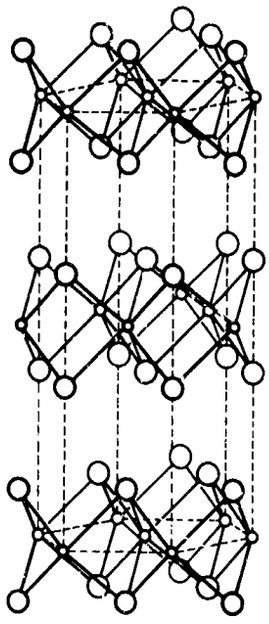


Fig. 4.12. Structure of hexagonal molybdenite, MoS_2 (Sulfur atoms, large circles; molybdenum, small circles.)

Winer [67] reviewed the general properties of MoS_2 in elastic deformation sliding.

Miscellaneous Materials

The lamellar solids $CrCl_3$ and TiI_2 show low friction analogous to MoS_2, not dependent on the presence of vapors [68]. Another material which, like graphite, has received attention because of its very low friction at high temperatures is boron nitride, BN. This material has good lubricating properties at room temperature in the presence of certain contaminants [69]. These materials are only a few of the many possible lamellar solids that can be used as lubricants; their application in metalworking is speculative.

4.25 Greases and Waxes

Greases can be used in metalworking applications where a highly viscous and adherent lubricant is desirable, as in heavy drawing operations. This contrasts somewhat with their use in machinery applications where the ability to remain in place protects certain types of bearings against intrusion of dirt and extraneous materials.

The modern definition of grease—a solid or semisolid lubricant consisting of a thickening or gelling agent in a liquid lubricant—embraces not only soap types but also complex nonsoap types. The material presented here serves as an introduction to grease technology rather than a description of specific viscous liquids, pastes, or greases applicable as metalworking lubricants; such applications are discussed under the appropriate metalworking process, particularly wire drawing (Chapter 7) and deep drawing (Chapter 11).

Greases

The fluids used in compounding greases are comparable with those used for lubrication. Thus, over 90% of the greases compounded contain oil in the SAE 20 to 30 range (Fig. 4.1). For high-temperatures, quite viscous oils (2000-3000 SUS at 37.8°C) may be used. Synthetic oils, such as aliphatic diesters, polymerized ethylene oxides, siloxanes or fluorocarbons may also serve as the base of the grease. Since, in general, greases perform their lubricant function as a thin film not conducive to heat dissipation, oil volatility is a more important physical property than with liquid lubricants.

Greases are usually described in terms of the thickening agent used: (1) soap-type greases; (2) complex greases; (3) nonsoap greases.

The majority of all industrial greases are composed of a soap or soaps and a petroleum oil; they may also contain filler materials and additives as well. The most common agents are the fatty-acid soaps of sodium and calcium, and more recently lithium. The fatty acids are usually oleic, palmitic, stearic, and other carboxylic acids derived from tallow, hydrogenated fish oil, petroleum acids, vegetable oils, as well as from wool grease, tall oil, and rosin. Unreacted fats, fatty acids, alkali, glycerol, rosin, etc., may also be present.

A complex grease is one in which the soap phase is prepared by the solidification of two classes of compounds: (1) the soap and (2) a complexing agent such as water, salt, or an additive of some type. Boner [70] suggests that much more than half of all lubricating greases now manufactured are of this type.

Many investigators have offered X-ray diffraction evidence for the formation of new chemical compounds, but generally it is concluded that strong adsorption interactions could account for the diffraction properties of complex soap greases. Current evidence tends to support this latter

view [18]. Because of their improved properties, complex greases are suited for multipurpose grease applications [71].

Nonsoap materials have been studied extensively as grease thickeners because of their resistance to oxidation, radiation, and thermal effects. Materials which have been used as gelling agents include organic pigments (particularly metal phthalocyanines and indanthrene blue), organic bases and derivatives, polymers, carbon black, silicas, silica gels, clays, and metal oxides. Organic materials such as arylureas, polyureas, polyethylene, and polytetrafluoroethylene (PTFE) have been developed for special purposes.

Solid powders are also added as fillers in greases for extreme conditions of boundary lubrication. These may include graphite, molybdenum disulfide, talc, zinc oxide, and, in certain cases, asbestos fibers.

One mechanism for the performance of these materials as grease thickeners suggests that colloidal dispersion of solids (polar and nonpolar) in both polar and nonpolar liquids may be attributed to attractive and repulsive forces at the solid/liquid interface. Another view proposes that chemically bound water at the surface is the controlling mechanism. The ionic double-layer theory has also been applied. For further review, refer to Bowers and Murphy [18], Boner [70], and Harris [72].

Greases are non-Newtonian fluids, and the apparent viscosity is dependent upon the shearing rates imposed. For the technical identification of grease flow properties, the consistency or hardness is determined in a cone penetration test by use of testing equipment defined in ASTM method D217. The penetration is determined both on the unworked grease and after a standardized working or shearing procedure. In addition to non-Newtonian behavior, greases exhibit viscoelastic properties [18].

Chemical additives similar to those used in fluid lubricants are generally added to greases for specific purposes such as oxidation resistance, rust prevention, and extreme pressure application. In using these additives, it is necessary to check for compatibility with the soap and oil in the given formulation.

Waxes and Miscellaneous Products

Gum rosin is usually distilled to recover rosin oils, certain of which have the ability to form metal soaps. Rosin as well as rosin residues are sometimes employed in grease manufacture.

Tall oil, a by-product of paper manufacture, is sometimes used as a low-cost source of fatty acids for grease manufacture. Tall oil consists largely of rosin acids and unsaturated fatty acids.

Waxes are compounds of long chain fatty acids and monohydric alcohols of relatively high molecular weight. Paraffin and microcrystalline petroleum waxes are not included under this definition. Among the products in this category are beeswax, carnauba wax, montan wax (from lignite), and spermaceti wax. One product of interest is wool wax; its composition is distinctly different from that of fatty materials.

Wool waxes, also known as degras and wool greases, are received as a by-product of the wool processing industry. Nearly half of the wax is composed of the esters of water-insoluble alcohols and slightly over half are esters of complex fatty acids. Lanolin results as a refined, neutralized product.

Wool grease is soft and tacky. Since it adheres well, it is often used in rust preventives and as a lubricant, chiefly in the textile industry. It has polar properties due to varying small contents of free acids and free alcohols (2-8%) and is generally viscous. Wool grease has good emulsifying properties and is compatible with petroleum oils. Many of these characteristics are valuable in metalworking operations. Lanolin, for example, has been used in both cold extrusion and in wire drawing.

Further information on the nature of wool grease, wool wax, and lanolin may be found in Truter [73].

4.26 Metal Coatings

The physical properties of soft metals were utilized by Bowden and Tabor [40] to describe metallic friction and to form a basis for a general theory of friction (Chapter 3). The action of a thin metallic film in frictional contact with harder metals has been discussed in Section 3.47. This phenomenology has practical application to metalworking lubricants. Examples of soft metal lubricants are cited for hot extrusion (Section 8.35) and for cold forging and extrusion (Section 10.35). Hard metal coatings serve to reduce the wear of tools and dies.

Hot-Dipped Coatings

Hot dipping, one of the oldest metal-coating methods, may be used to produce soft metal films. The coating is formed when an article is dipped into a bath of molten metal. In common commercial methods, the method is limited to relatively low melting metals to avoid thermal changes in the base metal. Thus, tin, lead, zinc, and aluminum account for most of the dipped coatings applied to steel and iron as the basis metal. These coatings are applied primarily for corrosion protection; their lubricating value, in this case, is incidental. Actually, for the purpose of metalworking lubrication, the hot dipping of steels in lead is extremely effective; however, it is no longer commonly used because of the toxicity problems associated with the lead coating process itself and with the intended service. Thus, it is unsuited as a lubricant for stainless steels used in the food industry as well as for atomic energy applications.

Prior to hot dipping in the molten metal, the underlying surface must be carefully cleaned with sulfuric and hydrochloric acids. The surface film of lead is held mainly by mechanical bonding, but is sufficiently strong to facilitate metalworking lubrication. The addition of small amounts of tin (e.g., 2 to 10 wt %) will improve the adherence of the lead. A zinc chloride or zinc ammonium chloride flux may be used. For other metals that are soluble in the basis metal, the film is bonded by a very thin alloy layer.

Diffusion Coatings

In this method, surface layers of the basis metal are transformed into an alloy by holding it in contact with a powder, a surface-deposited metal layer, a fused salt, or a gas. Coatings prepared by this method are highly uniform, but the method is limited to those metals capable of alloying with the basis metal. The actual coating mechanism is through the action of volatile metal-bearing vapors. In most cases, the diffusion layer is formed during the coating process, although the layer is often heated to high temperatures in subsequent operations. The process is used primarily to coat die surfaces with refractory, hard diffusion layers for the purpose of imparting greater hardness, wear resistance, or reduced adhesion (see Section 3.25).

Sprayed Coatings

Another general method that applies hard metals or ceramic coatings to die or tool surfaces is spraying. For example, a wire of the spray metal can be fed into the hot zone of an oxyacetylene flame gun. An electric arc can also be used, as in plasma arc spraying. Flame spraying and plasma arc spraying are used particularly for the application of refractory metals as well as ceramic materials at maximum hot-zone temperatures of approximately 5000°C and 15,000°C, respectively.

Various Coating Methods

A wide variety of other metal coating procedures is available to apply wear-resistant coatings to dies—for example, vapor deposition for titanium carbide surfaces and electroplating for chromium. Other possible methods include vacuum plating, sputtering, chemical vapor plating, and fused salt electrolysis [74, 75].

4.27 Polymeric Materials

Certain plastics, such as polyethylene and polytetrafluoroethylene (PTFE), have inherent properties which make them useful in many sliding applications. The following presentation is a brief introduction to the subject but with emphasis on frictional properties. Various textbooks may be consulted for detailed information on the constitution and properties of high polymers [76-79].

Nature of Polymers

The main characteristic of a "plastic" is that it is a high molecular weight polymer formed by repetitive chemical linking of one or more monomer units. Examples of the repeat units comprising linear-type polymers often used for frictional applications are presented in Table 4.15 [80]. The length of the linear chain is determined by the average number of repeat units in the structure. PTFE has a typical molecular weight of 10 million [80]; the rodlike molecule is very slender, 5.62 Å in diameter and 260,000 Å in length (this is comparable to a string of 1 mm diameter and 46.2 m length).

Linear polymers (with varying degrees of branching and cross-linking) are the most important for low friction uses. They are thermoplastic in nature. At normal temperatures, the linear molecules are in constant thermal motion accounting for their flexibility. Upon cooling, a glass

TABLE 4.15

Structure of Linear High Polymers and Transition Temperatures [80]

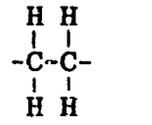
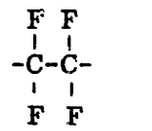
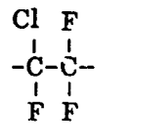
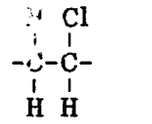
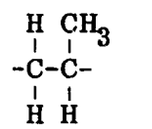
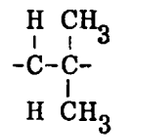
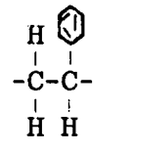
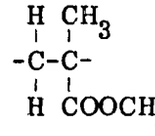
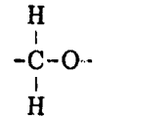
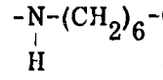
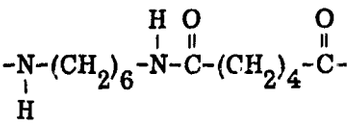
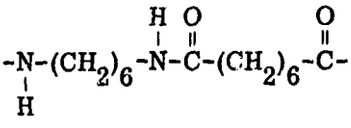
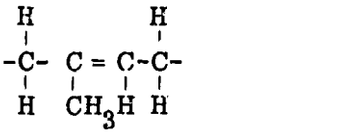
Polymer	Repeat Unit	T_g, °C	T_m, °C
Polyethylene		-120	137
Polytetrafluoroethylene		-50	327
Polychlorotrifluoroethylene		45	220
Polyvinylchloride		87	212
Polypropylene		-10, -18	176
Polyisobutylene		-70, -60	128
Polystyrene		100, 105	240
Polymethylmethacrylate		105	160
Polyoxymethylene		-50, -80	181
Polycaprolactam (6 Nylon)		50	225

TABLE 4.15 (Continued)

Structure of Linear High Polymers and Transition Temperatures [80]

Polymer	Repeat Unit	T_g, °C	T_m, °C
Polyhexamethylene adipamide (66 Nylon)		50	265
Polyhexamethylene sebacamide (6.10 Nylon)		40	227
Polyisoprene		-73	28
Polyimide		220-370	none

transition temperature (T_g) is reached where the molecules become immobile (Table 4.15). This point can be depressed by dissolving plasticizers that provide even greater flexibility. Below T_g the frictional mechanism of the plastic resembles that for metals. Above T_g the plastic is partly crystalline and partly amorphous so that frictional properties will be intermediate between that of a metal and of a viscoelastic material. The crystallinity of the plastic disappears at the so-called melting point, T_m. Above this temperature, the plastic may assume the character of a non-Newtonian fluid, provided extensive thermal depolymerization or decomposition is not involved.

Another broad class of polymers comprises those in which extensive cross-linking occurs upon application of heat. This property is used in processing since the materials soften and flow when heated, but then irreversibly harden to a rigid shape. Important examples of such thermosetting resins are the phenolics (phenol formaldehyde), amino resins (urea and melamine formaldehydes), epoxies, urethanes, and unsaturated polyesters. These often contain fillers such as carbon black, wood flour, paper,

fiber glass, graphite, and molybdenum disulfide, which further increase rigidity and other properties. In general, the inherent lubricating properties of this class of plastics may be considered poor, but the capability of good adherence to metal surfaces may be useful for metalworking purposes.

The physical properties of plastics cover a wide range. Table 4.16 lists a few materials along with comparable information on several metals [80]. Plastics are not as hard or as strong as metals. However, strength-to-weight ratios are often high, especially that of the nylons. The thermal conductivity of plastics is low, approximately 0.05% that of copper. This fact, along with the relatively low heat resistance of plastics, indicates that, in sliding applications, the removal of heat becomes important.

Polymer Classes

Since individual polymer classes have unique characteristics, specific comments will be made on a few of them.

Nylons. Nylons are known for good friction and wear properties, generally in bearing applications. Additions of PTFE, molybdenum disulfide, and graphite lower friction. Nylons tend to adsorb water, and this may increase friction [81]. Further information may be found in several references [82-84].

Acetal Resins. The term acetal resins is applied to polymers containing the linkage

$$-CH_2O-CH_2O-$$

as part of the chain structure. The materials have a low coefficient of friction as well as high strength and stiffness. Cost is relatively low. Both friction and wear properties can be improved by incorporating PTFE and powdered molybdenum disulfide fillers.

Polyimides. The polyimides are strong, temperature-resistant polymers. Compared to most plastics, the aromatic polyimides exhibit low thermal expansion and have good resistance to creep even at temperatures as high as 600°C. The sliding properties of the polyimides are good but can be improved by incorporation of graphite; Devine and Knoll [85] used a composite structure of this plastic as retainer rings for ball-bearing assemblies operating as high as 370°C and 10,000 rpm. At higher temperatures (e.g., at 800°C) a charred residue is obtained. The products are relatively recent

TABLE 4.16

Some Engineering Properties of Materials [80]

Material	Specific Gravity	Tensile Strength, psi	Young's Modulus x 10^6 psi	Rockwell Hardness	Linear Coef. of Expansion, (in/in)/°F x 10-5	Thermal Conductivity, Btu/(hr) (sq ft) (°F/in)	Maximum Allowable Service Temp., °C
			Metal Alloys				
Steel SAE 1020	7.85	55,000-65,000	28.5	B78	1.3	330	600-700
Aluminum alloy 2024	2.77	68,000	10.6	B70	3.8	850	450
			Thermosetting Resins				
Urea formaldehyde (cellulosic)	1.5	8,000	1.3	M120	2.5	2.0	130
Phenol formaldehyde (cellulosic)	1.7	10,000	1.2	M105	2.5	2.0	150
			Thermoplastic Resins				
Polyimide	1.4	11,000	0.46	R118	3.0	2.9	450
Nylon 66	1.14	11,800	0.41	R118	5.5	1.7	120
Nylon 6	1.12-1.14	9,000	0.30	R107	10.0	1.7	100
Acetal resin	1.4	10,000	0.40	R120	4.5	1.6	85
PTFE	2.2	2,500	0.06	R21	5.5	2.2	280
Polyethylene	0.9	1,800	0.015	R26	—	1.9	70

developments and can be prepared with a wide variety of aromatic structures that have unusual properties [79].

Polycarbonates. The polycarbonates are characterized by high impact strength, low thermal expansion, and high heat-distortion temperatures. The plastic itself has poor friction and wear properties but can be improved by incorporation of tetrafluoroethylene products. Low mold shrinkage of the plastic makes it useful for precision gears and sliding parts.

Polyethylenes. The polyethylenes have good friction properties, are quite low in cost, and are now available in both a low- and a high-density form. The latter form is stable at slightly higher temperatures but, in general, service is limited to about 70°C. However, inspection of the structure (Table 4.15) indicates that polyethylene, as well as polypropylene, is merely a high molecular weight hydrocarbon. In metal deformation processes, these polymers function as exceptionally high molecular weight paraffinic waxes.

Polytetrafluoroethylene. PTFE is unique among the plastics; its behavior is complicated by the existence of crystalline transitions at 19° and 30°C which confuse data at near ambient conditions. Various transient effects have been observed as a function of sliding speed and humidity. Early investigators including Shooter and Tabor [84] concluded that adhesion of PTFE was so low that shearing occurred at the interface rather than in the bulk. Makinson and Tabor [86] later suggested that a transferred film is formed in a manner similar to laying down a pack of cards; on glass, friction regimes related to fragments and to continuous film transfer can be discerned.

Hanford and Joyce [87] proposed that the low friction of PTFE is caused by the shielding of the charge on the carbon atom by the large fluorine atoms; this would minimize interchain bonding forces and lead to exceptionally low molecular cohesion. Steijn [80], reviewing the subject of PTFE friction, indicates that deformation and shear through the interface must be dominant; however, the fundamental basis for the astonishingly low friction has not been satisfactorily explained.

Fluoroethylene Polymer. A variation of PTFE can be made by forming a copolymer of tetrafluoroethylene and hexafluoropropylene, usually called FEP. This polymer is generally similar to PTFE but can be fabricated

more readily. Its crystalline melting point is 290°C compared with 327°C for PTFE, and its friction is slightly higher.

Kel-F. Another important commercial product closely related to PTFE is Kel-F in which one fluorine molecule is replaced by chlorine. In addition to lower cost, the product has different physical properties.

Plastics as Metalworking Lubricants

The use of polymers in industrial metalworking applications is suggested by a number of experimental studies that will be found in Chapters 6 to 11. Polyethylene should receive more attention because of its attractive low cost. Polyimides and polycarbonates may have application because of their exceptional high-temperature stabilities. Most plastics are not stable at high temperatures, but the decomposition products may contribute to lubrication. Despite low friction and good thermal stability, PTFE and related polymers have not found wide application in experimental metalworking studies. This may be related to the difficulty of attaching the polymer to metal surfaces as well as to high cost.

4.28 Oxides and Miscellaneous Solid Lubricants

The lubrication of metals at high temperatures is markedly affected by the presence of oxides on the contacting surfaces. Oxides may form on the metal or alloy surface; oxides unrelated to the metals can be interposed as parting agents in a relatively unattached fashion; and finally, oxides as well as any solid lubricant can be attached to the surface by bonding materials.

Because of experimental difficulties in assessing fundamental aspects of friction at elevated temperatures, the findings of many investigations may appear to be at variance with one another. The broad survey presented here highlights the variables most pertinent to deformation processing.

Oxide Films Formed on Metals

For metalworking purposes, the relatively thin oxide films formed on preheating in an industrial atmosphere (most frequently air) or on holding in air are of greatest interest. Thick oxide coatings cause surface damage and die abrasion and are usually removed prior to deformation.

In metalworking processes, the important factor is the surface strain to which the oxide is subjected and the mechanisms by which the oxide films act as a lubricant. The best experimental evidence is due to Male and

Cockcroft [88], who used the ring compression test (Section 5.25) as a means of studying friction during plastic deformation. Further studies by Male [89, 90] on the high-temperature friction of titanium, 60/40 brass, and 18/8 stainless steel suggested three possibilities for lubrication: (1) the oxide is friable or powdery; (2) the mechanical properties of the oxide film (or oxide films of dissimilar metals) may be such that the shear strength relative to that of the metal decreases at a greater rate as temperature is increased; (3) local surface melting occurs. Examples of all three mechanisms have been found.

Copper and Mild Steel. On these materials the mechanism is related to case (2) above. Tylecote showed that the strength of copper oxide films on copper decreased rapidly as the temperature was raised progressively above 500°C [91] and that the strength of iron oxide (FeO) decreased rapidly in the range 700-900°C [92]. These changes coincide with a decrease in measured friction in the same temperature range [90]. It should be emphasized that these changes are reversible with temperature, thus ruling out the formation of friable oxide layers; melting must also be ruled out since large variations in strain rate did not significantly influence the friction coefficient.

Of the three oxides formed on iron—FeO, Fe_3O_4, and Fe_2O_3—Tylecote [92] found that the weakest layer was that of wüstite (FeO) and that it suffered a large loss in strength over the range 700°-900°C. The strength of hematite (α-Fe_2O_3) actually increased to a peak at 1150°C. Both Male [93] and Schey [94] have noted a decrease in friction of mild steel above 700°C (Fig. 4.13).

Brass. In metalworking tests [88, 90], the friction of brasses increased with zinc content, friction becoming especially high with brasses containing more than 15% zinc. In simulating experiments with hemispherical riders on a flat specimen Hinsley et al. [95] observed that above 700°C, a friable layer of loose powdered ZnO which formed on 70/30 brass gave low friction that persisted even when the system was cooled to 20°C.

The difference in the behavior of the same oxide in the two sets of experiments may be explained from the test geometry. In the metalworking tests, the ZnO skin layers were compacted and confined, whereas in the sliding test, the friable oxide powder acted as an effective lubricant. A 90/10 Cu-Zn alloy gave high friction both in metalworking and in simulating

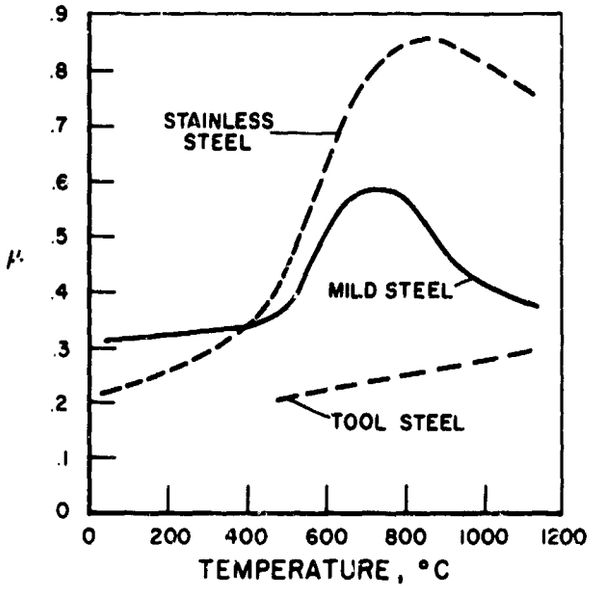


Fig. 4.13. Influence of temperature on coefficient of friction in twist compression of mild steel with three anvil materials [94].

tests, because the oxide consisted of two distinct layers: the outer, soft Cu_2O layer was penetrated by the rider, and the high friction of the underlying ZnO film prevailed.

These results indicate the need for a careful interpretation of frictional experiments. The Cu-Zn system is rather unusual in that the properties of Cu_2O and ZnO are distinctly different. Under appropriate conditions both the soft, ductile Cu_2O and the hard, friable ZnO can function as a lubricating agent.

Nickel and Nickel Alloys. Tylecote [92] found that nickel oxide (NiO) is exceptionally strong, with a peak strength at 900°C. It could be expected, therefore, that in deformation processes where the oxide is confined between the contacting surfaces, friction should increase with temperature. This was indeed found by Male [90] to hold in the temperature range 200°-925°C. It is conceivable that the high friction found around 900°C on stainless steel is associated with this peak (Fig. 4.13).

In contrast, Peterson et al. [96] and Foley et al. [97] found in sliding tests that nickel oxide must act as a lubricant for nickel at high temperatures since, in an inert atmosphere but under otherwise identical conditions, friction remained high. One might surmise that the beneficial effect of the

oxide is attributable to the formation of friable powders, which lubricated in the rider on flat tests, but not when confined between tool and workpiece surfaces.

Other Metals. Results obtained by Male [90] in ring compression tests suggest that both aluminum and titanium form hard oxide films which possess little or no lubricating quality. These oxides are known to be brittle, but remain embedded in the surface, and when the surface area is increased as a result of plastic deformation, fresh surfaces are exposed. Since both metals show high adhesion, high friction is registered.

The oxide film formed on magnesium is powdery and acts as a lubricant; therefore, friction decreases with increasing temperature. Friction increases on lead and zinc with increasing temperature, because the oxide films are harder than the respective metal substrates.

Refractory metal alloys form oxides which are effective lubricants. The low friction found in sliding stainless steel against tungsten carbide anvils may be attributable to the oxide formed from the carbide surface at temperatures in excess of 900°C [95].

Thickness and Relative Hardness of Oxide Films. One factor contributing to the difficulties of interpreting lubrication by oxide films formed on metal surfaces is the effect of thickness. Rabinowicz [98] suggests on the basis of pin-on-disk experiments that a critical oxide thickness of 0.01 μ must be attained if the oxide film is to act as a lubricant; this concept needs confirmation, particularly for surface extension typical of metalworking processes.

A second factor governing the lubricating properties of an oxide layer is the relative hardness of oxide and substrate metal. Rabinowicz [98] presents the following hardness ratios for a number of metal oxide-metal combinations:

	Hardness Ratio, H_{oxide}/H_{metal}
Molybdenum	0.3
Tantalum	0.6
Copper	1.6
Niobium	1.8
Nickel	2.0
Lead	20.0
Aluminum	70.0
Tin	90.0

While the effect of test temperature is not considered in this listing, metals with a ratio from 0.3 to 2.0 may be expected to show reasonably low friction in air, as confirmed generally by friction studies [90, 96, 98]. However, several additional factors need clarification, if an accurate prediction is to be made. These include changes of relative hardness with temperature, the nature of the attachment of the oxide layer (loose or adherent), ductility, friability, and melting.

Finally, as we have seen, the geometry of the frictional system itself will influence the lubricating performance of oxide layers. In many metalworking processes, the surface films will tend to be confined between contacting surfaces, and fresh metal surfaces exposed by the extension of the surface may not have access to oxygen.

Specific evidence for the role of metal oxide films as lubricants in metalworking processes will be found in Chapters 6, 8, and 9.

Externally Interposed Oxides

Externally interposed oxides have been applied extensively as lubricants for metalworking processes. The role played by such oxides at high temperatures has been considered by a number of investigators including Male [93], Rogers and Rowe [99], and Peterson, Florek, and Lee [96].

Oxides may be liquid, and glass lubricants have already been mentioned as a special case in Section 4.21. Male [90] demonstrated that a sharp drop in friction occurred when boric oxide powder coated on titanium was heated above the melting point (577°C). Peterson, Murray, and Florek [100] found that various complex molybdates and tungstates showed a reasonable correlation with melting point but that, in general, strict correlation was not possible.

Solid oxides may also be used as lubricants. Male [93] showed that various metals which normally give high friction could be lubricated by powdered oxides. Specific examples included the lubrication of 18/8 stainless steel by copper or iron oxides, titanium and 60/40 brass by copper, and 60/40 brass by zinc oxide. Rogers and Rowe [99] proved that infusible powders such as lime (CaO) and slate can be used effectively as lubricants for the hot extrusion of steel. Peterson, Florek, and Lee [96] investigated a series of oxides at 704°C; hard oxides (NiO, Fe_3O_4, and Cr_2O_3) were ineffective, the soft oxides (Cu_2O, ZnO, Co_2O_3) gave low friction, and PbO was the best lubricant. PbO was found effective both below and above its

melting point, particularly in combination with a small amount (less than 7.5%) of SiO_2 [101]. Some oxides (B_2O_3 and MoO_3) become effective only when the temperature is high enough to melt them. The principal problem with powdered oxides may be to achieve satisfactory attachment to the surface. This phase is covered briefly in the next section.

Bonded Lubricants

The nature of many solid lubricants is such that although they have outstanding low-friction properties, attachment to the surface is poor. Not only do powdered oxides suffer this disadvantage, but even solids such as graphite and molybdenum disulfide benefit from firm bonding. Two general methods of attachment are commonly used—resin bonding and inorganic bonding.

Resin-bonded, solid lubricants can be applied by brushing, dipping, or spraying. Such coatings may vary from 5 to 20 μ in thickness and show the best properties at about 12-13 μ. The resin itself can be air-dried (for example, certain thermoplastic resins such as cellulosics or acrylics). It is more common, however, to use heat-cured resins; a typical cure is 1 hr at 150-200°C. The heat-cured thermoplastics normally used include alkyds, phenolics, epoxies, and silicones.

Pretreatment of the metal surface is important. Phosphating, anodizing, and mechanical blasting are among the pretreatments that can be used; for stainless steel, a chemical etch might also be considered. The proportions of binder and solid lubricant are very important and will depend on the materials used, the hardness of the metal surface, and the intended use. A listing of commercial formulations, baking schedules, pretreatment recommendations, and other variables was given by Campbell, Loser, and Sneegas [102].

For high-temperature lubrication, ceramics or salt-based binders give greater heat resistance than resins. Also, lubricants which have more oxidative stability than either graphite or molybdenum disulfide may be used. The dry lubricants could thus include lead oxide, lead sulfide, calcium fluoride, gold, or silver. The bonding agents range from water-soluble silicates and phosphates to glasses and high-temperature ceramics.

An excellent review of the principles and applications of solids for lubrication is given by Braithwaite and Rowe [103].

4.3 EMULSIONS

In metalworking lubrication, it is often necessary to provide a mixture of lubricants and water to serve a number of functions including delivery of a lubricant (liquid, solid, or combinations) to the metalforming operation and use of water as a heat sink to limit temperatures. A thorough coverage of emulsions would be well beyond the scope of this presentation. Introductory material and a brief discussion of emulsions are given here; for greater depth, reference should be made to Becher [104], Osipow [105], and Griffin [106].

4.31 Definitions

When two immiscible liquids are combined and shaken, one of the liquids will assume the form of droplets dispersed in the other liquid. This system is called an emulsion. Once agitation ceases, the dispersed droplets begin either to rise or fall depending on whether the density of the surrounding external or continuous phase is greater or less than that of the dispersed or discontinuous phase.

Addition of an emulsifying agent reduces the size of droplets and delays settling and coalescense. Given sufficient time, the two phases will again re-form, but the elapsed time can vary from a few second to years.

The most important emulsions industrially are oil-in-water (O/W) emulsions having oil dispersed in water as the continuous phase, and water-in-oil (W/O) emulsions in which water is dispersed in oil. Proprietary "soluble oils" are O/W emulsions which can be diluted conveniently to concentrations appropriate for the desired operation.

In practical applications, emulsions are often classified by appearance. An approximation of the effect of particle size of the droplets is summarized in Table 4.17.

The stability of an emulsion depends upon particle size, density difference between phases, viscosity of the continuous phase as well as that of the prepared emulsion, particle charge, nature and amount of emulsifier, temperature, agitation, and dilution or evaporation in storage. When for any reason the emulsion breaks down, some of the dispersed phase separates.

It is customary to differentiate between creaming, inversion, and demulsification [104]. Creaming is separation into two emulsions, one richer in the dispersed phase ("cream") and the other poorer than the

TABLE 4.17

Effect of Particle Size on Appearance of Emulsions [106]

Particle Size, μ	Appearance
Macro globules	Two phases may be distinguished
>1	Milky-white emulsion
1-0.1	Blue-white emulsion
0.1-0.05	Gray semitransparent
< 0.05	Transparent

original emulsion. Inversion causes the emulsion to change from O/W to W/O and vice versa. The breaking of emulsions or demulsification, is encountered in connection with the disposal of emulsions. First, there are the problems of separating and recovering the lubricant emulsion phase from tramp oils and other wastes. Second, the discharge of emulsions and oils into streams must be carefully controlled in order to minimize water and stream pollution.

4.32 Emulsion Theory

The prediction of emulsion behavior remains largely a matter of art rather than science; nevertheless, the simple adsorption theory given below is sufficient to describe many emulsions of the type encountered in metal-working lubrication.

The fatty acids, alcohols, amines, and amides—already discussed as boundary lubricants--have in common a molecular structure in which each molecule may be considered to consist of two distinct sections, one polar and the other nonpolar. The polar portions are characterized by varying degrees of water solubility. In acetic acid,

$$H_3C\text{-}\overset{\overset{O}{\|}}{C}\text{-}OH,$$

the carboxyl group, -COOH, dominates the molecule and the compound is infinitely soluble in water, while the much longer chain stearic acid is only slightly (0.034 g per 100 ml of water) soluble in water. The polar portion

of the molecule is commonly referred to as the hydrophilic (water-loving) group, and the nonpolar as hydrophobic (water-hating) or, better, as lipophilic (oil-loving). This description of stearic acid is shown in Fig. 4.14, where the carboxyl group is the polar, hydrophilic head and the $C_{17}H_{35}$- hydrocarbon group is the nonpolar, lipophilic tail. This useful convention, introduced by W. D. Harkins, is particularly helpful in describing the role of soaps as emulsifying agents.

Langmuir and Harkins [107] showed that the stabilizing surface film at the oil/water interface consists of a monomolecular film with the polar groups oriented toward the water phase and the nonpolar hydrocarbon chains oriented toward the oil. An oil-in-water emulsion stabilized by sodium stearate is represented schematically in Fig. 4.15a. The hydrocarbon tail tends to dissolve in the oil, and its chains are oriented inward. The polar

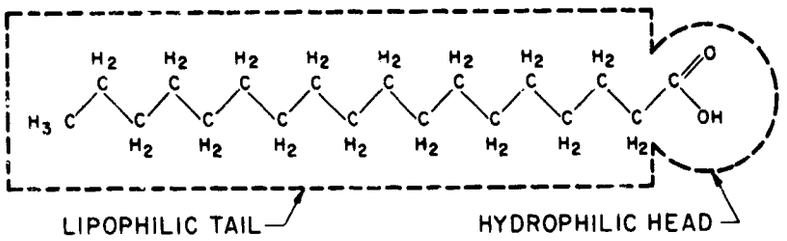


Fig. 4.14. The hydrophilic-lipophilic structure of stearic acid.

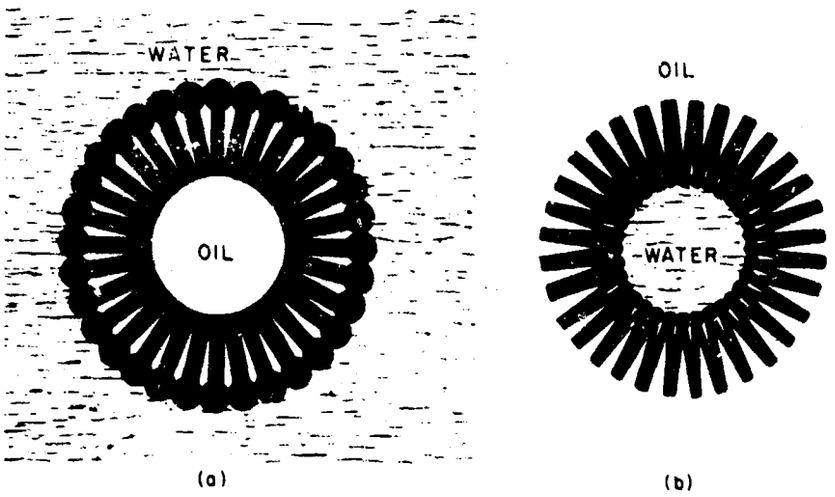


Fig. 4.15. Stabilization of emulsions according to the oriented wedge theory [104].

sodium carboxyl groups, -COONa, are oriented toward the water phase. The stabilized configuration has been called the "oriented wedge," by Harkins [107].

Figure 4.15b portrays the film surface in an emulsion stabilized by a bivalent metal soap and demonstrates that a water-in-oil type of emulsion is highly favored for this class of soaps, while oil-in-water emulsions are formed by soaps of univalent metals (Fig. 4.15a).

The above theory affords a ready conceptual interpretation of emulsions but has obvious shortcomings in explaining emulsions in general. Further discussion will be found in Becher [104], Osipow [105], Sheludko [108], Sherman [109], and McBain and Hutchinson [110].

4.33 Emulsifiers

Surface activity has been defined as the pronounced tendency of a solute to concentrate at an interface. Our interest is directed here towards an ability to form and stabilize emulsions, but surface-active agents also have ability to wet surfaces readily (wetting agents), remove dirt (detergents), penetrate porous materials (penetrants), and disperse solid particles (dispersants). It should be mentioned that surfactants are also capable of producing lubricant films.

The water-solube surfactants are, by far, the most important for metalworking emulsions. Classification can be made into four general types: (1) anionic (long chain carries a negative charge); (2) cationic (long chain carries a positive charge); (3) nonionic (does not ionize in solution); (4) amphoteric or empholytic (ionizes in solution with the long chain containing either a positive or negative charge depending on the pH of the solution).

Anionic Emulsifiers

The water-soluble soaps based on long-chain carboxylic acids are the best known of all the surfactant agents and are still important emulsifiers. These soaps generally contain from 12 to 18 carbon atoms per molecule and are derived from the mixed fatty acids of tallow, palm oil, coconut oil, lard oil, etc. Both potassium and sodium soaps are used, but sodium soaps are the most common. Soaps prepared from unsaturated fatty acids are more water-soluble. The soaps are highly alkaline with a pH of approximately 10 and are therefore incompatible with (mineral) acid and hard waters from

which insoluble calcium and magnesium soaps are precipitated. In use, the soap itself tends to hydrolyze and form mixed surface films containing both soap and fatty acids.

Other anionic surfactants are, with few exceptions, based on the hydrophilic groups $-SO_3Na$ or $-SO_4Na$ (sulfonate or sulfates). The reason is that sulfuric acid is the cheapest acid that can be used to introduce a hydrophilic group into a lipophilic organic molecule. The compounds, such as dodecylbenzene sulfonate and sulfated vegetable oils, typify this class. The latter group includes "Turkey Red Oil" or sulfated castor oil and "sulfonated red oil" which is really a sulfated oleic acid. These oils are frequently used for the preparation of emulsion systems.

Cationic Emulsifers

Cationic surfactants are sometimes called "invert soaps" because their ionization is the reverse of that of the anionic soap agents. In the cationic agents, the long-chain hydrophobic group becomes the cation and the anion is generally a chloride or bromide ion. These compounds (usually quaternary ammonium compounds or amines) are soluble in water over the entire pH range but the surfactant is ionized and carries a positive charge only in acid solution. The cationic agents are strongly adsorbed on negatively charged surfaces (e.g., many metals) and all have germicidal properties.

Anionic and cationic agents are incompatible, forming precipitates in aqueous solution. Both anionic and cationic agents are compatible with nonionic agents discussed next.

Nonionic Emulsifiers

The hydrophobic groups in the nonionic compounds are the same as in the anionic and cationic classes, but the hydrophilic groups are different. They are generally end-substituted polyethylene glycols, $R(OCH_2CH_2)_nOH$, where R is the hydrophobic group (e.g., derived from stearic acid, oleic acid, etc.) and the hydrophilic group is a chain of ethylene oxide units (polyethoxy groups, $-OCH_2CH_2-$) ending in a hydroxyl group.

Ampholytic (Amphoteric) Emulsifiers

Ampholytic surfactants contain both an anionic and a cationic group; they are cationic in acidic solutions and anionic in alkaline media. The long-chain amino acids serve to illustrate this type of behavior:

$$RNHCH_2COOH \xrightarrow{HCl} (RNH_2CH_2COOH)^+Cl^-$$
$$RNHCH_2COOH \xrightarrow{NaOH} (RNHCH_2COO)^-Na^+$$

Ampholytic surfactants may also be prepared with a sulfate, sulfonate, or phosphate as the anionic group in place of the carboxyl group.

Naturally Occurring Emulsifiers and Solids

Many members of this class may be grouped under the previous headings. Many of them by themselves are relatively inefficient but are of value in conjunction with other emulsifying agents. Frequently, they contribute to high viscosity and may have value in reducing creaming. Phospholids and sterols, found as minor constituents of many fats and oils, may be grouped in this class. Lanolin, long known as a stabilizer of W/O emulsions, is another natural emulsifier. Water-soluble gums of vegetable origin (such as gum arabic, gum tragacanth, guar gum) are complex salts of naturally occurring acids, e.g., calcium salt of arabic acid.

Finely divided solids also may have emulsifier properties. These include basic salts of the metals, carbon black, and various clays (particularly bentonite). The type of emulsion obtained depends on the extent to which the solid particles are preferentially wetted by either the aqueous or oil phases.

4.34 HLB Evaluation

The efficiency of an emulsifier is difficult to express in exact terms. Perhaps the best approach is that originated by Griffin [111]. The hydrophile-lipophile balance (HLB) of an emulsifier is an expression of the balance of the size and strength of the hydrophilic and lipophilic groups contained in a given compound. An emulsifier that is lipophilic in character is assigned a low HLB number (below 9.0) whereas one that is hydrophilic is assigned a high HLB number (above 11.0). Those in the range of 9-11 are intermediate. The O/W dispersions encountered in metalworking lubricant emulsions have the broad range 8-18. The advantage of the method is that the selection of

emulsifiers can be expedited and rationalized. In almost all practical systems, the synergistic action of a blend of emulsifiers can be selected that will provide the maximum emulsion stability and other desired properties.

The HLB values of materials used in metalworking lubricant compositions can be found in Becher [104] and in other sources. For practical purposes, it is useful to know the "required HLB" of an existing emulsions system, as in Table 4.18, or to make a determination of this value by comparison of trial emulsions prepared with known HLB emulsifiers. It is then

TABLE 4.18

HLB Values Required to Emulsify Various Oil Phases

Oil Phase	W/O Emulsion	O/W Emulsion
Acid, lauric	-	14
Acid, linoleic	-	16
Acid, oleic	-	17
Acid, ricinoleic	-	16
Acid, stearic	-	17
Alcohol, cetyl	-	15
Alcohol, lauryl	-	14
Benzene	-	15
Castor oil	-	14
Chlorinated paraffin	-	8
Cottonseed oil	-	7.5
Kerosine	-	14
Lanolin, anhydrous	8	12
Oil: mineral, aromatic	4	12
mineral, paraffinic	4	10
Mineral spirits	-	14
Naphtha	-	13
Pine oil	-	16
Wax: Beeswax	5	9
Candelilla	-	14-15
Carnauba	-	12
Microcrystalline	-	10
Paraffin	4	10

possible to evaluate various emulsifier blends in order to determine minimum concentration, lowest cost, maximum stability, and so on, by trial-and-error preparations made under experimental conditions simulating those prevailing in the plant. At best, the procedure is highly empirical but it provides a rationale that is useful in resolving plant problems.

4.35 Demulsification

Parameters associated with breaking of emulsions or demulsification may be beyond the province of lubricant emulsions but deserve some mention because of their importance in lubricant disposal.

Emulsions, in a practical sense, can be broken by adding an emulsifier that will throw the emulsifier combination out of balance with the required HLB for the oil. The destruction of nonionic emulsifiers is quite difficult except by relatively drastic means such as chemical attack. Anionic emulsifiers can be readily destroyed by addition of acid. For example, the HLB of sodium oleate is 18 whereas that of oleic acid is 1; acidification thus completely destroys the balance. Emulsions stabilized by ionic emulsifiers may, in general, be broken by addition of electrolytes such as aluminum or ferric salts since the stabilizing charges of individual particles may be eliminated [104].

Practical methods of breaking W/O emulsions include settling, heating or distilling at atmospheric or elevated pressures, electrical dehydration, use of chemicals, centrifuging, and filtration—alone or in combination.

4.36 Bacteriological Attack

Since lubricant emulsions contain bacterial nutrients (fats and their derivatives), water, and oxygen, it is not surprising that microorganisms can flourish in emulsion systems. Phosphorus, sulfur, and nitrogen compounds, normally included in many lubricant formulations, are also effective nutrients. The growth of microorganisms can cause significant lubricant deterioration, filter stoppage, and corrosion.

High temperatures will kill the bacteria, but continuous and complete pasteurization would generally be impractical. Also, while pockets of stagnation in the pipes and storage tanks can be minimized, they probably cannot be eliminated completely.

Chemical sterilization of the lubricant emulsions can be effected through the use of chemical bactericides including chlorinated compounds, such as dichlorophenol, or tar acids. Since biological conditions tend to change, some type of microbiological test should be used to indicate the extent of infection and the efficiency of any control methods. Hill [112] has described a case history of control in an aluminum rolling mill. Generally speaking, high concentrations of bactericide are necessary to kill the organisms while much lower concentrations can be used to prevent growth and reproduction.

4.37 Emulsions of Metalworking Lubricants

A great variety of emulsions find use in various metalworking operations. Water-in-oil emulsions are occasionally used, in the form of paste, but most frequently the emulsions are of the oil-in-water type. Water has a high heat capacity, good heat transfer properties, and is also inexpensive. For this reason it is used whenever the deforming die or the workpiece has to be cooled or where the duties of the lubricant are modest enough to permit substantial dilution of the oily phase. The detailed compositions, mode of application, and quite often even the terminology used to describe various emulsions vary according to the metalworking processes; therefore, more detailed discussion of the subject will be found in Chapters 6 to 11. Section 6.3 covers the most important application, cold rolling lubricant emulsions, with details and treatment in Section 6.34.

4.4 CONVERSION COATINGS

Coatings have proven valuable and sometimes essential for assuring adequate lubrication in several metalworking processes, including wire drawing, cold extrusion, and sheet forming of various ferrous and nonferrous metals and alloys. Prior to lubrication, an adherent coating is applied to the workpiece surface; the most familiar example is that of phosphating of steels. Conversion coating processes are described in this section, but for their application to specific processes and materials, reference should be made to Chapters 6 to 11 of this book.

4.41 Phosphate Coatings

Phosphate coatings find a wide application on steel for corrosion prevention and for bonding lacquers, paints, or other protective and decorative coatings to the surface. However in the mid-thirties, German technologists found that phosphating greatly improved lubrication in severe metal forming operations and, after World War II, the practice became widespread. Originally, some investigators thought that the phosphate had plastic properties and acted as a lubricant. It has since been found that the phosphate film alone has high friction; the combined action of the phosphate film and added lubricant is needed to obtain effective results. Zinc phosphate coatings are widely used in metalworking applications; manganese phosphate and iron phosphate coatings are also encountered, but they are generally applied for other purposes [113-115].

Chemistry of Phosphate Coating

All phosphate coatings are produced by the same chemical mechanism. Phosphating is carried out in a weak acidic solution of the primary phosphates of a heavy metal. The acid reacts with the metal, and a thin film of solution adjacent to the metal surface becomes neutralized by virtue of this attack. A rise in pH occurs coincident with the formation of local electrolytic cells on the metal surface [116]. At the anodic points metal goes into solution, whereas hydroxyl ions produced at the cathodic points induce deposition. Thus, the bath always contains metal ions from the surface being treated (e.g., ferrous ions from treatment of steels), in addition to the heavy metal (Zn or Mn) phosphates present in the bath originally. The following reactions occur with zinc, which is the metal phosphate most commonly used in metalworking [117]:

$$2H^{+} + Fe \rightarrow Fe^{+++} + H_2\uparrow \qquad (4.11)$$

$$3\ Fe^{++} + 3\ Zn^{++} + 4\ PO_4^{---} \rightarrow Zn_3(PO_4)_2\downarrow + Fe_3(PO_4)_2\downarrow \qquad (4.12)$$

$$Fe^{+++} + 2H_2PO_4^{-} \rightarrow Fe(H_2PO_4)_2 \qquad (4.13)$$

The acidity of the zinc-phosphating bath depends on the method of application. In immersion zinc-phosphating baths, the pH range is limited to 1.8 to 2.4 to avoid pickling of the metal, whereas spraying solutions may use a pH as high as 3. Ferrous phosphate coatings are generally quite thin, but have excellent adherence.

All phosphating solutions require activators, which function as depolarizers or oxidizers that react with hydrogen as it is formed. The activators may also passivate the anodic areas. The activators range from mild oxidants, such as nitrates, to more vigorous nitrites, chlorates, or peroxides. These accelerators not only speed the reaction but allow the bath to operate at a lower operating temperature (40-70°C). Immersion time is reduced to a few minutes. The presence of ferrous ions in the phosphating bath is known to affect the nature of the deposit which is formed by epitaxial growth [117].

Properties of the Phosphate Layer

Midgley and Wilman [118] examined a representative type of phosphated layer and found that crystal platelets (10-30 μ in diameter and with a thickness about 1/10 of this dimension) were deposited on high areas of the surface. The channels between these areas were 10-20 μ deep and 30-50 μ wide.

Machu [116] has indicated that the properties of the phosphate coating such as grain size, thickness, smoothness, porosity, and grain growth are dependent on the history of the metal surface. Thus, if strong alkaline solutions are used for degreasing, coarse-grained coatings result. Degreasing by organic solvents or emulsion cleaning produces fine-grained, high-quality coatings, possibly because of a residual monolayer of oil. Etching with strong mineral acids can lead to a coarse-grained, slowly growing phosphate coating. Sand- or grit-blasting may result in a fine-grained coating, but this ability is lost if phosphating is not conducted soon after treatment or if the surface is treated with a strong acid after sand-blasting.

To preclude haphazard effects, it is common practice to apply a conditioning treatment. This comprises immersion in a very dilute solution containing ions more noble than that of iron, e.g., copper or nickel. It is presumed that minute nuclei are electrolytically deposited which stimulate local solution of iron and thereby nucleation of phosphate crystals. A light etch with oxalic acid or a treatment with a dilute sodium phosphate solution

containing titanium compounds gives similar results [117]. These effects may be explained, according to Machu [116], in terms of nucleation at "active centers." Midgley [119] has shown that initial nucleation occurs on strained areas adjacent to scratches on a polished surface. Similar effects should be obtained by sandblasting. Etching with strong acids removes these active centers, alkali solutions form passivating oxide films, and dilute conditioning solutions of noble metal salts increase the number of local cells.

Phosphate films form readily on carbon steels and on low alloy steels. Coatings form with difficulty on steels containing more than 5% chromium, and the austenitic chromium-nickel steels require an oxalate coating (Section 4.42).

Application of Phosphate Coatings

The application of a phosphate coating for metal deformation lubrication comprises three main steps: (1) cleaning, (2) phosphating, and (3) lubricant application. Cleaning is necessary to remove rust and mill scale as well as grease contaminants. The procedures used are pickling (Section 4.5) and degreasing (Section 4.61).

The phosphating step is frequently conducted at 70-77°C for 3-7 min. However, the amount deposited and the nature of the coating depend on a number of interrelated variables including composition, concentration, pH, temperature, method of application (dip, spray, continuous, semicontinuous, batch), and contact time [113, 114, 120]. The depth or weight of coating is used as a control; in general, weights range from 1.0 to 2.5 g/sq ft.

The lubricant is then usually applied by dipping in a warm soap solution. The solutions recommended include sodium-, potassium-, resin-, or naphthenic acid-soap emulsions containing free fatty acids. Prior to this step, the coating is washed in warm water to remove excess phosphoric acids and the metal is dried thoroughly. This last condition is important since it is postulated that firm attachment of free fatty acid occurs by adsorption and that—with the so-called reactive lubricants—the sodium ion of the soap reacts with zinc phosphate to release the zinc ions that form zinc stearate within the coating [120]. Nonreactive dry soap, such as calcium soaps, may also be used, mostly for lighter duties. Solids (graphite and MoS_2) and high-viscosity fluids have also found application.

Fluoride-Phosphate Coating for Titanium

Since titanium and its alloys are highly resistant to attack by acids, a more reactive phosphating treatment is necessary. Sabroff and Frost [121] used a phosphating solution containing sodium phosphate, potassium fluoride, and hydrofluoric acid, which formed a dark gray, adherent coating. The best lubricant was 10% graphite in a gum resin; soaps failed to provide good surface finish. The coating is known to contain potassium, titanium, and fluoride although the exact composition has not been determined [122].

4.42 Oxalate Coatings

Zinc phosphate coatings cannot be applied effectively to austenitic stainless steels, straight chromium steels containing more than 5% chromium, or high-nickel steels. On these materials, it is necessary to use oxalate coatings. The procedure is essentially the same as for phosphating, but the solution now comprises oxalic acid (HOOC · COOH), ferric oxalate, and a chemical accelerator such as a chlorate; the application temperature is about 45°C. Oxalic acid is a strong organic acid that reacts with iron oxide to form soluble ferric oxalate; even though only slowly and superficially, it also attacks iron to form ferrous oxalate which is insoluble in the oxalic acid solution and remains as an adherent layer on the metal surface. The oxalate coating is then treated with a complex soap lubricant [123].

An advantage of the oxalate coating over the previously used metallic lead lubricants is its ease of removal by alkaline degreasing treatment, followed by an acid dip or by a normal heat treatment that thermally decomposes the coating [120].

4.43 Conversion Coatings for Light Metals

Chemical conversion coatings are also applied to aluminum and aluminum alloys. They produce adherent surface layers of low-solubility oxide, phosphate, or chromate compounds through a reaction of these compounds with the metal surface. The reaction involves the removal of 0.2 to 2.5 μ thickness of metal.

Oxide coating is applied in low concentration sodium carbonate and chromate solutions at 88-100°C for periods of 3 to 20 min.

Phosphating baths contain dichromate, fluoride, and phosphate salts, the last predominating; treatment time may be 1.5 to 5 min at 18-50°C.

Chromate conversion coatings are applied at 15 to 55°C from a low concentration solution of dichromate salt and other salts, such as ammonium or sodium fluoride or tin chloride. Time of exposure varies from a few seconds to 8 min. Chromate coatings are used alone or as supplements to other nonmetallic coatings. Activators (e.g., sulfate, nitrate, chloride, or fluoride) are necessary to overcome passivity that normally occurs in a solution of chromate anions alone. Upon attack, some metal is dissolved and a slightly soluble, hydrated compound ($Cr_2O_3 \cdot CrO_3 \cdot xH_2O$) is deposited on the surface.

Magnesium alloys are chromated in nearly neutral solutions, whereas aluminum alloys are treated in solutions of appreciable alkalinity or acidity. Details of the processes may be found in the Metals Handbook [114].

Anodizing is an electromechanical process which converts the metal surface to oxide by the action of an electrical current. The coating is porous and can be extremely thin. The method has been used to a limited extent as a pretreatment prior to lubricant application. It is most commonly applied to aluminum and its alloys, but other metals such as magnesium, tantalum, titanium, and zirconium can also be treated by this method.

On aluminum the anodic oxide coating consists of two layers. That in contact with the metal is nonporous and has been termed the barrier layer, its thickness being determined by the applied voltage and electrolyte ranges from a few hundred angstroms to about 1 μ. The second, outer layer is porous and consists of hexagonal prisms, each with a pore along its axis. The distance between pores is of the same magnitude as the barrier layer. The layers consist essentially of γ-alumina. The structure of the layer has been reviewed by Waterhouse [117].

4.5 SURFACE PREPARATION

This section is devoted to processes in which the surface of the metal workpiece is prepared for deformation. The surface preparation process is often very similar to treatments used as a finishing operation. Thus, grit- or shot-blasting can be used to remove scale as well as to roughen a metal surface prior to metal deformation in order to trap lubricant; on the other hand, grit-blasting may be used to apply a desired surface finish to the

product. Discussion will be limited here to two important surface preparation processes, oxide removal and abrasive blasting. The subject of metal cleaning both prior and subsequent to metal deformation will be covered in Section 4.6.

4.51 Oxide (Scale) Removal

Thin, dense surface oxides may be tolerated on some metals (e.g., aluminum), but nonuniform or loose oxides are normally removed prior to cold deformation because they impair the surface finish of deformed products, contaminate or interfere with the lubricant, and accelerate die wear. A prime example is the scale found in steels. The most common procedure for scale removal is acid pickling, but salt-bath descaling has also gained prominence for certain applications. Mechanical scale-breaking or the use of water jets may also be used under appropriate circumstances.

Semifabricated products intended for further working are often covered with lubricants, carbonized residues, and scale. Prior to removal of the scale, it may be advisable to remove lubricants and residues by alkaline precleaning.

A brief summary of techniques for scale removal is given in Table 4.19; details will be found in the Metals Handbook [114].

4.52 Abrasive Blasting

Although increasing die surface roughness generally increases friction, a rougher workpiece surface may offer considerable benefits. If the workpiece is suitably roughened, surface depressions are available to trap lubricant and compel the fluid to enter the critical region between the tool and workpiece; examples of this will be found in Sections 7.2 and 11.2.

Abrasive blasting entails the forceful application of abrasive particles—either wet or, more often, dry--against a metal surface. The purposes may include (1) scale removal, (2) surface preparation for subsequent processing, and (3) surface finishing as well as many special uses. The abrasive particles are propelled either by a stream of air or a rapidly rotating wheel; less frequently, the abrasive material is suspended in a liquid jet.

For details of equipment, abrasives, particle sizing, cycle times, etc., the Metals Handbook [114] is suggested. All metal surfaces can be abraded as desired provided that the abrasive medium is suited to the application;

TABLE 4.19

Scale-Removal Techniques

Metal Class	Prior Treatment (Optional)	Type of Scale	Typical Conditions	Comments
			Pickling[a]	
Ferrous metals (other than stainless steel)	Blast, degrease, alkaline precondition	Moderate to heavy	5-15%, sulfuric acid solution, 60-95°C	Inhibitors to control extent of pickle.
		Rust to light	As above; or 25-75% phosphoric acid solution, 30-95°C	
Heat-resisting alloys	Blast, alkaline precondition	Adherent	Dilute nitric acid or hydrofluoric-nitric acid solutions	Also oxidizes organic contaminants. Fused salt bath descaling may be preferred for alloys subject to embrittlement.
Stainless steels and high-nickel alloys	Blast, degrease	Adherent	10% sulfuric acid + 1-2% sodium thiosulfate or hydrosulfite solutions	
			20% nitric + 2-4% hydrofluoric acid solutions, 15-70°C	
Cuprous alloys	Degrease	—	10-30% hydrochloric acid solution, 30-70°C	
			5-10% sulfuric acid solution, 30-70°C	
Magnesium and its alloys	Degrease	—	Chromic acid, phosphoric acid solutions	Hydrofluoric acid added if silica is present.

TABLE 4.19 (Continued)

Scale-Removal Techniques

Metal Class	Prior Treatment (Optional)	Type of Scale	Typical Conditions	Comments
			Sulfuric or nitric + chromic acid solutions	
			Salt Bath Descaling[b]	
Stainless and high nickel alloys, titanium and its alloys	Blast, degrease	Adherent	1.5-2.0% sodium hydride in molten sodium hydroxide, 360-380°C	Oxidizing bath
			7-32% sodium nitrate, 1.5-6% sodium chloride in molten sodium hydroxide, 425-540°C	
			Alkaline Removal of Light Scale	
Ferrous metals	Blast, degrease	Rust to light scale	10-30% sodium hydroxide solutions containing sequestrants, 60-90°C	Time of application varies from 15 min to several hours.
Stainless steels and high nickel alloys	Blast, degrease	Light scale	Molten salt baths as above; also with anodic or cathodic current	Requires salt bath descaling sequence as above.

(a) Pickling is followed by rinsing, neutralizing, rinsing steps to minimize rusting, pitting, etc., where necessary.

(b) Salt bath descaling requires the further sequence of quenching, blasting, acid neutralizing, rinsing and pickling. Degreasing is not essential since the process also removes organic residues.

the surfaces of soft, ductile metals can be severely damaged by improper blast abrasion.

Abrasive blast cleaning is widely used to remove all types of scale and rust from steel mill products, either alone or preparatory to pickling. Stainless steel is blast-cleaned with clean sand; if iron particles become embedded in the surface from abrasive blasting with iron-bearing sand or steel shot, passivation with nitric acid (e.g., 6-15% by volume of 70% nitric acid for 10-30 min or more) is required or an acid pickle is needed.

Abrasive cleaning of nickel alloys is often a satisfactory method for removing oxide. Abrasive blasting with dry aluminum oxide followed by flash pickling is useful for heat-resistant alloys. Aluminum and its alloys are usually blasted with washed silica sand or aluminum oxide. Coarse high-carbon steel shot or grit might be used for titanium and its alloys; for finishing, mineral-type abrasives such as silica, alumina, or zircon are more common. Safety precautions are necessary because of the fire hazard associated with titanium dust.

4.6 LUBRICANT REMOVAL AND WASTE TREATMENT

The removal of lubricants is often a very important aspect of the total metalworking process. In many cases, problems in lubricant removal may be introduced by a modification of the lubricant formulation. Such problems should be recognized and anticipated, because product acceptance often depends on the success of the cleaning and finishing process.

Disposal of spent lubricant, handling of aqueous wastes from lubricant emulsions, and handling of cleaning wastes is also a highly specialized technological area. A brief account of waste treatment procedures and principles is presented, with reference only to wastes generated from metalworking processes.

4.61 Lubricant Removal

Worked metal surfaces are frequently covered with lubricant residues. Pigmented lubricants usually present more serious problems than unpigmented ones. The most difficult lubricant ingredients to remove are graphite, molybdenum disulfide, white lead, and insoluble soaps. Higher processing temperatures lead to lubricant decomposition which, in turn,

tends to increase adherence. A prolonged elapsed time between metalworking and cleaning also contributes to tenacity of the lubricant.

Alkaline Cleaning

Oils and associated semisolid and solid soils are frequently removed by alkaline cleaning. The mechanisms of removal include any or all of the following: saponification, emulsification, dispersion, flocculation, and film breakdown.

Alkaline cleaning solutions contain, first of all, water—which acts as the diluent, solvent, reaction medium, and carrier of the soil. Dissolved in the water to provide alkalinity and other properties are the builders; these are the chief constituents of alkaline cleaners and vary in concentration from 15 to 40% by weight. The sodium compounds used as builders include hydroxide, carbonates, phosphates, and silicates. Minor (0.5 to 5% by weight) but highly important ingredients are the surface-active wetting agents. Two types are employed to lower surface and interfacial tension—soaps and synthetic detergents. Alkaline cleaning is only marginally effective in removing pigmented lubricants, such as graphite or white lead.

Acid Cleaning

Acid cleaners are comprised of a solution of an acid (mineral acid, organic acid, or acid salt), in combination with a wetting agent and detergent. The distinction between acid cleaning and acid pickling is a matter of degree; they may overlap. Phosphoric acid-ethylene glycol-monobutyl ether mixtures are commonly used since the light phosphate coating they leave on iron and steel surfaces is conducive to rust inhibition.

Emulsion Cleaning

The most effective method for removing lubricant soils is emulsion cleaning, based on the use of common organic solvents dispersed in water with the aid of an emulsifying agent.

The petroleum solvents generally used range from low flash point naphthas to heavy naphthas and kerosines. Emusifiers include polyethers and high molecular weight sodium or amine soaps or hydrocarbon sulfonates, fatty acid esters of polyglycerides, glycerol, or polyalcohols. Cationic agents are also used.

Stable emulsion cleaners are used for light soil. Unstable (diphase) emulsion cleaners are more effective for removing lubricant soils because of the more intimate solvent action in contact with the metal surfaces.

Solvent Cleaning

Petroleum naphthas and solvents remove the nonadherent pigments of lubricant oils (such as whiting, zinc oxide, or mica) but will not completely remove graphite or molybdenum disulfide types of solid lubricants. Ultrasonic cleaning and vapor degreasing are also important cleaning methods.

Cleaning Process Equipment

The equipment chosen depends upon many variables including the type of soil, scale and surface oxides, the production method (batch, intermittent, or continuous), and the size of products. Introductory material to finishing equipment may be found in Blundell [124].

General

The topic of metal cleaning and finishing requires consideration of many factors too detailed for inclusion here. Various texts may be consulted for further information [125-128].

4.62 Waste Treatment

Water use varies greatly, but the figures contained in Table 4.20 are typical of large steel plants [129]. Only wastes generated from the metal-working processes will be discussed here; aqueous discharges from the

TABLE 4.20

Water Use in an Integrated Steel Mill [129]

Department	Volume of Water	
	Gallons per Ton of Finished Steel	Percent of Total
Blast furnace	10,000	25
Open hearths	5,000	12.5
Coke plants	5,000	12.5
Hot mills	10,000	25
Finishing mills	8,000	20
Sanitary, boiler and other uses	2,000	5
	40,000	100

coke ovens, in particular, present somewhat different problems. Within limits, the wastes from the many operations in the steel mill are handled separately. Processing plants for alloy steels, aluminum, copper, and their alloys will have somewhat similar waste problems.

Nature of Wastes

Water wastes from the various processes are roughly segregated according to operation in order to simplify treatment. Wastes originating from metalworking operations may be classified as (1) scale-bearing waters, (2) acid waters, (3) oil-bearing waters, and (4) alkaline cleaning solutions.

The scale-bearing waters originate from the various rolling mill operations. In primary mills, the water both cools and dislodges scale from the rolled product; further, the water is used to transport scale from the mill line (flume water). The scale averages 90% or more coarser than 200 mesh. If such particles are not removed, they tend to clog sewers and deposit in streams.

The scale from finishing mill rolling operations is comparable to that from primary mills, but considerably greater variations among installations occur; 80-90% of the scale particles are coarser than 200 mesh in most plants. The finest particles may be 5 μ or less and may increase stream turbidity.

Acid waters derived from pickling and from rinsings vary widely in quantity, composition, and concentration. Sulfuric acid constitutes about 90% of the total acids used in pickling, but hydrochloric, nitric, phosphoric, and hydrofluoric acids may also be found, particularly from the pickling of stainless steel. Spent pickling solutions may inhibit biooxidation processes in streams and injure aquatic life. Acid rinse waters have the same constituents as pickling solutions but are much more dilute.

Rolling oils, lubricants, and hydraulic oils are present in the effluents from many of the metalworking operations. Free oils form oil films injurious to marine and aquatic life. Emulsified oil can add significantly to the BOD (biological oxygen demand), a test commonly used to evaluate stream and lake pollution. Typically, the effluent from once-through use in cold rolling will contain up to 200 mg oil per liter, partially as a stable emulsion.

Alkaline cleaning solutions used to remove rolling oils prior to finishing operations can contain alkalis, silicates, and phosphates. The spent cleaning solutions contain saponified oils, scale, dirt, and residual alkalinity.

Treatment Procedures

Rolling mill flume water is usually clarified in simple sedimentation basins, known as scale pits. The deposited scale is periodically removed and forms a source of ore. In newer plants, the scale pits are often designed for continuous mechanical cleaning. Treatment following the scale pits consists of primary clarification and oil removal in large rectangular sedimentation basins. Secondary clarification includes chemical treatment, typically with additions of lime, ferric sulfate, and polyelectrolyte coagulating agents.

Flume water from the hot rolling operations is contaminated by free oil and oil bound to the mill scale. Most of this oil is readily separated by gravity and may be skimmed in the primary scale pit or in secondary sedimentation basins. Reuse of the water may require chemical treatment or air flotation. Most hot-mill effluents contain 10-20 mg oil/liter, but this can be reduced to 1-5 mg/liter by secondary chemical treatment.

Effluents from the cold-rolling mills are sent first to oil separation sumps where the floated oil may be removed; this oil is given nominal treatment to remove water and sediment before sale to oil reclaimers. The sump effluent contains emulsified oil in concentrations from 50 to 100 mg/liter. Generally the effluent will be given secondary treatment in a basin of the API oil-water separator type. Ferrous sulfate and lime are added, and air flotation carries the oil to the surface. Aluminum sulfate and calcium sulfate are also often used to break emulsions and recently polyelectrolytes, such as water-soluble polyamines, have shown promise. With effective treatment, the oil content of plant effluent may be as little as 10-15 mg/liter.

Wastes from spent pickling solutions, particularly those containing fluoride, are probably the most difficult to handle. Neutralization with lime or other materials is the general practice, but disposal costs are high especially in urban areas. Land area is then needed to lagoon and eventually to dewater the neutralized slurry. By-product recovery processes have been proposed, generally with reference to production of copperas, $FeSO_4 \cdot 7H_2O$. The processes involve reaction of scrap iron with the hot acidic water and recovery by evaporation, differential solubility. or refrigeration. Since 5% of the industry potential for copperas satisfies the market, this method of disposal is limited. Where ammonia is available, ammonium sulfate can be produced and sold. The spent acid solution can also be used to extract manganese from low grade ores. Ion exchange processes are available to

recover the acid; this procedure might be best applied to the more dilute and relatively clean acid rinse waters. Disposal in deep wells is attracting attention where suitable underground strata are available.

The water wastes derived from metalworking operations represent only about half of the total mill wastes. Comprehensive surveys are given by Nordell [130], Bramer [129], and Nemerow [131]. The last author lists 103 references to the practice of mill waste treatment. A recent survey by the Federal Water Pollution Control Administration [132] indicates that the total wastes of lubricating oils and emulsions amounted to 306 million pounds and 51.6 million pounds, respectively, in 1963 in the U.S.A. The totals projected for 1977 are 486 million and 11.25 million pounds per year; the latter figures reflect anticipated developments for improved treatment and water reuse.

4.7 HEALTH AND HYGIENE

The health hazards associated with metal forming may be classed under three general headings. First, the principal hazards in the metal forming operation itself are heat, noise, and exposure to metal or metal oxide dusts. Second, physical contact of workers with metalworking lubricants, including both oils and additives, may induce skin diseases. Third, processes associated with metalworking expose the workers to acids (pickling, acid cleaning), alkalis (scale-removal metal cleaning), solvents (emulsion cleaning, degreasing, and metal cleaning in general), and dusts (abrasive blasting, grit blasting, polishing, etc.). This discussion can do no more than indicate the major hazards encountered in metal forming processes and related operations. A most useful text is that of Patty [133], and other references will be cited when pertinent.

For details on the toxicity of individual metals and metal oxides possibly encountered in metal forming, reference can also be made to Browning [134] and Davies [135].

4.71 Lubricants

Oils, especially cutting oils, account for a high percentage of reported industrial diseases particularly of the skin. Bourne [136] indicates that in England, 9 out of 13 affected workers were employed in engineering and metal manufacturing; in the United States, nearly 19% of the total of

occupational dermatitis incidents were due to petroleum products and greases. In general terms, mineral oil presents a probable skin hazard, but the nature of the oil, temperature, and length of exposure are important factors. Initially, the effect is that of irritation, perhaps accompanied by redness or pimples. On exposure to soluble oil, the skin is liable to macerate and become soggy, followed by scaling, cracking and fissuring. Additives, upon contact with the skin, may produce local sensitization which then spreads over larger areas.

Most workers in contact with these oils show some degree of plugging of the skin (blackheads or acne), inflammation, and septic pimples (folliculitis). Scars may result from boils and abscesses occasioned by long exposure.

With oils containing sulfur or chlorine, continued exposure gives rise to a characteristic skin disease called chloracne. The disease results in plugged black pores with small swellings (cysts) on the face, arms, forehead, neck and ears, and wherever oil-soaked clothing touches the body.

Long exposure to mineral oils may cause discoloration and growths on the skin. In textile mills, untreated mineral oil has been replaced by highly refined white oils; cancer from prolonged contact with oil-soaked clothing is an occupational hazard.

In general, use of protective barrier creams for exposed areas of the hands and face is recommended. General contact with oils should be kept to a minimum, and exposed skin areas should be washed as soon as possible with soap and water. Clothing should be cleaned regularly, and oily rags should never be placed in pockets, particularly the trousers. Cleaning with solvents or naphthas should be avoided since these also induce dermatitis. The vegetable oils themselves, such as coconut oil, lard oil, rapeseed oil, cottonseed oil, etc., seem to have lesser if any effects.

4.72 Acids

The danger presented by splashing acids used in metal cleaning is well recognized, and rules of preparing dilute acids must be strictly followed. In the process of pickling and acid-cleaning, bubbles of hydrogen rise from the treating tanks and carry an acid mist that endangers not only personnel but also equipment. Ventilation is necessary. The possibility of exposure to arsine and other toxic metal hydrides should not be overlooked either.

4.73 Alkali Cleaners

Alkaline cleaners involve the general hazard of splashing; contact can cause deep and painful destruction of skin tissue. Trisodium phosphate cleaners are less caustic than caustic soda, while tetrasodium phosphate and sodium metasilicate are even less alkaline. Preventive measures include splash shields and general safety precautions. Flushing copiously with water is the best initial treatment should an accident occur.

Molten caustic used for descaling alloy steels presents danger of caustic burns. The hazard of moisture or oils entering the baths and causing splashes of explosive violence must also be mentioned. Safety shields and remote-control measures are indicated.

4.74 Emulsion Cleaners

Since emulsion cleaners used in various metal-cleaning operations contain kerosine or other petroleum solvents combined with various chemicals, skin contact should be avoided. The volatile hydrocarbons in the cleanser dictate positive fume extraction. Similar comments apply to solvent washing and degreasing processes. Patty [133] and Browning [137] have prepared extensive reviews of the toxicity and hazards of industrial solvents.

4.75 Dusts

Dusts represent a hazard common to many industries and may be encountered in various aspects of metalworking processing. In conjunction with abrasive blasting, extensive quantities of dusts may be entered into the environment. Use of hoods, adequate ventilation, and individual respirators are indicated. Silicosis is due to retention of silica within the lungs of exposed workers; no cure is known, and only prevention can protect the individual. Other dusts, apart from burning oxides, seem to be less harmful except for their content of silica. For further details, refer to Drinker and Hatch [138], Davies [135], and Patty [133].

4.8 SUMMARY

A knowledge of the nature of lubricants is essential for understanding their role in complex metalworking lubricant systems. In this Chapter, broad categories of lubricants that have the greatest significance in the

metalworking process industry were discussed showing, where possible, relationships between chemical composition and lubricating performance.

Hydrodynamic lubricants are highly dependent upon the interrelationship of temperature and pressure with liquid viscosity and solidification. For the regimes of interest in metal deformation processes, the discussion is mainly qualitative since disappointingly few accurate data are available. Mineral oils dominate this category because of low cost and generally acceptable performance, but some synthetic lubricants offer promise in that they can be tailored to provide suitable high-temperature stability and a minimum of staining. Glass lubricants are already established for high-temperature deformation processes, but much more basic information is needed on the relationship between composition and physical properties.

Boundary lubricants, based on higher fatty acids and derivatives, are well established in deformation processing. The fatty acids are frequently a component of the natural oils and fats used, or they may form upon thermal degradation of these materials. The use of these organic lubricants is limited by the temperature of desorption (approximately 150°-250°C) or by undesirable changes in composition.

The performance of E.P. compounds is closely related to the active groups incorporated in organic compounds. Chlorine-, sulfur-, and phosphorus-containing compounds are the most extensively applied, but other reactive groups are under investigation. Frequently, reaction rates are too slow to assure the development of the surface film; therefore, the kinetics of film formation and new systems with faster but controlled reaction rates remain areas of study for improved action of E.P. components in metalworking lubricants.

The outstanding ability of certain solid films to lubricate effectively can be attributed to lamellar crystal structure; graphite and molybdenum sulfide find widest application particularly at high temperatures, but other compounds are entering the field. The attachment of solid films is important, and various methods of bonding show promise. Polymers of various types have been considered for metalworking lubricant films, and new applications will undoubtedly develop. Soft metals have been successful as lubricants, but their application appears somewhat limited in the future. Adherent, thin oxide films have been shown to have value in metalworking lubrication, but friable or ductile solid films also have proved useful in specific cases.

The mode of introduction of the lubricant into the contacting zone between die and workpiece has a signficant effect on lubricant performance. For some processes, a compounded oil can be entered in neat form; in others, a grease, wax, or semisolid may be more advantageous. The emulsification of lubricants to form an oil-in-water dispersion or emulsion has been treated briefly; an improved understanding of the complex factors affecting the performance of metalworking lubricant emulsions would be most valuable. The introduction and retention of lubricants may be aided by modifications of the workpiece surface. Conversion coating and surface roughening help to trap lubricant on the surface; phosphate, oxalate, and fluoride coatings are the most common chemical conversion methods, while blasting with grit or other solids provides a mechanically roughened surface.

Within this Chapter, a number of other subjects were treated that are peripheral yet essential to the proper functioning of metalworking lubricants. Scale-removal techniques, metal cleaning procedures, as well as health and hygiene were briefly covered.

Chapter 3 has treated elements of friction, lubrication, and wear with reference to deformation processing, and the present Chapter has considered lubricants within the same context. The operating characteristics of the individual components of a metalworking lubricant can usually be described and evaluated separately, and this should also aid in understanding the action of the lubricant in a given metal deformation process. It should then be possible, at least to a limited degree, to propose and utilize improved lubricants that optimize a set of process parameters, such as surface finish, die wear, and production rate. The interplay of lubricant functions may, however, load to a very complex and often unpredictable relationship, and it becomes necessary to ensure that lubricant evaluation techniques have relevance to the specific environment of lubricant application. This is the subject of the next Chapter.

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Chapter 5

LUBRICANT PROPERTIES AND THEIR MEASUREMENT

John A. Schey

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Preceding chapters have shown how friction affects process conditions in deformation processing; the mechanisms by which friction and wear may be influenced have also been indicated. It will now be possible to summarize the functions a lubricant is expected to fulfill, including those that are not necessarily amenable to a mathematical treatment. A definition of the desirable attributes of metalworking lubricants will be developed, followed by a description of the methods by which lubricant properties may be qualitatively and, quite often, quantitatively assessed.

5.1 ATTRIBUTES OF METALWORKING LUBRICANTS

In practice, a lubricant is expected to fulfill a number of different functions. Some of the requirements may be contradictory or mutually exclusive, thus the choice of the lubricant may become a matter of best compromise and is directed by specific needs. There are, however, some attributes which are generally valid for the majority of applications, and these are given here, using an evaluation due to Schey [1]:

1. Controlled friction. Low friction reduces forming forces and power requirements, allows greater reductions to be taken, and results in more homogeneous deformation. Nevertheless, zero friction is seldom approached, and is not always desirable. It is certainly acceptable in extrusion and wire drawing, but a minimum friction is required to prevent uncontrollable instability and skidding in rolling or random shifting of the workpiece in forging and deep drawing.

2. Reduced wear. Ideally, the lubricant would completely separate the die and workpiece surfaces and would, therefore, eliminate wear. However, in most metalworking operations the formation of some debris is unavoidable. Most of the debris is normally a wear product of the workpiece material and, as long as the surface finish is acceptable, it is not a cause for undue concern. However, as soon as metal-to-metal junctions are sheared in the die material, accelerated die wear is encountered. Similarly, hard scale and/or hard constituents of the workpiece material may cause rapid abrasion. The rate of wear may become exceptionally high when a combination of high temperatures, high pressures, and high adhesion between workpiece and die materials exists. The lubricant should efficiently reduce wear of the die, as well as limit wear of the workpiece material to tolerable proportions. The wear products themselves should be, preferably, nonabrasive.

3. Avoidance of metal pickup on the tool surface. The lubricant should prevent metal-to-metal contact and resulting pickup on the die surface. Depending on the affinity (adhesion) of the die and workpiece materials, pickup may reach catastrophic dimensions. The process is often self-accelerating; once initial pickup is formed, the lubricant loses its efficiency in the changed environment and the workpiece material welds to the incipient pickup at an increasing rate.

4. Thermal insulation. In hot working operations, lubricants should provide thermal insulation between the workpiece and die surface, partly to reduce heat loss from the hot stock and partly to protect the die from excessive heat. This requirement necessitates a continuous blanket of a lubricant, capable of withstanding high pressures and temperatures, yet giving low enough shear strength to assure a low coefficient of friction. It may also be desirable that the lubricant protect the workpiece against oxidation or gas pickup during deformation. This again necessitates a continuous film having high tenacity, adherence, favorable viscosity, and a good self-healing capacity.

5. Cooling. In many instances, especially if the metalworking operation is of the continuous type, the lubricant should cool the dies and the workpiece material, if the heat generated during deformation more than offsets heat losses.

6. Controlled surface finish. The optimum surface finish is not necessarily the brightest one. A relatively rough finish may be preferred for keying a coating onto the surface, while a smooth finish may be desirable for mating surfaces or for visual appeal. The lubricant should aid, together with the die surface and properly selected process conditions, in obtaining the desired finish. This finish should be uniform and free of chatter, ripple, herringbone, or other periodic or random markings.

7. Adaptability to varied working conditions. The lubricant must perform its functions in the environment presented by the pressure, temperature, and relative sliding velocities prevailing during deformation. Pressures may reach values of over 500,000 psi; temperatures of the order of 200-300°C may be encountered at the interface even in so-called cold-working operations, and temperatures in excess of 1200°C are not uncommon in hot-working the refractory metal alloys. Sliding velocities range from near zero to several thousand feet per minute, and variations of this order may

occur even during one and the same deformation process—for example, rolling.

8. Protection of old and new surfaces. The most important phenomenon that separates plastic metalworking from all other friction problems is the continuous generation of new surfaces. New surfaces are produced at the highest rates in operations where bulk deformation is accompanied by surface straining (rolling, wire drawing, extrusion), but rates diminish in more moderate metal shaping operations such as deep drawing. The lubricant is called upon to cover both old and new surfaces efficiently even though the chemical activity of these surfaces may be radically different. Old surfaces may consist of oxide films, adsorbed layers of gaseous and liquid substances, remnants of lubricants employed in earlier stages of processing, and surface layers deposited intentionally prior to deformation. The lubricant must have favorable wetting and spreading characteristics to follow the extension of the metal surface, so as to part the contacting surfaces efficiently.

9. Compatibility with die and workpiece material. The lubricant must perform its function in the system defined by the die or tool surface, the old and new metal surface, the lubricant, and occasionally by the surrounding atmosphere. The reactivities of various surfaces may differ greatly, and the performance of a lubricant should always be judged against the inherent characteristics of the contacting metal pair.

10. Durability of lubricant film. The lubricant film formed on the surface of the die must be capable of withstanding the repeated encounters characteristic of most metalworking processes. Even if the lubricant acts primarily by deposition on the workpiece surface, some transfer onto the die surface is always possible and, indeed, most desirable. The durability of this film will then become a factor of importance.

11. Rapid response. The lubricant must exert its influence in the short time (of the order of a few milliseconds) available during the actual forming process itself. Even when the surface of the workpiece is conditioned beforehand, the efficiency of the operation will depend on whether the newly developed surfaces can be protected during their formation. Thus, the rate of forming boundary films will be a governing factor where monomolecular films are relied upon. For fluid films that protect essentially by hydrodynamic and hydrostatic action, the rheology of the lubricant will assume overriding importance.

12. Controlled stability. The lubricants should remain unchanged with time and despite repeated encounters. Therefore, they should be stable, unaffected by temperature, oxidation, bacteriological attack, and contaminations often unavoidable in industrial practice. If changes occur, they should be beneficial or at least harmless; there may be components of the lubricant that become activated at high temperatures. In such case, replenishment may be necessary, as practiced with surface-active additives, or a new batch of lubricant may be introduced. Neither the lubricant nor the breakdown or reaction products should be abrasive. Gases liberated should contribute to lubrication or at least not interfere with the deformation process.

13. Controlled reactivity. Even though efficient lubrication frequently presupposes a certain amount of reactivity, the lubricants should not be corrosive to the product, the die, or the metal forming machine or machine tool.

14. Harmless residues. Residues of the lubricant should preferably not cause discoloration (staining) of the product on subsequent annealing or storage, nor should they exert chemical or metallurgical effects on the product. They should not be allowed to interfere with finishing operations such as painting, enameling, printing, welding, and electrodeposition. Cleaning before such final operations may be necessary.

15. Application and removal. The lubricant should be easy to apply to the workpiece and/or die in a controlled manner, and it should be readily removed.

16. Handling, safety, and cost. There are other aspects which do not necessarily have a direct bearing on the lubrication properties. Examples are absence of skin irritation, toxicity, fire hazard, and odor. Finally, the lubricant that conforms to all the requirements should also be inexpensive. This is a very important consideration for mass-production industries where the cost of the basic material is often low and processing contributes a substantial portion to the total cost. Conversely, price considerations may take a secondary place when processing more expensive materials or when the savings accumulated through superior lubrication more than counterbalance higher lubricant costs.

5.2 MEASUREMENT OF FRICTION

5.21 Purposes of Friction Measurements

We have seen that friction determines forces and power requirements, and is responsible for a number of process limitations. Improved lubrication is immediately noticeable in reduced equipment loading, in greater reductions per pass and, frequently, in an increased output from a given installation. Simple evaluation techniques or production observations are usually adequate for a semiquantitative ranking of lubricants. More sophisticated measurements and calculations are needed if the quality of the lubricant is to be judged from a coefficient of friction value. In principle, this has advantages in that clues to the operative lubricating mechanism may be gleaned, generalized conclusions may be drawn for various production conditions, optimum production sequences may be planned, and equipment may be designed on a more scientific basis. It must be recognized, though, that friction values are, very frequently, specific to the given experimental conditions, and indiscriminate extension of "typical" values could lead to serious errors. In this chapter, the limitations inherent in the measurement and use of a coefficient of friction value will be referred to whenever appropriate.

The perfect technique of lubricant evaluation would be in full-scale production, on fully instrumented equipment that would allow an objective measurement of all process variables, followed by a gradual tailoring of process conditions to achieve optimum performance with each lubricant. The cost of such an approach is usually prohibitive, and ways of evaluating lubricants under laboratory conditions have been sought.

The first logical step is the evaluation of lubricants in the same deformation process as it is intended for, but on a smaller scale; the problem here is to determine how far dimensions, speeds, strain, and other process variables may be scaled down before the test loses its relevance. A further step toward simplification involves the selection of a simple metalworking process that can be performed at a low cost to evaluate lubricants for another, more costly, process. For example, wire drawing has been proposed and used for the evaluation of rolling lubricants. The question here arises as to whether one metalworking operation can be used to simulate lubricant performance in another. The final step, of course, is the development of a simulating technique that may be performed on a bench-type apparatus.

Such tests may involve plastic flow or may be limited to elastic contact between tool and workpiece material. The task then remains to show the applicability of such test results to real metalworking processes. The main limitation is usually the absence of sufficient surface strain that would expose new surfaces at a rate comparable to deformation processing.

5.22 Rolling

From the beginning of this century, a large number of approaches have been tried to measure friction in the hot and cold rolling of flat products. The sophistication of these techniques has increased with time, even though it is sometimes doubtful that the results justify the effort.

Lubricant Evaluation from Rolled Gage

We have seen in Section 2.23 that, with increasing friction, the roll-separating force increases. This, in turn, causes an increasing elastic deflection of the mill housing, the rolls, and other mill components. In consequence, for any given initial roll gap setting the issuing strip thickness increases with increasing friction. This principle offers a very simple method of ranking lubricants. Two approaches are possible.

First, short strips of a constant width and thickness may be rolled at a number of preset roll gap settings, and the issuing thickness plotted against the nominal roll gap settings (Fig. 5.1a). Secondly, one strip may be rolled repeatedly, with gradually decreasing roll gap settings, and the issuing gage may be plotted against the number of passes or the actual settings for each pass (Fig. 5.1b). Neither of these methods gives a quantitative measure of lubricant performance, but they are very convenient means of determining the order of merit in a set of lubricants. The sensitivity of the technique is increased if reductions are taken far enough to reach the condition of limiting reduction (Section 2.26). The curve in Fig. 5.1b will then end in a horizontal line, and the lubricants may be ranked by the minimum attainable gage. The reliability of the process is set largely by the accuracy of thickness measurement; in the laboratory, the length increase of relatively short pieces may be found a more convenient measure of the average reduction in thickness. The strips, however, should always be long enough to establish equilibrium conditions on the roll surface.

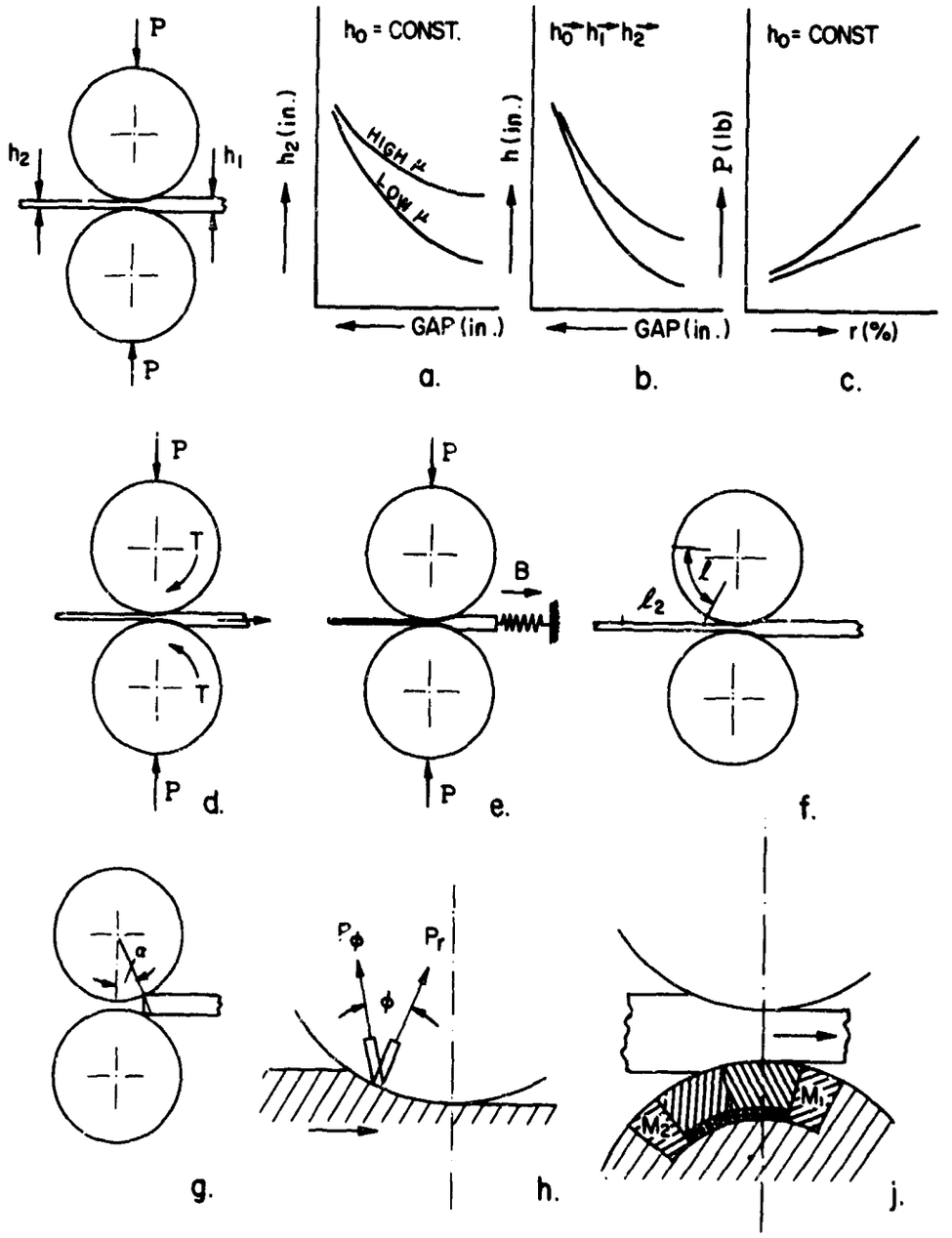

Fig. 5.1. Methods of measuring friction effects in rolling.

Friction Derived from Roll Force

When the rolling mill is equipped with load cells, a more detailed picture of lubricant performance may be gained by plotting roll force (typically, for unit width) against thickness reduction in single passes (Fig. 5.1c).

An average friction coefficient may also be derived by accepting the validity of any of the rolling theories. The major drawback of this method is that the true yield strength (σ_m in Eq. 2.16) of the workpiece material needs to be known at the temperatures and strain rates prevailing in the roll gap. This is known for only a few materials with sufficient accuracy. The possible error increases with improving lubrication. With lower friction, the friction hill is smaller and contributes little to the total roll force. Therefore, a small percentage error in the yield stress value may lead to a disproportionately large error in the calculated coefficient of friction. Calculations become even more doubtful if rolling is accomplished with tension. Very few mills have sufficiently sensitive and reproducible tension control, and minor, incidental, and often undiscovered variations in tension may readily mask the lubrication effects.

Since all practicable solutions for roll force assume plane strain in the roll gap, the strip width should be at least 10 times its thickness. Otherwise the variation of spread with friction affects the accuracy of observations and calculations.

The actual value of the coefficient of friction derived from roll force depends, of course, on the particular theory accepted as valid. As Schey [2] has shown, deviations for the same set of results may be considerable. Therefore, any published data of μ must be regarded as approximate and should be compared only with data derived in a similar manner. It is important that for cold rolling with marked elastic flattening of the rolls, the flattened roll radius according to Hitchcock (Eq. 2.21) should be calculated and the contribution of the elastic arc of recovery [3] not neglected.

Friction Derived from Force and Torque. In the discussion on rolling of strips with tension (Section 2.22), mention was made that if front tension is eliminated and back tension is increased until the neutral plane moves to the exit point, the strip begins to skid (Fig. 5.1d). Under these conditions only, the following simple relationship exists between torque, force, and coefficient of friction:

$$\mu = Q/PR \qquad (5.1)$$

Following a proposal by Bland, this relationship was used by Whitton and Ford [4] for evaluating rolling lubricants. The expression is independent of rolling theory; the only assumptions involved are plane-strain deformation and constant μ along the arc of contact. If the mill is not equipped with torque meters, the strip may be stopped by attaching it to a spring dynamometer (Fig. 5.1e) according to Pavlov [5]. Assuming that the normal force P_n acts in the middle of the arc of contact of angle α, the balance of forces in a horizontal direction gives

$$2P_n \sin\frac{\alpha}{2} + B = 2P_n \mu \cos\frac{\alpha}{2} \tag{5.2}$$

Since the roll force can be represented as

$$P = \frac{P_n}{2}\cos\frac{\alpha}{2} + \frac{P_n}{2}\mu\sin\frac{\alpha}{2} \tag{5.3}$$

or, since the second term of the equation is small and can be ignored, the normal force can be expressed as

$$P_n = \frac{2P}{\cos(\alpha/2)} \tag{5.4}$$

and the coefficient of friction can be readily calculated

$$\mu = \frac{B}{4P} + \tan\frac{\alpha}{2} \tag{5.5}$$

Whether torque or back tension is measured, the method has the disadvantage that an artificial situation is created in the roll gap. Instead of allowing the friction conditions to select the position of the neutral plane, the somewhat unrealistic condition of skidding of the rolls on the strip surface is introduced. Nevertheless, the technique is important because it is one of the few direct methods available for determining friction in rolling.

Using the same technique, but considering also the elastic deformation of the roll, Yamanouchi and Matsuura [6] derived the following equation:

$$\mu = 1\left[+\left(1 - \frac{R}{R'}\right)\left(\frac{RP_o\alpha}{2T_o} - 1\right)\right]\left[\frac{T}{PR}\right] \tag{5.6}$$

where P_o and T_o = force and torque with no tension applied; P and T = force and torque with back tension sufficient to cause slipping.

Recently, Inhaber [7] produced a solution which, for positive forward slip, allows the derivation of a coefficient of friction from simultaneously measured roll force, torque, and forward slip values, without the need of introducing artificial slipping. The position of the neutral plane is determined from forward slip and, by assuming that the friction hill is of an inverse exponential shape, the coefficient of friction may be obtained. The advantage of this process is that the actual yield strength of the material need not be known, but it appears to involve substantial calculating effort for a result that may not necessarily be more accurate than a simple derivation from forward slip alone.

Friction Derived from Forward Slip

When a strip is rolled without tension, the position of the neutral plane is determined by the balance of frictional forces (Section 2.22). Therefore, forward slip is a very sensitive measure of friction, and has been extensively used for evaluating lubricants. For a measurement of forward slip, one or more lines are scratched on the roll surface parallel to the roll axis. If the distance of these scratches is accurately known, forward slip is readily determined from the imprints of any two successive lines on the rolled material (Fig. 5.1f). At any given roll speed v, the rolls take t seconds to travel a distance ℓ between successive scratch lines. During the same time, the imprints of these marks travel at the higher speed v_2 of the issuing strip and cover a correspondingly greater distance ℓ_2. Therefore, forward slip may be expressed as:

$$S_f = (\ell_2 - \ell)/\ell \tag{5.7}$$

Using any of the available theoretical solutions for the position of the neutral plane and forward slip, an average coefficient of external friction may be calculated. The absolute value of μ is dependent on the particular theory adopted, and variations in friction values calculated from the same set of experimental data may be substantial [2]. The trends, however, are consistent regardless of method of solution, and it appears that Ekelund's equations (Eqs. 2.12 and 2.14) may be used for the extraction of μ. The undeniable advantage of friction determination from forward slip is that the yield stress of the strip need not be known and no special instrumentation of the rolling mill is needed.

In calculating friction from forward slip at elevated temperatures, the shrinkage of the ℓ_2 distance on cooling must be taken into account [8]. Whenever roll flattening is significant, a flattened roll radius, calculated according to Hitchcock (Eq. 2.21) should be substituted. For a constant coefficient of friction, forward slip reaches a maximum when the angle of contact equals the friction angle as shown by Dahl [9]. This would allow a direct determination of μ by simply rolling with gradually increasing reductions until the maximum forward slip value is found. This method, however, has very limited use because with most materials friction tends to rise with increasing pass reduction and the maximum of the forward slip vs. reduction curve is obscured.

The position of the neutral plane is markedly affected by the presence of tension. Thus, increasing back tension causes the neutral plane to move forward, suggesting a decrease in friction. There is no evidence that commensurate changes in friction do indeed occur and, at present, it appears safer not to apply the method of forward slip measurement to friction investigations with applied tension.

A somewhat related method of determining a coefficient of friction has been proposed by Capus and Cockroft [10]. Small irregularities such as pickup on the roll surface cause scratches to appear on the surface of a polished strip. If rolling is carried out slowly enough to stop the rolls with the strip in the gap, the length and direction of scratches may be observed under a microscope and the position of the neutral plane determined. From this, the coefficient of friction may be determined according to Eq. 2.12. This technique, however, is limited to small reductions and low rolling speeds, and entails more careful evaluation than the very simple technique of measuring forward slip. Since forward slip may be measured at any speed and pass reduction, without stopping the rolls, it still appears to be the more satisfactory technique.

The position of the neutral plane could be determined also from backward slip; some means of accurately measuring the speeds of the ingoing strip and of the roll is then needed. In a technique developed by Kasuga and reported also in the review article of Saeki and Hashimoto [11], the rotation of disks pressed on the ingoing strip surface is transmitted to a slotted disk. A similar slotted disk is attached to the roll, and the light signals passing through the slots are recorded on the same light-sensitive film. From the

relative distance of the signals, a very accurate determination of backward slip is possible, although the technique offers no obvious advantage over the much simpler forward slip measurement.

Friction Derived from the Angle of Acceptance and from Skidding

It was pointed out (Section 2.26) that the workpiece enters the roll gap unaided only if the entry angle is smaller than or equal to the frictional angle ($\tan\alpha \leq \mu$). This would appear to offer a very simple way of determining the coefficient of friction; the roll gap is opened until the strip enters the rolls without push (Fig. 5.1g). However, small irregularities of the roll shape, local variations of surface roughness, and variations in lubricating conditions as well as localized pickup on the roll surface may all aid in drawing the strip into the roll gap. Furthermore, the frictional force is unidirectional at the point of acceptance; this is not representative of friction sustained during rolling, when two-directional flow occurs from the neutral plane outwards. The method does offer, however, a convenient if not necessarily accurate means of determining friction under conditions of dry lubrication (e.g., in hot rolling with oxide performing the function of a lubricant), and it may be used for a very approximate ranking of lubricants.

A method based on the onset of skidding during rolling has been suggested by Avitzur [12]. Strips of constant thickness are rolled with increasing reductions, until the strip begins to skid in the roll gap. At this point, the neutral point coincides with the exit point and, if elastic roll flattening can be ignored, the coefficient of friction may be calculated from the pass geometry according to the following equation:

$$\mu = \frac{1}{2}\sqrt{h_2/R}\,\frac{\ln\,(h_1/h_2) + \frac{1}{4}\sqrt{h_2/R}\,\sqrt{(h_1/h_2) - 1}}{\tan^{-1}\sqrt{(h_1/h_2) - 1}} \tag{5.8}$$

If friction is assumed to be a constant m fraction of the shear strength τ_o of the workpiece material, a similar equation results except that the factor of 1/2 is eliminated. Avitzur points out that skidding can be induced only with small workroll diameters. It should be added that the method also calls for reductions that are beyond the practically useful range for many lubricants; therefore, this procedure—even though attractive—is likely to find only limited use.

Temperature Rise

Some of the heat developed by the frictional energy generated at the interface enters the rolled product (Section 2.25). The temperature of rolled copper strip was taken as a measure of lubricant effectiveness by Reynolds [13]. Sufficiently long coils of strip were rolled at roll settings that produced identical issuing gage; temperatures obtained with different lubricants could then be used as a semiquantitative measure of lubricant efficiency. Such an approach offers the advantage of minimum instrumentation; however, close control of initial roll temperature and highly reproducible cooling techniques are required. It would appear that lubricant evaluation by presetting the roll gap and measuring the issuing gage (Fig. 5.1a) is more simple and reliable.

Direct Friction Measurement

From the theoretical point of view, the ultimate aim of all friction measurements is the point-to-point determination of the real coefficient of friction between workpiece and roll surface.

Pressure-sensitive pins embedded in a radial direction in the roll surface have been repeatedly used for determining the pressure distribution along the arc of contact (Siebel and Lueg [14]) from which the effect of friction may be judged indirectly. The combination of a radial pin with an oblique pin, first used by Van Rooyen and Backofen [15] could, in principle, allow the direct determination of a coefficient of friction ($\mu = \tau_i/p$) from the geometry shown in Fig. 5.1h. If p is the normal stress between the roll and strip, τ_i the friction-induced shear strength at the same point, and A the cross-sectional area of the pins, the coefficient of friction may be determined from the stress p_r ($\equiv p$) in the radial pin and the stress p_ϕ in the oblique pin as follows:

$$p_\phi A = \sigma \frac{A}{\cos\phi} \cos\phi + \tau_i \frac{A}{\cos\phi} \sin\phi \tag{5.9}$$

$$p_\phi / p_r = 1 + \mu \tan\phi \tag{5.10}$$

hence

$$\mu = \left(\frac{p_\phi}{p_r} - 1\right) \cot\phi \tag{5.11}$$

After the pin passes the neutral point, the shear stress is reversed, but can still be measured if the same experimental roll set is used in a reverse rolling direction. The authors point out a number of complicating factors and inherent inaccuracies that affect the validity of friction determination--for instance, with an angle $\phi = 26^{\circ}34'$ and $\mu = 0.2$, an error of only 1% in either the radial or oblique pin pressure measurements results in a 10% error in the coefficient of friction. Binding between the pin and the roll, friction at the interface, protrusion of the pin, and the elastic distortion of the roll are among the major sources of error. As shown by Smith, Scott, and Sylwestrowicz [16], the pressure-sensitive pins register a force even when they are outside the actual arc of contact. This may amount to 5-10% of the total force and could seriously affect the validity of friction measurements. The results are also greatly influenced by the stiffness of the pin relative to the roll, and Van Rooyen and Backofen show that with a pin stiffer than the roll, measured pressures will be artificially high and a friction coefficient cannot be practically determined. Further aspects of importance will be discussed in conjunction with Fig. 5.4e.

A somewhat similar arrangement, but utilizing one radial and two oblique p s at an angle of $53^{\circ}45'$, has been used by Katashinskii and Vinogradov [17] for measuring the coefficient of friction in powder rolling. It is claimed that friction in the radial pin bushing causes an error of only 1-2%, and that the friction in the oblique pin bushings may be ignored.

Grosvald and Svede-Shvets [18] increased the number of pins to four: one radial, two inclined in a plane perpendicular to the roll axis, and a fourth inclined to this plane. This allowed a determination of shear forces both in the longitudinal and transverse direction along the entire area of contact.

A pressure pin embedded radially in the roll surface with a clearance sufficient to allow both radial and lateral deflection of the pin was used by Grishkov [19] for the simultaneous measurement of radial pressure and of lateral and longitudinal interface shear stresses in the course of rolling. The pin bore on three dynamometers that measured the three deflection components. Because a finite gap is needed between the pin and its bushing, material extruded into the gap when rolling aluminum and its alloys, but it is claimed that valid results were obtained when hot-rolling steel. The attraction of this method is that it yields a complete set of information with

a single pin, but the original paper gives no indication of the difficulties that may be encountered with such instrumentation.

The technique developed by Pavlov and De-Yuan, reported by Veiler and Likhtman [20], could be regarded as a variant on the oblique pin technique. Closely fitting but freely sliding segments are built into the roll surface and are supported on needle bearings (Fig. 5.1j). Tangential forces developed on these elements are registered through the load cells M_1 and M_2. As the rolled strip passes through the rolls, the two movable elements experience opposing forces which become equal when the dividing line between the two elements falls onto the neutral line. The problem of elastic distortions of the measuring elements and possible binding must no doubt exist, and the friction values determined from the experiments are averages rather than point-to-point values.

In general, while the direct measurement of friction is attractive, the complexity of the equipment outweighs its advantages for lubricant evaluation. It is, however, an important tool for basic investigations into interface conditions.

5.23 Drawing

The geometry of the drawing operation resembles that of rolling; however, the moving force is supplied entirely by the draw force, thus limiting the number of measurable variables. Also, because there is sliding over the entire die surface, no externally measurable friction balance exists.

Derivation of Friction from Draw Force

Draw dies—whether for drawing round wire or flat, wide strip—are much more rigid than a rolling mill. The dimension of the drawn product, therefore, does not give a reliable measure of frictional conditions. At the very least, it is necessary to measure the absolute magnitude of the draw force (Fig. 5.2a). Accepting then the validity of a theory (Section 2.33) relating draw force to pass reduction, die angle, and coefficient of friction, the frictional value may be calculated. As in rolling, this method requires that the yield strength of the material over the range of reductions and speeds (strain rates) employed in drawing be known accurately. The situation is, nevertheless, more favorable than in rolling—particularly hot rolling—because strain-rate sensitivity is only moderate at room temperature and materials that are highly strain-rate sensitive are usually drawn at

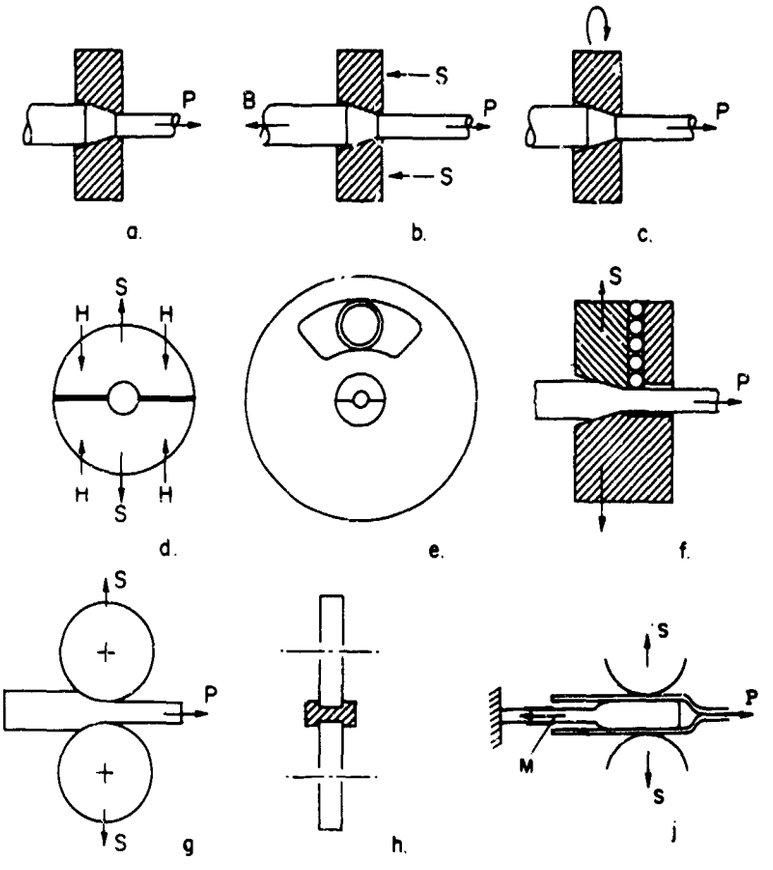

Fig. 5.2. Methods of measuring friction effects in wire drawing and in strip drawing.

low speeds. If the contribution of friction to the total draw force is small, a small error in the yield strength or the measured force may lead to a very large error in the calculated value of the coefficient of friction. On the other hand, it is also true that, under such circumstances, a very accurate knowledge of the friction coefficient is seldom needed.

The uncertainty introduced by the yield strength of the drawn material as one of the independent variables can be eliminated by a technique suggested by Lunt and MacLellan [21]. The method is based on the simultaneous measurement of back-pull B and draw force P (or, if more

convenient, the force S acting on the die support, where S = P - B) (Fig. 5.2b). Back-pull lowers the interface pressure between the die and the wire; however, if it is assumed that this drop does not change the lubricating mechanism and thus leaves friction unchanged, the effect of back-pull on draw force can be expressed from the theoretical analysis of Körber and Eichinger as

$$P = P_0 + B(A_2/A_1)^{1 + \mu \cot \alpha} \tag{5.12}$$

In this simplified expression P_0 represents the drawing force in the absence of back-pull. Thus, if experiments are conducted first without and then with gradually increasing back-pull, a number of experimental points may be obtained from which an average coefficient of friction can be derived using Eq. 5.12. Alternatively, if the reaction force on the die support S is measured, and for convenience a back-pull factor $b = (P_0 - S)/B$ is introduced (where $P_0 = S_0$), the coefficient of friction may be obtained from the following explicit relation:

$$\mu \cot \alpha = \frac{\ln(1 - b)}{\ln(1 - r)} - 1 \tag{5.13}$$

where r is the reduction from Eq. 2.23.

A number of methods have also been devised which permit the determination of the draw force with two states of friction. From the difference of the two a measure of the contribution of friction may be derived, eliminating the need of knowing the yield stress of the material.

One such special method applicable to wire drawing with axial symmetry was proposed by Linicus and Sachs [22]. The wire is drawn through a die; first with the die stationary, then with the die rotating at a speed of 0 to 15 rpm (Fig. 5.2c). Assuming that the lubrication mechanism is not affected by die rotation, the friction value may be derived from drawing stresses measured with and without die rotation, using formulae that take into account the change in direction of the frictional force component incurred by the rotation of the die. The method is somewhat limited by the torsion imposed upon the wire which may cause it to break, especially if the friction coefficient is high.

The contribution of friction may be measured in a plane-strain drawing device containing two rollers which may rotate freely or may be locked, in

an arrangement similar to Fig. 5.2g, with only P measured. The strip is pulled through the rolls in both conditions, using the same lubricant. The difference in the measured draw forces is usually reported as the frictional force or, according to Veiler and Likhtman [20], as the force F required to overcome the shear resistance τ_i on the material surface, over the die contact area A_f:

$$F = \tau_i A_f \tag{5.14}$$

Such techniques cannot, of course, claim absolute accuracy because the force measured with the freely rotating die is larger than the true minimum force required for plastic deformation and the differences in the inhomogeneity of deformation between rotating and fixed rollers are also neglected.

In principle, friction could be studied equally well in a plane-strain die set, with a strip of at least 10:1 width-to-thickness ratio serving as the workpiece, and flat-faced die halves enclosing the desired draw angle serving as the draw die. The distance between the die halves can be made variable, permitting the exploration of a range of reductions in the same die set. However, elastic deflection of the die halves and their supports could easily cause a major change in the die angle during drawing. Truly valid data will be obtained only if the die set is sturdily built, and the extra care involved in its construction may then justify a more comprehensive approach, allowing simultaneous measurement of normal and draw forces: this approach will be discussed in the next section. Alternatively, the die halves may be replaced with fixed rollers, which have the advantage that several areas of the cylindrical surface may be used before a redressing of the surface becomes necessary.

Simultaneous Draw and Normal Force Measurement

While the draw force may be measured in any convenient way, even at low speeds on a tensile testing machine, simultaneous draw force and normal force measurement requires more sophisticated instrumentation and equipment. Nevertheless, it offers a direct way of deriving the coefficient of friction.

The direct measurement of the normal forces in axial symmetry presents substantial problems. Strain gages affixed to the outer circumference of a die could, in principle, give a measure of the hoop stress, but nonuniform elastic distortion of the die is likely to give erroneous results,

even though Majors [23] and others reported success in the drawing of rather large diameter bars or tubes. Usually, the die is calibrated for hoop stress by applying hydraulic pressure to the inside of the die with the help of specially constructed closing plugs.

A direct measurement of radial forces would be more attractive. MacLellan [24] used a die split in an axial plane, and measured on a load cell the force separating the two halves. The technique was refined by Wistreich [25]. In experiments conducted by both researchers, the force holding the two die halves together was gradually reduced until the halves separated. The point of separation was judged from measurements by a dial gage; Wistreich also noted the break from an electrical circuit. At this point, the holding force H is equal to the die separating force S (Fig. 5.2d). From a simultaneous recording of the drawing force P, the coefficient of friction may be determined—for a straight tapering die—without resorting to a theory, as follows:

With a die of α half-angle (Fig. 2.7), the contact area between die and wire is $(A_1 - A_2)/\sin\alpha$. The draw force P is balanced by the axial component of the forces developed by the mean die pressure $\bar{p}$:

$$P = (A_1 - A_2)\,(1 + \mu \cot\alpha)\,\bar{p} \tag{5.15}$$

The die separating force S acts on the projection of the contact area and equals

$$S = \frac{1}{\pi}\,(A_1 - A_2)\,(\cot\alpha - \mu)\,\bar{p} \tag{5.16}$$

Combining the two equations,

$$\mu = \frac{\cot\alpha - \pi S/P}{(\cot\alpha)\ S/P + 1} \tag{5.17}$$

and

$$\bar{p} = \frac{\pi S}{(A_1 - A_2)\,(\cot\alpha - \mu)} \tag{5.18}$$

While the method is simple in principle, the preparation of the die set requires great care and skill, and opening of the die halves along the parting line under load is bound to cause lubricant leakage, thus upsetting the intended lubricating action and generating additional separating force. This objection is overcome by the split die of Yang [26] which is restrained in a

large ring. A small load cell is built into a window at a selected point of the circumference to measure the hoop strain in the large ring (Fig. 5.2e), giving a direct measure of the die separating force. This solution also relies on a repeatable elastic deformation pattern, which can be realized only if the drawn wire diameter is kept constant for any one die.

Plane-strain (strip) drawing offers a more practicable system because the two die halves can be separated and normal forces measured. It was first used by Sachs but only for light reductions, and it was not until recently that Pawelski developed it to a high degree of accuracy [27]. The moving die half is supported against a flat roller bearing (Fig. 5.2f), and the true draw angle is continuously monitored with an arm bearing on two linear differential transducers. Pawelski showed that, at least with very good lubricants, the error introduced by neglecting the changes in draw angle under load can be 30 times as much as the mean error in force measurements. With more typical, moderate friction coefficients and a mean error of 1% in force measurement, the friction coefficient would still be ±10% in error if the true die angle were not continuously monitored. Even though this die is of relatively complex construction, there is little doubt that it yields more reliable data than any other, more simple approaches previously reported.

A number of variations on the strip drawing test exist. One variant uses a device similar to a small rolling mill in which the rolls are clamped so that the strip is pulled (or pushed) through a cylindrical die entry zone. This approach has been pursued by, among others, Polakowski and Schmitt [28]. If draw (or push) forces and roll separating forces are simultaneously measured, the coefficient of friction can be calculated even though a large number of simplifying assumptions must be accepted. A simplified formula may be obtained if the metal between the rollers is regarded as a simple truncated wedge with an apex half-angle of α where

$$\tan \alpha = \Delta h / 2L \tag{5.19}$$

In calculating the contact arc L, elastic deformation is considered according to Hitchcock (Eq. 2.21). The coefficient of friction is then

$$\mu = \frac{S - 2P \tan \alpha}{2P + \tan \alpha} \tag{5.20}$$

Alternatively, the absolute value of drawing force P for various pass reductions may be plotted and the relative positions of the resulting curves taken as an indication of lubricant efficiency.

The simplicity of roller devices is appealing, and if plane-strain conditions are assured, measurements should be reasonably accurate. Unfortunately, plane-strain drawing does not necessarily simulate the lubricating conditions that exist in axial symmetry, because the open side-gap in plane strain allows escape of the lubricant.

One further advantage of plane-strain drawing should be noted. In wire drawing, the leading end of the wire must always be reduced in diameter by swaging, forging, roll forging, etching, or machining. In contrast, plane-strain (strip) drawing dies can be constructed so as to allow closing the dies under a predetermined force (e.g., by hydraulic or air operated cylinders), which then causes the dies to indent the strip prior to commencing drawing.

A variant of the strip drawing test was proposed by Wiegand and Kloos [29], who indented a strip with two fixed rollers, the width of which was two-thirds that of the strip (Fig. 5.2h). The undeformed, overhanging strip edges restrain deformation and limit the maximum reductions that may be taken, and must also complicate the stress system in the deformation zone. There is no obvious advantage of this method over the simple wedge drawing test.

Finally, the photoelastic method used by Cook and Wistreich [30] should be mentioned. Strips of lead alloyed with 3 and 5% tin were coated with a soap film and drawn through dies made of stress-sensitive plastics. Since friction at the die-wire interface causes the principal stresses to deviate from the direction normal to the surface (Fig. 2.7), the inclination of isoclinics can be used to estimate friction along the draw surface. Even though difficulties were experienced in locating isoclinics close to the interface, it was estimated that the coefficient of friction varied from approximately 0.05 at the die entry to 0.01 near the die exit. While the use of simulating materials makes the direct applicability of this technique limited, it is still the only known way by which friction variations along the die face have been determined. There is, of course, no reason why the oblique pin technique developed for rolling (Fig. 5.1h) should not be used also for drawing, but no record of such work could be found.

Friction in Tube Drawing

As discussed in Section 2.33, tube sinking is similar to wire drawing, with friction limited to the outer surface. Drawing on a mandrel (plug) causes the inner tube surface to slide over a stationary mandrel (plug); the draw force over the mandrel can be measured with a load cell. Drawing in plane-strain has the advantage that readily available strip material can be used. Lancaster and Rowe [31] studied friction effects with a die set composed of two fixed cylindrical dies and a parallel-sided plug, and measured the draw force P, the die-separating force S, and, with strain gages attached to the plug holder, the mandrel force M (Fig. 5.2j).

5.24 Extrusion

Plasticity theory has often regarded extrusion as an analog of wire drawing, except that the workpiece is pushed rather than pulled. In reality, the much steeper die angles result in a substantially different material flow, as discussed in Section 2.4. From the frictional point of view, there are other significant differences: in addition to die friction, container friction must be overcome, and the new surfaces exposed by large reductions must be protected.

Total Friction

Because of the great stiffness of an extrusion die, the dimension of the extruded product gives no clue as to the magnitude of forces; therefore, even the most rudimentary lubricant evaluation requires measurement of at least the ram force (total extrusion force, Fig. 2.14). The maximum force (breakthrough force) registered at the beginning of the stroke is representative of the transient situation that prevails before a steady-state lubrication is attained, while the minimum force observed towards the end of the stroke contains an indefinite mixture of container and die friction. Therefore, measurements of maximum and minimum extrusion forces can be used only for a semiquantitative ranking of lubricant quality.

Separation of Container Friction

From a continuous recording of extrusion force against the work stroke (Fig. 2.14) the forces P_1 and P_2 can be read for two well-identified ram positions ℓ_1 and ℓ_2 (Fig. 5.3a). Provided that there are no disturbing heating or cooling effects, the difference of these forces may be attributed to

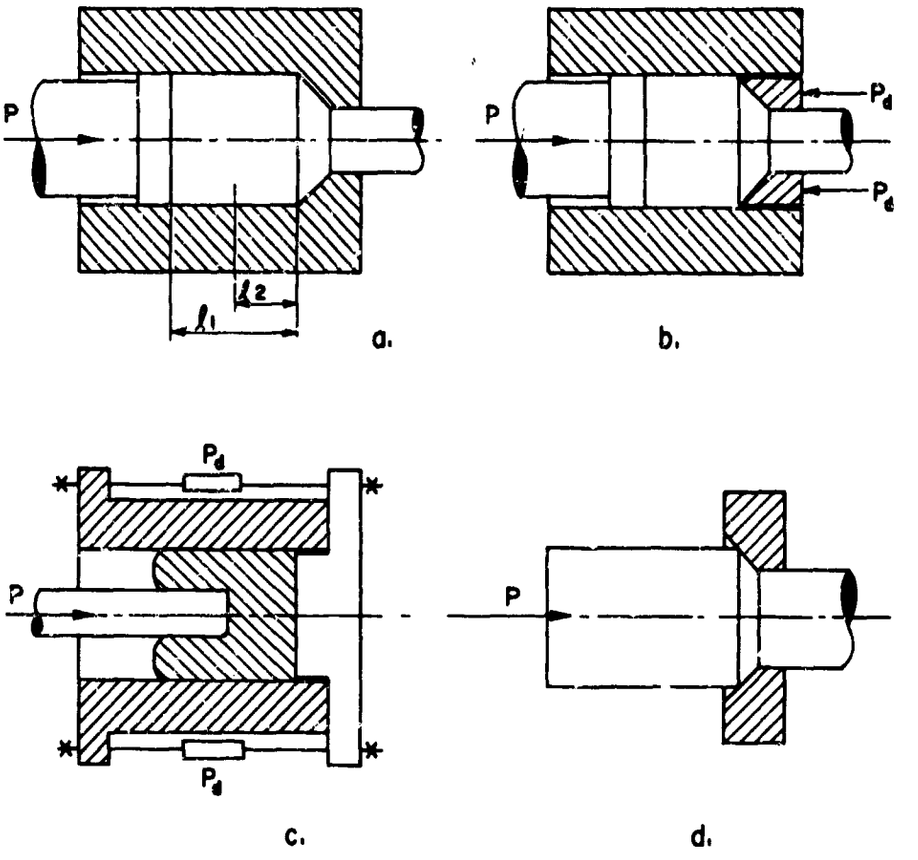

Fig. 5.3. Methods of measuring friction effects in extrusion.

friction on the container wall. A friction coefficient may be readily calculated from a substitution into Eq. 2.39.

$$\mu = \frac{D - d}{4(\ell_1 - \ell_2)} \ln \frac{P_1}{P_2} \approx \frac{0.575(D - d)}{\ell_1 - \ell_2} \log \frac{P_1}{P_2} \tag{5.21}$$

Since the interface pressure (radial pressure) always exceeds the yield strength of the material, such friction coefficients are meaningless unless pressures are defined as discussed in conjunction with Fig. 2.2.

Alternatively, an interface shear strength may be derived according to Eq. 2.40 and, if the lubricant is of a constant shear strength, this solution is preferable:

$$\tau_i = \frac{D - d}{4} \cdot \frac{P_1 - P_2}{\ell_1 - \ell_2} \tag{5.22}$$

The technique of measuring the pressure acting on two pins, one placed radially and the other at an angle to the container surface (an arrangement identical in principle to that discussed in conjunction with Fig. 5.1h), has been used by El-Behery et al. [32] for the direct determination of container friction in the room-temperature extrusion of lead. Difficulties inherent in this technique make its use doubtful for the more practical instances of hot extrusion from a heated container.

Separation of Die Friction

Separation of die friction calls for more sophisticated instrumentation. In addition to the ram force measurement, the forces acting on the extrusion die must be separately measured by supporting the die on a load cell (Fig. 5.3b). Perlmutter, DePierre, and Pierce [33] found that measurements are reproducible and that binding of the die in the container may be avoided if clearances are properly chosen (diametral clearance 0.001 in/in). In calibrating the equipment for the effect of friction between the die and the container, steel billets were machined to fit the contour of the dies and then pressures normally encountered in hot extrusion were applied. When a graphited grease lubricant was applied at the interface between die and container, the force due to friction at that interface rose linearly with applied extrusion pressure but never exceeded 20 tons at an applied load of 500 tons. These authors also indicate that direct recording of the total ram force from the hydraulic system causes erroneously high initial readings due to surges in the hydraulic system, and found it necessary to apply strain gages directly to the extrusion ram.

Once the die force is separated, a friction value may be derived using any one of the theoretical solutions linking friction, yield stress, and extrusion force. The problem is, of course, the same as in all calculations where an exact knowledge of the yield strength is needed and, at present, it is preferable to use the directly measured die forces without a further attempt at reducing them to friction values. This is particularly true of hot working where large variations in yield stress may be expected across the die face.

The force acting on the extrusion die can also be separated by measuring the forces in tie-rods (Fig. 5.3c). This configuration was chosen by Haddow and Chudobiak [34] for measuring the frictional drag generated by

the reverse flow of material in piercing experiments. As in all experiments with divided dies, great care must be taken to guard against the extrusion of a flash.

The similarity between extrusion and drawing offers an interesting possibility of establishing die friction without the complication of container friction. When a workpiece of sufficient stiffness is pushed through a die (as is done in push pointing on modern draw benches), the force essentially represents that of containerless extrusion (Fig. 5.3d), even though with a small reduction. In order to derive a coefficient of friction, one must again rely on theoretical formulas. However, any of the methods discussed for drawing (Section 5.23) may be used for a simultaneous measurement of axial and normal (radial) forces. A split die based on the same principle as used by MacLellan [24] in wire drawing was employed by Broscomb [35] for axial symmetry and the plane-strain technique by Polakowski and Schmitt [28]. Unfortunately, compressive instability of the workpiece limits reductions typically to below 25%, a very small value by extrusion standards.

Hydrostatic extrusion (Fig. 2.11f), in which the billet is completely surrounded by a fluid and wall friction is substantially eliminated, also allows a measurement of the die force, since the total force is now attributable to the die alone. However, the presence of a highly pressurized hydraulic fluid inevitably causes a marked change in the lubricating mechanism, and results from this technique cannot be transferred to conventional extrusion.

5.25 Forging

Some of the elementary forging operations, such as upsetting of a cylindrical specimen, appear very simple and sensitive to frictional conditions; therefore, they have been used extensively for frictional studies and lubricant evaluation. However, as we shall see, some of this simplicity is rather deceptive, and results must be viewed with reservations.

Upsetting of Cylinders

The dependence of upsetting force on interface friction offers a simple way of ranking lubricants. The force required to upset specimens of constant size to a predetermined height may be noted or, conversely, a constant force may be applied and the resulting deformation measured (Fig. 5.4a). These techniques are suitable for an overall ranking of lubricants. But since

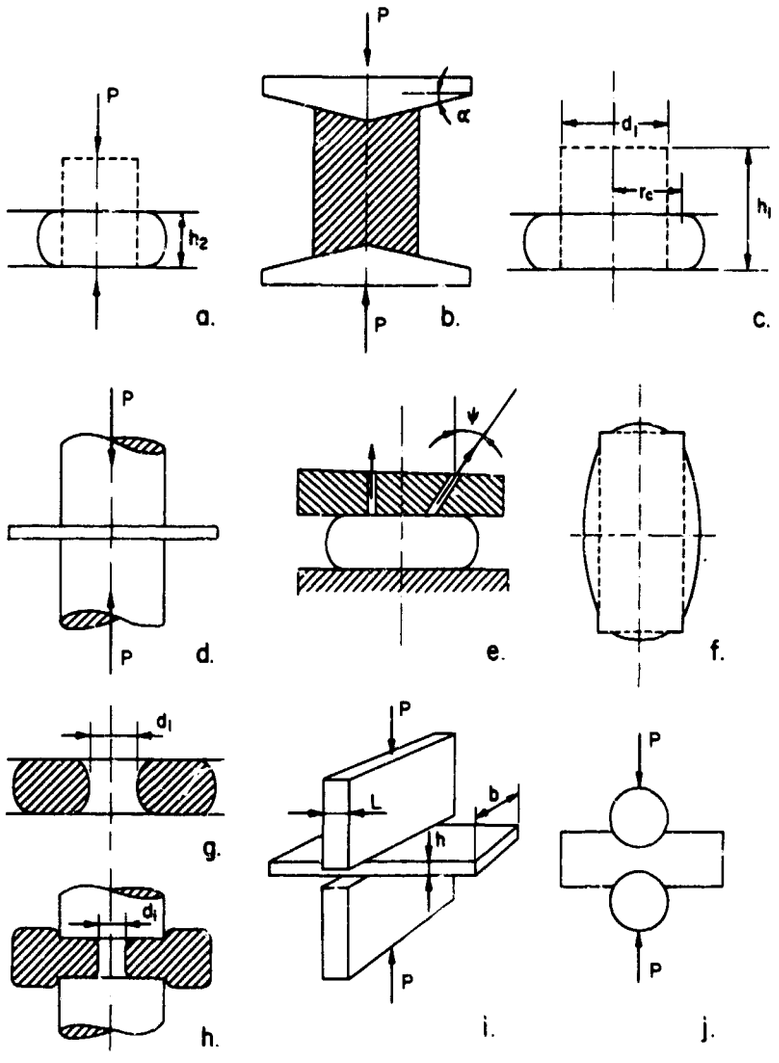

Fig. 5.4. Methods of measuring friction effects in upsetting and indenting.

friction is bound to vary from the center toward the edges and since partially sticking friction or complete sticking along with folding over of side surfaces is likely to occur, friction coefficients derived with the use of any of the theoretical formulas (e.g., from Fig. 2.20) are subject to suspicion. The validity of theoretical solutions is better for small deformations, but incremental upsetting would interfere with the natural development and breakdown of lubricant films and could, therefore, invalidate the test. In general, specimens with a relatively large diameter-to-height ratio (at least 4) are preferable so as to encourage expansion of the original end face even when

friction is high. These reservations apply even more to upsetting at elevated temperatures, since cooling at the interface restricts end face movement and indicates an apparently higher coefficient of friction. If a lubricant is used, the results may be indicative more of heat insulating than lubricating characteristics.

Siebel and Pomp [36] drew attention to the possibility of determining the coefficient of friction in cylindrical upsetting by using conical compression platens (Fig. 5.4b). At the die-workpiece interface, a component of the normal force, $P_2 = P_n \tan\alpha$, acts to move the material in a radial direction. This force is opposed by the frictional force $F = P_n\mu$. When the frictional force balances the radial upsetting force component ($P_2 = F$ or $\mu = \tan\alpha$) the cylinder deforms uniformly; when the frictional force is higher, barreling occurs; whereas if the radial force component of the upsetting force prevails, the end faces spread. Even though the method is accurate—at least if the absence of barreling can be correctly judged—a large number of precise specimens and dies must be prepared [37]. The artificial geometry could also severely interfere with the lubricating mechanism.

Earlier discussion has shown that with high values of friction, a zone of sticking develops in the center of the interface. The extent of the sticking zone may be found by applying a measured grid onto the end faces of cylinders with heights h_1 greater than their diameter d_1. After deformation, the radius of the edge of the sticking zone r_c is readily measured (Fig. 5.4c). According to Shutt [38], a mean coefficient may then be determined for the sliding zone from the following equation:

$$\ln \frac{1}{2\mu} + \frac{2\mu}{h_1}\left(r_c - \frac{d_1}{2}\right) = 0 \qquad (5.23)$$

Since this equation holds only at the moment of yielding, the coefficient of friction is underestimated unless the test is repeated at several reductions and the results are extrapolated to zero reduction. Such extrapolation does not pertain, of course, if the lubricating film changes during compression. The grid should be printed rather than engraved (otherwise, the trapped lubricant may falsify the results), and the surface topography must be very uniform.

The high interface pressures often obtained in practical metalworking processes may be reproduced on a small scale by upsetting cylinders of rather large diameter-to-height ratio. A variant of this technique has been developed by Rastegayev, quoted by Veiler and Likhtman [20]. A

disk-shaped specimen is compressed between anvils of somewhat smaller diameter; thus the area of contact remains constant and calculations are simplified (Fig. 5.4d). In this respect, the test is similar to plane-strain compression; however, the annular overhang of the workpiece material exerts a restraint on the deforming portion and raises the apparent resistance to deformation. The lubricant effectiveness may be judged from forces generated without and with the lubricant, and an order of merit can be established, but a coefficient of friction is difficult if not impossible to calculate. Therefore, plane-strain compression remains preferable to this method.

For theoretical purposes, the variation of friction (interface shear strength) from point to point is of interest and this has been accomplished by Van Rooyen and Backofen [39] with oblique pins similar to those described for rolling in Section 5.22. The principle of measurement is shown in Fig. 5.4e. Two pins are embedded into the surface of the compression platen at the same radial distance on the specimen. The measured pressure is composed of the normal pressure acting on the interface and of the frictional force between pin and platen. If the local coefficient of interface friction μ is defined as the friction-induced shear stress τ_i divided by the normal pressure prevailing at the same point and if friction between pin and platen is μ_o, the pressure acting on the normal pin may be expressed as

$$p_n = \sigma - \mu_o \mu \sigma \tag{5.24}$$

For the oblique pin, with μ smaller than tan ϕ

$$\frac{p_\phi}{\sigma} = 1 + \tan\phi\,(\mu - \mu_o) + \mu_o \mu \tag{5.25}$$

From these

$$\frac{p_\phi}{p_n} = \frac{1 + \tan\phi(\mu - \mu_o) + \mu_o \mu}{1 - \mu_o \mu} \tag{5.26}$$

from which the coefficient of friction may be derived if friction between pin and platen (bushing) is known.

Experiments conducted with this technique call for careful calibration. Possible binding or rotation of the pin in the platen and variations of pin-platen friction μ_o with lubricants penetrating into the clearance must be considered. Molybdenum disulfide applied in a resin carrier resulted in a remarkably constant and low friction in Van Rooyen and Backofen's

experiments. The clearance between the pin and the platen must be small enough to preclude penetration of specimen material into the gap, yet large enough to allow sliding of the pin without binding.

Upsetting of Slabs

From a consideration of stresses and displacements in the compression of a thin sheet between overhanging platens, Hill [40] concluded that the friction coefficient may be determined if the lamina is rectangular, its length at least 10 times its width, and its height similar to its width. Under these conditions, the only stress components are the compressive stress, the interface pressure, and the friction, allowing a simplified analysis of the problem. The width change is measured in the middle length of the specimen; the ends deform less, giving a characteristic cigar-shape (Fig. 5.4f). The analysis shows that the test is sensitive to very small friction values but becomes inoperable at higher friction, and the test has found little use.

The variation of interface shear stresses along the width of a compressed, rectangular workpiece was measured by Tarnovskii et al. [41], who utilized a technique similar to that shown in Fig. 5.1j. A divided platen was sandwiched between two identical workpieces, which were then compressed between two overhanging platens. The separating force acting on the divided central platen was measured on load cells; this indicated the net frictional forces at a selected point of the interface. From a simultaneous measurement of the local interface pressure with a pin embedded in the outer platens, friction coefficients could also be determined.

Ring Upsetting

This technique was originally developed by Kunogi [42] for cold working and was later adapted by Male and Cockcroft [43] for hot working. Since the position of the neutral zone is a function of friction, there is no need to measure forces—it is sufficient to measure only the changes in internal diameter (Fig. 5.4g). If the specimen geometry is kept constant and the reduction can be exactly reproduced, no other variable needs to be considered. This simple procedure allows a ranking of lubricants.

As soon as a quantitative value of the coefficient of friction is sought, one of the theoretical treatments of the position of the neutral plane must be adopted (Section 2.52). Alternatively, the indirect method employed by Male and Cockcroft [43] may be followed. They compressed both rings and

cylinders under identical lubricating conditions, and calculated friction from the cylinder upsetting experiments using Schroeder and Webster's formula (Fig. 2.20). These friction values were then plotted against the changes in internal diameter of the ring and were used as a calibration (Fig. 5.5). Such procedure allows comparison of data obtained at different reductions, provided that lubricant breakdown does not occur.

Results obtained by various authors are directly comparable as long as relative specimen geometry is identical. In most past work, the inside diameter equaled half the outside diameter, while the height was one-third of the outside diameter.

Some uncertainty enters into the evaluation when high friction causes severe barreling in the hole surface. The minimum diameter essentially represents the consequences of inhomogeneous deformation, the diameter

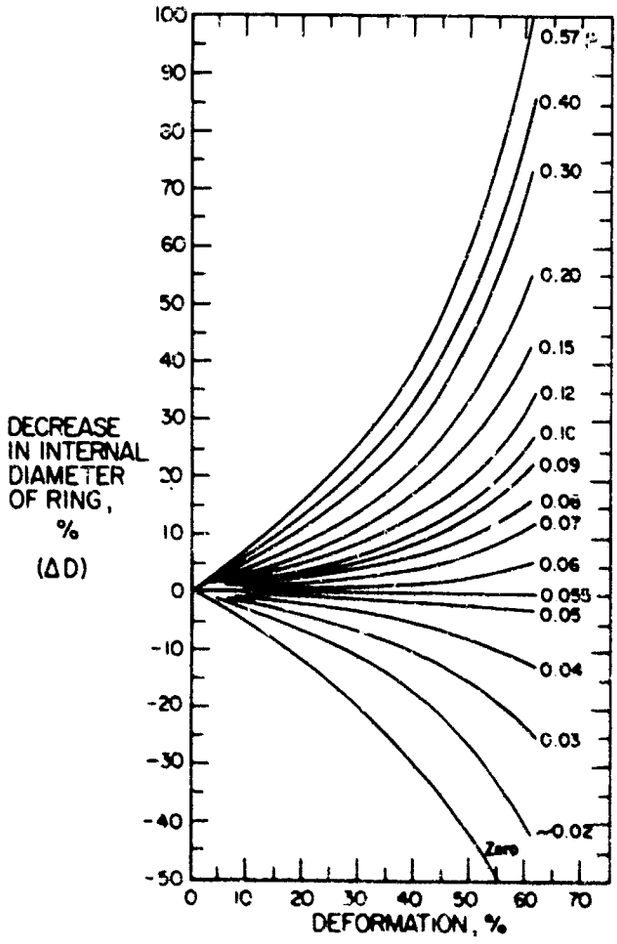

Fig. 5.5. Calibration curves for the decrease in internal diameter of standard rings (outside diameter: inside diameter: height = 6:3:2) [43].

measured at the surface is more typical of interface sliding, while an average diameter, calculated according to a suggestion made by Burgdorf [44] on the assumption that the deformed surface is parabolic, represents a compromise. For most purposes, the minimum inner diameter seems to serve well. Further complications arise when friction changes during the course of compression, as discussed by Burgdorf and others.

A variant of the ring compression test is described by Veiler and Likhtman [20] in which the specimen is upset between two punches, the diameter of which is smaller than the OD of the specimen but larger than the hole (Fig. 5.4h). Lubricant efficiency is again judged from the increase of the bore, but it would appear that the restraint provided by the overhanging, elastically strained material must interfere with evaluation; the test offers no visible benefit over the more generally accepted ring compression test.

Plane-Strain Compression

Plane-strain compression (Fig. 5.4i), originally developed by Watts and Ford [45] for the accurate determination of the compressive yield strength of materials, has been repeatedly applied for the measurement of friction. As discussed in Section 2.53, a coefficient of friction can be determined from measured compression pressures (Fig. 2.22). Most experimental work has been conducted along one of two different lines.

First, a qualitative rating of lubricants may be obtained by presetting the compressing force and measuring the issuing thickness or, conversely, by compressing to a preset thickness and measuring the maximum force developed. If a coefficient of friction is to be derived, the plane-strain yield strength of the material needs to be known to a great accuracy. This may be achieved by plane-strain indentation with a lubricant that gives close to zero friction and, preferably, with the technique of incremental deformation, in which the surfaces are relubricated after small (2 to 5%) compressive increments. To assure plane strain, the strip width b should be at least 6-10 times the thickness h. Also, for the measurement of yield stress, the L/h ratio should be kept between 2 and 4. If the test is then repeated with the lubricant to be investigated, the coefficient of friction may be derived, for example, from Fig. 2.20b. The determination of μ becomes less accurate as L/h becomes smaller and, in common with most forging experiments, sensitivity is lost when the coefficient of friction is greater than 0.2. The yield strength of the material need not be known if the test is repeated with a

constant reduction in height and with the same lubricant at two L/h ratios, because μ can then be taken directly from Fig. 2.22b.

The technique described by Kravcenko [46] may be regarded as a modification of the plane-strain indentation technique. A thick specimen is indented by two cylindrical anvils (Fig. 5.4j); since the indentation force is dependent on penetration, a constant penetration is standardized. From a slip-line field solution, the coefficient of friction may be determined if the indentation stress for zero friction is known. In practice, it is easier to determine the indentation stress in sticking friction with a roughened indenter. Repeating the test with a smooth indenter and the experimental lubricant, the indentation pressure is determined and a coefficient of friction may be obtained. It is not clear whether this test has any advantages over plane-strain compression; deformation and the generation of new surfaces is rather limited, and friction conditions are unlike most of those prevailing in practical deformation processes. Nevertheless, an essentially similar test using constant load instead of a constant indentation has been found useful for a fast and simple ranking of lubricants, particularly at elevated temperatures [47].

A variant of this test, developed by Tamura and Kudo, and also reported by Kudo [48] in a review article, employs two wedges of, say, 30° included angle. The force developed during penetration may be calculated from slip-line field theory, and the test seems to retain sufficient sensitivity even for higher friction values.

Technological Tests

Even though the effect of friction in aiding die filling in impression (closed) die forging is little understood, methods of evaluating lubricants are still required.

In order to avoid at least some of the complexities of closed die forging, a simple workpiece geometry is attractive. Shaw, Boulger, and Lorig [49] measured the height of a rib formed in a trapped die (Fig. 5.6a) with various lubricants at identical forces. The geometry resembles somewhat that of extrusion and, since no flash is formed, the balance between friction in the flash and in the die cavity is not established. Also, a fin extruded between punch and die could confuse the results. Such a test is, however, useful for simulating trapped die forging.

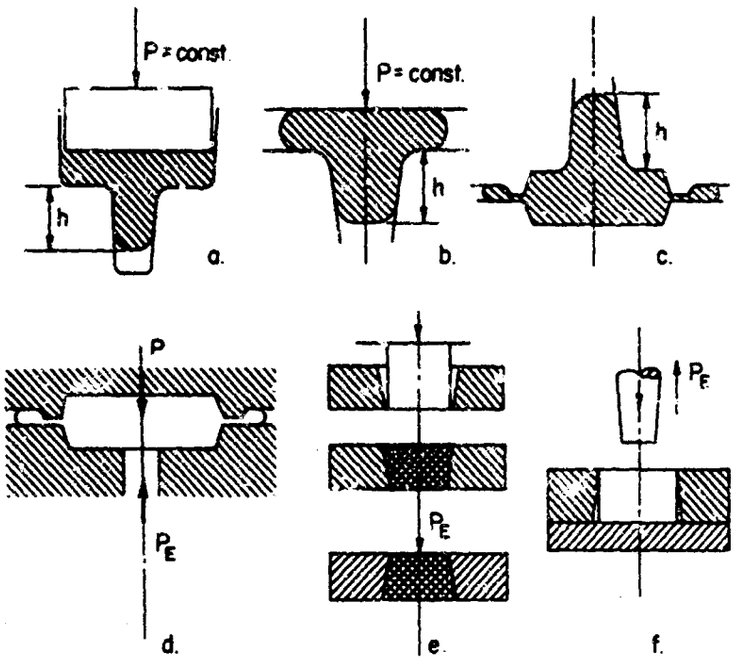

Fig. 5.6. Methods of measuring friction effects in impression (closed) die forging.

It could be assumed that high friction would be desirable in the flash gutter and low friction in the die. Conditions approaching such practical closed die forging may be obtained with a simplified specimen of axial symmetry; if the workpiece is unsupported on its sides, the depth to which the material penetrates in the open-ended cavity may be regarded as a measure of the ease of die filling. It should be noted, however, that greater penetration means less material available for upsetting (Fig. 5.6b), and it may be argued that this introduces an uncontrolled variable into the test. The depth of die filling is, obviously, a function of friction on the die wall, of the geometry chosen, and of reduction in area and strain hardening of the unsupported section of the billet. The test may allow a qualitative ranking of lubricants if one and the same billet material is used, but materials of different strain-hardening characteristics cannot be directly compared.

More satisfactory is the arrangement where a cylindrical test piece is forged in an impression die containing a central hole (Fig. 5.6c). The height h of the boss formed in this hole is then a measure of friction. It should be recognized, though, that the height of the boss will increase not only with decreasing friction on the wall of the die, but also with increasing

friction in the flash gutter, since this will retain more material in the die cavity. However, this is a desirable situation in practical closed-die forging operations; therefore, while the test is by no means readily analyzed, it is acceptable as a scaled-down version of real forging, and has taken a prominent place in German work (e.g., Stöter [50]).

Frictional effects may also be evaluated from the measurement of the total force required to forge a given (usually simplified, axially symmetrical) shape (Fig. 5.6d). This technique was used by Tolkien [51] who forged a flat disk, somewhat similar to a gear blank, and thus achieved die filling mostly by spread over the end faces. The total forging force P was therefore regarded as an indication of sliding friction. The force P_E required to eject the workpiece was taken as a measure of sticking in the die.

Sticking friction is of great importance in that easy removal of the workpiece from the die cavity is a prerequisite of a smooth production flow. Forces required for ejecting a forged workpiece from the die cavity reflect friction and adhesion between die and workpiece after conformity between the two surfaces has been achieved through plastic deformation. Several techniques have been proposed for simulating this effect. The one due to Sakharov, and quoted by Veiler and Likhtman [20], utilizes a ring die with a conical hole (Fig. 5.6e). A cylindrical billet is upset forged to fill the hole and then, after turning the die over, the forged plug is ejected. The force P_E required for ejection is taken as an indication of the efficiency of the lubricant to prevent seizure and facilitate workpiece removal. Breznyak and Wallace [52] used a conical punch coated with the experimental lubricant for penetrating the workpiece material to a predetermined depth (Fig. 5.6f). The force required to extract the punch after a specified holding time (5 sec) was taken as a measure of sticking friction.

The pressure generated by gaseous components of the forging lubricant is of special importance because, if properly controlled, it aids the removal of the forging from the die. On the other hand, excessive pressures may prevent complete filling of deep-seated portions of die cavities that are closed by the flow of material in early stages of deformation. Tolkien [51] built a special die in which the pressure developed in the cavity was measured with a suitable pressure transducer, connected with the cavity through a small hole.

5.26 Sheet Metalworking

Of the great number of practical sheet metalworking techniques, only deep drawing has been extensively investigated, and techniques for measuring friction are usually aimed toward this application. Lubrication may assume considerable importance also in shearing, blanking, and punching, but measurement of die wear, tool pickup and, rather infrequently, blanking force must be carried out under actual or simulated production conditions, since the cumulative effect of repeated encounter is the only useful index of lubricant quality. Other sheet metalworking operations, such as bending and stretch drawing, involve mostly elastic contact between the die and workpiece, and lubricant evaluation may be satisfactorily performed with tests involving elastic contact (Section 5.27). Discussion in this section will be limited to deep drawing operations.

Cupping

The first operation in forming a sheet metal body is usually that of drawing without intentional thinning of the walls (Fig. 2.23a and b). The bottom of the vessel may be flat or curved. In either case, the frictional conditions are extremely complex, and no meaningful average coefficient of friction may be derived (Section 2.63). The only useful purpose of lubricant evaluation is that of assigning an order of merit. This can be obtained by drawing a predetermined cup geometry from circles of constant diameter, and measuring the maximum force developed during the draw (Fig. 5.7a). Alternatively, circles of gradually increasing diameter may be drawn and the maximum drawable diameter D_{max} or, preferably, its relation to punch diameter D_{max}/d (limiting drawing ratio) taken as a measure of lubricant quality. For adequate distinction between lubricants of similar performance, the circle diameters must increase in small increments; in addition, a number (usually a minimum of five) circles of identical diameter should be drawn in order to eliminate accidental variables and establish a characteristic process condition. These requirements demand a rather large number of circles for each lubricant when the limiting draw ratio is used as a means of evaluation.

A die set with complex instrumentation, developed by Kawai et al. [53] permits simultaneous recording of punch force P, blankholder force P_B, punch travel, and—by splitting the blankholder into two halves and measuring

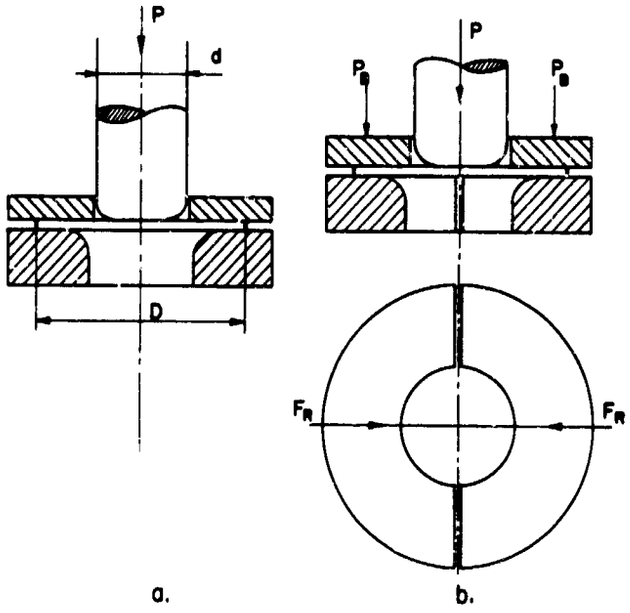

Fig. 5.7. Methods of measuring friction effects in deep drawing with a blankholder.

the forces acting on them—also the frictional force on the blankholder surface F_R (Fig. 5.7b). This technique appears to be especially valuable since it allows separation of blankholder friction from die and punch friction under realistic conditions.

Ironing

Friction conditions are substantially different and, in some respects, less complex when a drawn cup wall is further reduced by ironing (Fig. 2.23d). Measurement of the total force is again a convenient means of ranking lubricants. If so desired, a coefficient of friction may be derived from an appropriate formula; however, the validity of such procedure is highly questionable because it is unlikely that the same friction conditions pertain to the outside and inside cup surfaces (consider Eq. 2.33). The similarity of ironing to drawing on a bar has been pointed out (Section 5.23). Both processes are characterized by the punch or bar moving together with the cup or tube. Separation of friction on the outer and inner interfaces then calls for rather complex instrumentation which is often more easily accomplished for plane-strain conditions.

Drawing in Plane-Strain

Various means have been devised to obtain direct friction measurements and, at the same time, to simplify the experiments. Typically, the cup of axial symmetry is replaced with a strip, thereby reducing the problem to that of plane strain.

In the simplest form, sheet metalworking lubricants are rated by drawing a strip between two flat die surfaces. Even though this simulates to some extent the conditions existing between the blankholder and die surface, contact is essentially elastic; therefore, this test will be discussed in more detail in Section 5.27. In a modified form due to Sachs [54], friction is measured with concurrent plastic deformation, by cutting a specimen with a wedge-shaped portion which is then drawn through a draw die (Fig. 5.8a) consisting of two flat grips (brake blocks) and two draw die surfaces defining a small included angle 2α. In measuring the forces separating the draw die halves, great care must be taken that bending moments do not contribute to

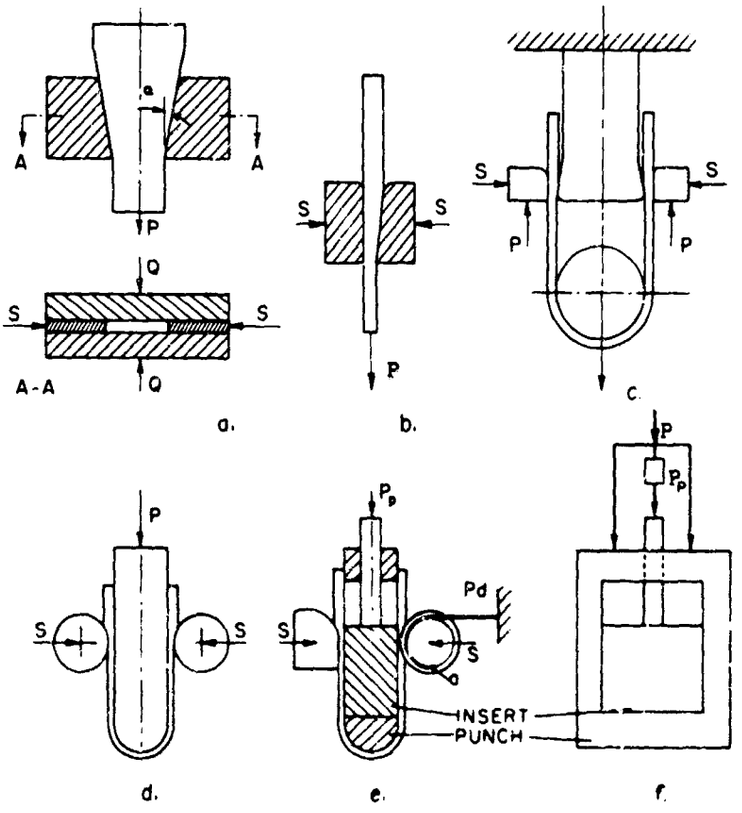

Fig. 5.8. Methods of measuring friction effects in plane-strain tests designed to simulate ironing.

the measured normal force Q. The response of a lubricant to gradually increasing forces is readily measured during the drawing of the same strip by increasing the normal forces on the parallel (brake-block) surfaces in a stepwise fashion. This test approaches deep drawing closer because it provides some of the lateral compression typical of the deformation of the partly deformed flange. It appears though from experiments by Panknin and Reihle [55] that the slight additional plastic deformation does not affect the ranking of lubricants.

When the purpose is to simulate ironing, it should be borne in mind that the drawn cup is reduced from only one side; it is in contact with a flat (cylindrical) surface on the other (punch) side. Therefore, the wedge drawing test used for the evaluation of drawing lubricants (Fig. 5.2f) is not suitable for simulation. Instead, the die set must be composed of a flat and an angled surface (Fig. 5.8b). An approximate coefficient of friction may be derived, at least for small die angles, simply from the ratio of the pull (frictional) force P to die separating force, $\mu = P/2S$. The hidden assumption in this test is, of course, that friction is the same on the parallel and the angled die surfaces. This assumption is seldom valid. A further point, apparently seldom recognized, is that the strip slides on both the flat and the angled die face at the same speed, whereas in ironing it would choose its own speed over the punch. This test then is really more relevant to drawing a tube over a mandrel; for this situation, however, the arrangement shown in Fig. 5.2j is preferable.

An improved version of the test has been developed by Fukui et al. [56]. A bent strip is drawn by a push pin through a pair of dies composed of an inner die, which bears the inclined draw surfaces, and two flat outer dies (Fig. 5.8c). The die separating force S and the draw force P are measured independently and, therefore, $\mu = P/S$. The experimental arrangement assures that there will be no interaction due to bending moments. It will be recognized that this test is a variant of that shown in Fig. 5.2j and is, basically, more suitable for the simulation of drawing a tube on a stationary mandrel.

In ironing, material flow on the outer and inner surfaces may be substantially different, and sliding velocities may be lower on the cylindrical punch than on the surface of the conical draw die. Therefore, tests that allow the material to select its natural flow pattern may provide better

approximation to such metalworking processes; they can then give a realistic appraisal of improvements due to differential friction (usually higher on the punch).

One such device proposed by Veiler et al. [20] consists of a flexible frame dynamometer which contains two cylindrical, freely rotating dies. The strip specimen is bent around a round-edge flat punch and is pushed through the rollers (Fig. 5.8d). The coefficient of friction over the punch is then approximately given by $\mu = P/2S$. The amount of reduction is controlled by the size of the punch or, with a constant punch size, by setting the distance of the rollers. Alternatively, a flat plate of the punch material may be sandwiched between two sheets and the assembly drawn through the die.

A modification of the same principle was undertaken with the aim of separating friction between the workpiece and the die (μ_d) and between metal and punch (μ_p). Of the two cylindrical dies, one is fixed, the other is allowed to rotate freely (Fig. 5.8e). The frictional force P_d developed on the rotating die (corresponding to the draw die) is transmitted by a flexible band to a dynamometer. The punch itself is specially constructed (Fig. 5.8f). A well-fitting, but freely moving insert is fitted in a window (cut-out) of the punch, and the frictional forces P_p developed on the side surfaces of this insert are transmitted through a pressure pin to a dynamometer or load cell. In order to avoid the disturbing effects of material extruded in a gap between the punch and the insert, the specimen is first partially deformed with a solid punch, then the special punch is put in place and the draw is completed. This device is amenable to various modifications, so that it can be adapted to simulate a number of operations. It is important that the frictional losses in the bearings of the rotating die be determined and used as a correction factor in all experiments. Such calibration may be conducted, for example, by attaching a flexible steel band to the roller die at the point a where the dynamometer band is attached, and applying increasing forces in the drawing direction. The difference between the applied force and the dynamometer indication is the loss due to bearing friction. This device permits the measurement of friction between the workpiece and the die ($\mu_d = P_d/2S$) and between the metal and the punch ($\mu_p = P_p/2S$).

5.27 Simulating Tests

Because of the complexity and cost of experimentation with actual deformation processes, simple simulating tests have always been desired which would, ideally, yield results applicable to all metalworking processes. A great number of such tests have been designed, and those resulting in substantial plastic deformation of the workpiece material are undoubtedly closer to metalworking practice. Even though a friction coefficient is usually calculated, many of these tests are more useful for the study of adhesion, material transfer, and wear.

Tests with Partially Plastic Contact

One of the most widely used test methods employs a pin riding over a flat surface, such as a table or disk. While a flat-ended pin (Fig. 5.10a) establishes essentially elastic contact and provides an ostensibly constant contact area, the slightest cocking of the pin due to elastic deflection of the supporting members is bound to cause highly localized contact and plowing.

Much more suitable is a pin with a hemispherical end (Fig. 5.9a), which may be allowed to penetrate rather deeply into the specimen surface without basically altering contact conditions. The mode of deformation is somewhat between plastic deformation and metal cutting, since a buildup

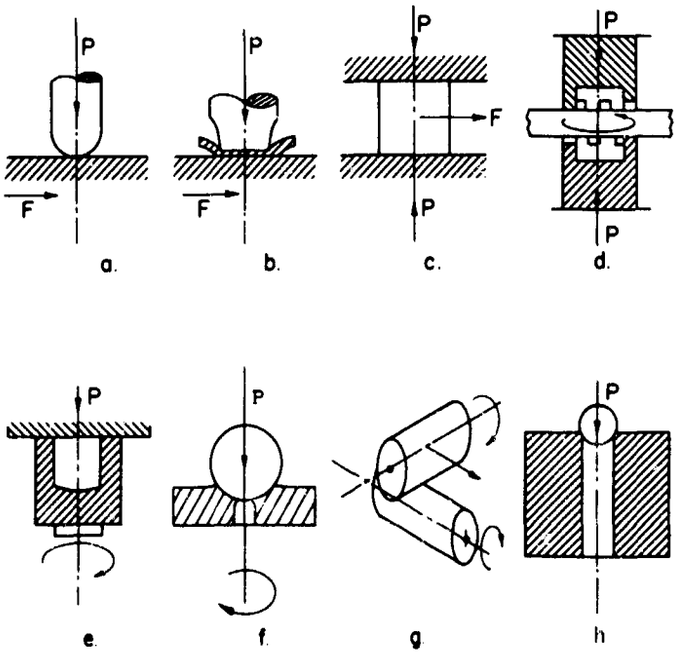

Fig. 5.9. Methods of measuring friction and wear with localized plastic deformation of surfaces.

of metal in front of the rider is unavoidable, at least in small numbers of passes. Repeated contact, typical of many practical deformation processes, can be simulated by repeated traverses, but only if interface pressures are kept low enough to avoid deep plowing of the surface. The maximum stress that may be applied is essentially determined by the indentation hardness (approximately $3\sigma_0$) of the specimen. Simultaneous measurement and recording of normal and lateral forces is relatively simple, but sturdy construction is essential if stick-slip is to be avoided, although the onset of stick-slip in a particular test setup is also an indication of lubricant quality (a partial review of the subject has been given by Barwell [57]).

Most difficulties of construction are avoided when the rider is made to rest on three balls. This maintains automatic uniform distribution of the load, and assures smooth movement of the rider over the surface. Such a simple technique has been used apparently successfully by Smith [58] for investigating the effect of viscosity and temperature on static and sliding friction. The rider resting on the three nonrotating balls was moved simply by gradually increasing the inclination of the flat test surface. A similar arrangement, but with the rider drawn by a rope, pulley, and weight was used by Hinsley et al. [59] for investigations into the high-temperature friction properties of oxidized metal surfaces.

A modification of the pin-on-disk principle by Peterson and Ling [60] aims at generating high interface pressures. A thin (0.04 in. thick) sheet of metal representing the workpiece is compressed between a flat anvil and a 1/6 in. diameter punch (Fig. 5.9b). On applying the normal force, material is extruded from between the dies. The remaining thickness is a function of the material properties, the applied load, and friction. By its large diameter-to-thickness ratio, the sheet is able to support a multiple of the uniaxial yield stress of the specimen material. The punch is then moved sideways, and from the measured lateral and normal forces a mean coefficient of friction is determined. The simplicity of the test is attractive; however, it appears that only short traversing distances are practical, the pressure distribution is uncertain, and the temperature range is limited by the need of heating the whole equipment to a common temperature. Elastic deflections and consequent cocking of the pin might also cause problems.

A much more satisfactory specimen geometry is obtained if the die material is used to form a flat deforming surface and the workpiece is compressed and laterally moved at the same time.

In the method suggested by Pavlov and Kostychev and reported also by Veiler and Likhtman [20], a cylindrical specimen is upset between two parallel flat platens and, at the same time, moved perpendicular to the direction of upsetting by a special screw mechanism (Fig. 5.9c). Since the lateral (frictional) force is distributed over the two end faces, the average coefficient of friction $\mu = F/2P$.

In the method developed by Orowan and Los [61], a flat anvil is loaded from both sides in a compression testing machine by two specimens (Fig. 5.9d). The specimens have an annular surface of a mean radius r and are slotted (castellated) so that three segments of the annulus contact the anvil surface. The anvil is then slowly rotated by hand, the force F being applied through a spring scale attached to a lever of arm a. The coefficient of friction is found from

$$\mu = \frac{Fa}{2Pr} \tag{5.27}$$

Normal stresses in excess of the tensile strength of the material are readily supported, elastic distortions have little effect on the geometry of the interface, and the effect of prolonged sliding can be investigated if a suitable drive is devised. This was accomplished by a number of investigators who studied adhesion under elastic load conditions, and by Schey [62] for frictional studies at interface pressures in the plastic deformation range. Local binding of surfaces may cause very high deflecting forces; therefore, the construction must be extremely sturdy. Great care must be taken to separate the torque T (frictional force $F = T/r$) and the normal force P in the sensing system, and to eliminate interaction that could falsify results. With these precautions, it is possible to measure friction over a wide range of values. The coefficient of friction is: $\mu = T/Pr$. For heavy deformations it is desirable that the specimen should have an uninterrupted annular surface (Fig. 5.9e). The technique offers a method of quick appraisal for surface damage and material transfer, and the shape of the deformed specimen also provides a direct clue to the magnitude of the frictional forces. With low friction, the specimen upsets uniformly. When friction is high, twisting of the specimen is observable from surface markings, and the combination

of normal and high frictional forces causes rapid yielding and a collapsing of the specimen in a combined compressive and shear stress system. The method used by Shaw et al. [63] is a variant of twist-compression in that a steel ball is rotated against the predrilled workpiece material (Fig. 5.9f).

A crossed cylinder technique (Fig. 5.9g) with loads high enough to cause at least some plastic yielding has been also used repeatedly for lubricant evaluation. A cylinder, representing the workpiece material, is rotated while another cylinder, representative of the die material, is moved gradually across the length of the rotating cylinder so that a helical path is described [64]. The torque required to rotate the cylinder is taken as a measure of friction, or a coefficient of friction is calculated from the normal force and torque.

A lubricant evaluation method based on partially elastic contact has been described by Veiler and Likhtman [65]. A hardened steel ball is forced through the hole of a container (Fig. 5.9h). After a number of passes (4 to 6 with lubricants and 12 to 14 without a lubricant) the force required to push the ball through becomes constant, indicating that purely elastic contact is maintained. The cylindrical container may be made of any workpiece material. The maximum forces recorded in pushing the ball through the hole may be plotted against the number of passes to show the efficiency of the lubricant in reducing friction and preventing galling and seizure.

Tests with Elastic Contact

Simulating tests in which plastic deformation of the specimen is completely avoided are one step further removed from metalworking operations. They have some obvious justification for simulating deformation processes where plastic deformation is limited; for example, they may be used for simulating the conditions existing in the blankholder area in a deep drawing operation.

The difficulties associated with a flat pin riding on a flat surface (Fig. 5.10a) have already been discussed, and the test is seldom used for lubricant evaluation. The strip drawing test, first used by Sachs [54] and further developed by Wojtowicz [66], is much more suitable for simulation of metalworking. The strip is drawn between two opposing flat die surfaces that are wider than the strip (Fig. 5.10b), and the coefficient of friction is simply obtained as a quotient of draw force F and normal force P: $\mu = F/2P$.

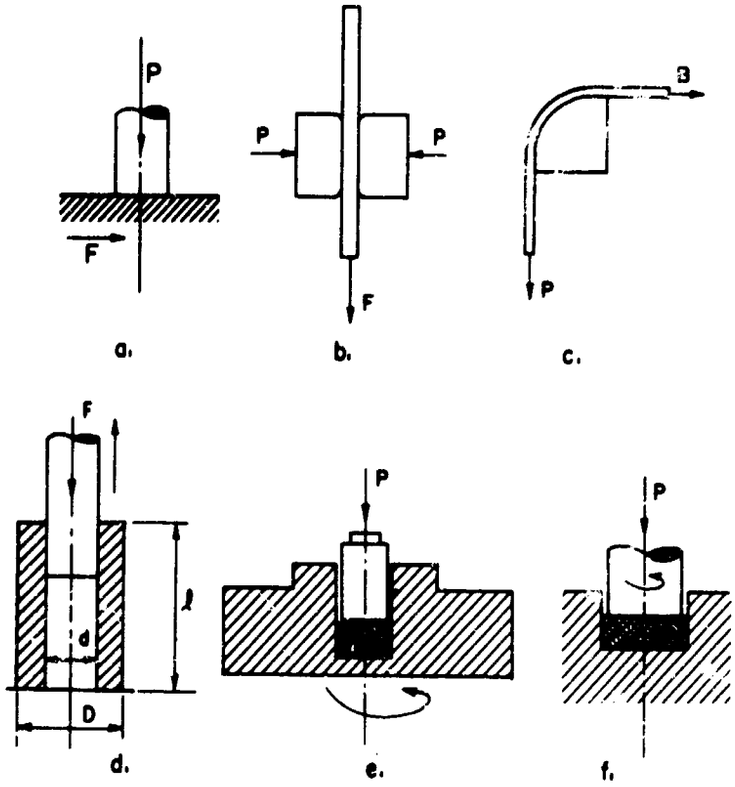

Fig. 5.10. Methods of measuring friction and wear with elastic deformation of surfaces (a-d) and with the test material in a confined space (e, f).

On the premise that deep drawing involves sliding as well as bending, Littlewood and Wallace [67] described a test where a strip is drawn by a force P over a quadrant die against a back tension B (Fig. 5.10c). The construction of the die permits the variation of the angle of contact over the forming die, and the test should be a fairly faithful simulation of conditions around the draw radius of a deep drawing die.

Purely elastic contact is used in the press-fit test described by Sonntag [68]. An oversized pin is driven by a hydraulic piston into a bushing, while the pressing force is measured by a hydraulic pressure gage (Fig. 5.10d). Expansion of the bushing gives rise to an interface pressure or normal load P. The coefficient of friction is found by dividing the force required to overcome friction (F) by the normal load (P). The normal load is determined from the following relationship:

$$P = \pi p l d \qquad (5.28)$$

where d = bushing ID and ℓ = length of bushing, and p, the pressure between the surfaces, is calculated according to Timoshenko from:

$$p = \frac{E\delta(D^2 - d^2)}{2D^2 d} \tag{5.29}$$

where E = elastic modulus of bushing material; D = original OD of bushing; δ = interference. The test was originally designed to evaluate lubricants and interferences for press-fitting machine components, and has been subsequently advocated for general lubricant evaluation.

A variant of the twist-compression test was used by Haverstraw [69] for screening hot extrusion lubricants. A 100 lb flywheel was brought up to 1400 rpm, the drive was disengaged, and a die steel representing the tooling and preheated to 427°C was dropped in a hole in the center of the flywheel (Fig. 5.10e). The lubricant was then applied to the die, and a preheated billet of the workpiece material was placed in a holder on top of the die. The two die halves were then brought together. The time taken for stopping the flywheel was regarded as a measure of the ability of the lubricant to reduce friction, and inspection of the surfaces after the test revealed evidence of scoring. The change of the angular velocity with time against pressure was plotted, and the slope of this curve was taken to be representative of the (average) coefficient of friction. Because deformation of the specimen interferes with free rotation, stresses must be kept below the yield strength of the softer material and new surfaces are not generated. Furthermore, continuous deceleration prevents the development of representative conditions. Therefore, the relevance of this test for the simulation of metalworking processes is doubtful.

Several attempts have been made to devise a laboratory test in which the normal pressure may be increased so as to explore friction over a wide range of interface pressures without introducing difficulties of interpretation arising from bulk plastic flow. Ideally, a twist-compression test in which the workpiece material is confined could provide a solution, and Peterson et al. [70] and Lauterbach et al. [71] have made use of such test geometry (Fig. 5.10f). While the test is appealing in its apparent simplicity, certain features are dubious. One cannot but wonder whether the fin of metal that is bound to extrude in the gap between the rotating punch and the stationary container does not affect the accuracy of measurements. Construction of the

test equipment presents obvious problems, calibration for any disturbing secondary friction surfaces is difficult, and sliding velocities change along the radius.

Many bench-type test machines developed primarily for general friction and wear studies have also been used for metalworking lubricants. Those most generally employed are shown in Fig. 5.11 [72, 73]. Contact is established over a cylindrical surface in the Almen machine (a) in which a bar is rotated in a split bushing pressed against it. Load is increased at 10-sec intervals until the initiation of scoring. The Timken machine (b) is typical of those employing line contact; a steel block is pressed against a rotating cylindrical steel ring for a period of 10 minutes. The highest pressure under which no scoring occurs is recorded. Line contact is combined with rolling in the SAE machine and the somewhat similar Amsler tester (c); two disks are driven independently at different speeds and are pressed at increasing load until failure occurs. The motion provides a combination of rolling and sliding friction which can be varied by changing the relative speed of the two rollers. Line contact is typical also of the Falex machine (d), in which a bar is rotated between two hard V-shaped bearing blocks, which are pressed against the bar with automatically increasing pressure. Wear occurs mainly

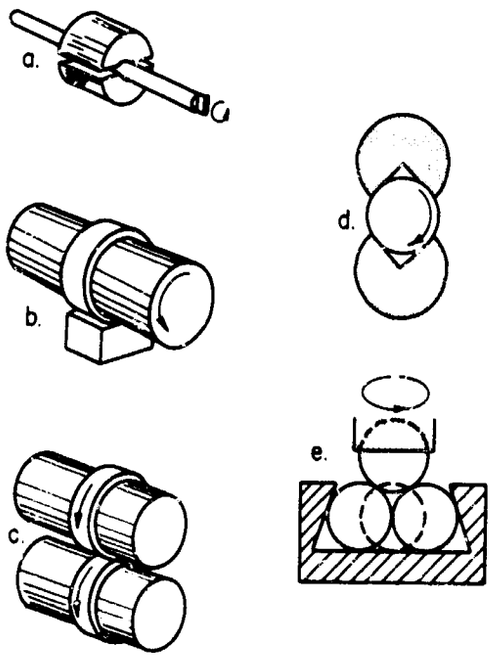

Fig. 5.11. Principles of laboratory friction and wear test apparatus 72.

on the softer shaft; total load and torque are measured. In the four-ball machine (e), a 0.5 in. steel ball is rotated in contact with three similar but stationary (clamped) balls; therefore, contact is reduced to points. Wear and coefficient of friction can be measured and the test may be run at increasing loads until the frictional heat welds the balls together. In the "pendulum oiliness tester" a steel cylinder attached to a pendulum rubs against four symmetrically arranged steel balls, and a coefficient of friction is derived from the decay of pendulum movement [74]. In the basic form of these bench tests, the purely Hertzian nature of the contact demands that contacting members be made of hardened steel; contact pressures have been given in graphical form by Carroll [75]. While tests based on point contact are most suitable for the evaluation of boundary and E. P. lubricants and wear, the others have found use also in studies of thin film and hydrodynamic lubrication.

In most tests, one of the contacting members may be made of the workpiece material, assuring that at least the right tool and workpiece material combination is used. Contact is essentially elastic, but the effect of continued running can be assessed and a lubricant breakdown point may be determined by raising the contact stresses in a programmed fashion.

Apparent success has occasionally been reported in assessing the performance of rolling lubricants on modified bench testers. One such method has been described by Griffin [76]. From a consideration of the gradually decreasing and finally zero relative movement between roll and strip in the roll gap, a Shell four-ball tester was slowed down to 0.3 rpm, and the load increased. For better agreement with rolling performance, it was also found necessary to conduct the experiment at temperatures typical of mill operation. The torque value measured during a 900-sec run was taken as a film characteristic of the lubricant.

A simulating test (similar to the Timken test) involving elastic contact between a steel roll and a flat block of the workpiece material (brass) was described by Reynolds [13] for the laboratory evaluation of brass and copper rolling emulsions. Reasonable agreement between wear scar and rolling mill performance is claimed, although the examples given in the original paper do not seem to support this contention. In general, it is difficult to see how any of the bench type wear testers can be used to predict performance in such a complex operation as rolling.

5.28 Validity of Tests

The above survey shows the bewildering variety of small-scale and simulating tests that have been proposed. The advantages and limitations of some of them are obvious, but it should be useful to summarize here those factors that increase the validity of results for practical deformation processing.

Problems of Scaling-down

When the scale of a metalworking operation is reduced in order to make it amenable to an attack on the laboratory scale, a number of factors are changed, not all of which show a linear relationship. The principles of scaling up have been discussed to some degree by Pawelski [77], but experimental evidence to show the validity of any generalized scaling laws is almost nonexistent. Experimentation in the laboratory is often carried into production practice, but few examples of well-documented investigations are in the open literature.

As a rule of thumb, it is advisable to scale the geometry of the process linearly. In other words, if the diameter of the experimental rolling mill is one-third that of the production unit, strip thickness should also be one third. Although such scale-down appears permissible for cold working, it may be completely useless for hot deformation processes. Smaller specimens lose heat much more rapidly through the relatively larger surface area, and heat balance between die and workpiece may become entirely atypical.

It is doubtful whether slowing down of the deformation process is permissible at all. The generation of squeeze films and of hydrodynamic (full fluid) films is very much a function of relative velocity between die and workpiece. Similarly, heat generation in the workpiece and distribution of heat between the die, the deformed and the undeformed portions of the workpiece are also functions of time and, thereby, of velocity. In addition, the yield stress of most materials is highly strain-rate dependent, especially in the hot working range and, accordingly, interface pressures will vary with deformation velocities (strain rates). The shear stress of many lubricants, particularly of soft solids, may be highly strain-rate sensitive too.

The surface topography of the workpiece and of the dies must remain unchanged, because they play an important role in determining the thickness of the lubricant film and the prevailing lubricating mechanism, neither of

which must be affected during scaling down. Similarly, new surfaces must be generated at the same rate as in the full-scale process, so that the higher reactivity of these virgin surfaces should come to play its proper role in determining adhesion, pickup, and reactions with lubricants.

It is rather obvious that no changes in workpiece and die temperature are permissible either. Ideally, the interface temperature should be kept the same, because this will determine the activation or breakdown of chemically active substances and the viscosity and viscosity gradients in thick films.

Cooling of workpieces of too small masses usually limits the degree of scale-down for hot-working operations. Heat losses during transfer from the preheating furnace to the metalworking equipment cause substantial inaccuracies. As the size of workpiece is decreased, contact times with the colder dies should be reduced; however, this usually violates the rule of maintaining similar deformation rates. Some of these difficulties are insuperable, and account for the relative paucity of experiments under hot working conditions. The situation is much more favorable in cold working, although care must be taken that temperatures typical of the production operation are maintained. Bulk die temperatures of the order of 150°C are often obtained once production conditions stabilize, and experiments performed with dies at lower temperatures may be completely irrelevant.

Linear scale-down of the process geometry sometimes leads to impracticably thin specimens, and it may be necessary, for example, to use greater sheet thicknesses in deep drawing operations. On scaling up to production size, performance is not always matched, as shown by Siebel and Kotthaus [78]. Frictional losses form a larger portion of the total draw force in the full size operation; therefore, these authors have suggested that the blankholder pressure should be increased in the cupping test; yet, investigations by Panknin and Eychmuller [79] showed that this solution is not satisfactory either. As the ratio of punch diameter to sheet thickness increases, the maximum draw ratio decreases, and this is not fully counterbalanced by the increased blankholder pressure. The only explanation possible is that increasing blankholder pressure causes a decreasing friction value, as proven by later experiments of Panknin and Reihle [55].

A further difficulty of scaling down is that many practical lubricants, especially those used in recirculating systems, may undergo changes

affecting lubricant performance. Initial changes (break-in) may be rather rapid, to be followed by gradual and usually undesirable aging. The simulation of these processes is extremely difficult in the laboratory.

Transfer of Results from One Process to Another

The small-scale metalworking operations are quite often still too expensive or demand too complicated equipment or measurement techniques to present an attractive choice for all lubricant research. For this reason, several attempts have been made to perform the majority of tests with a simplified or cheaper deformation process and then to transfer the results to the more expensive production technique of interest.

Most frequently, correlation between wire drawing and rolling has been attempted. Wire drawing may be carried out, even though at only low speeds, even in a standard tensile testing machine. Johnson et al. [80] used wire drawing for the evaluation of palm oil substitutes for the cold rolling of steel and found that the lubricants selected on the basis of slow-speed drawing tests performed well in production practices. Similarly, Barnes and Cafcas [81] reported good agreement between the mill power requirements of three brass rolling emulsions and the drawing work measured in slow-speed wire drawing with the same lubricants. In contrast, Williams and Brandt [82] found no correlation between coefficient of friction data derived from rolling and room-temperature wire drawing; when wire drawing was performed with heated lubricants, the temperature of lubricant breakdown gave the same order of merit as the overall performance in rolling. The suitability of wire drawing experiments for the evaluation of rolling lubricants was critically assessed by Lueg and Dahl [83]. Selected emulsions and dispersions, including palm oil, were used in carefully controlled rolling and wire drawing experiments; conditions for wire drawing were chosen to be identical to those used by Johnson et al. [80] because of their reported success in simulation. The order of merit in wire drawing was judged from the level and steadiness of drawing forces; in rolling, the minimum obtainable gage in eight passes was taken as an indicator of lubricant quality. There was no correlation between the two sets of results, and Lueg and Dahl came to the conclusion that a wire drawing test is completely unsuitable for the simulation of rolling, mainly because of the drastically different process conditions.

Reviewing the conflicting evidence, one must suspect that the favorable agreement found by some researchers may have been fortuitous and that a universally valid proof of direct correlation has not been presented yet.

A selection process that is more severe than the full-scale process might well serve as a preliminary screening test, although the danger of eliminating useful lubricants cannot be overlooked. A more severe test is apt to predict breakdown, but this may have nothing to do with overall performance if production conditions are favorable enough.

Few published examples exist of a rigorous comparison of lubricant performance in various deformation modes. In one instance, upsetting, rolling, reverse extrusion, and wire drawing were carried out (Fig. 5.12), and correlation between the performances of a given lubricant was extremely poor [84]. The difficulty of transferring results from a simulating test (the ring compression test) to actual metalworking operations (rolling and drawing) is also illustrated by some results of Male [85]. Agreement was good with dry lubricants and with thick films but was rather poor when mixed lubrication prevailed, indicating that differences in process conditions were just as important as lubricant variations. If the great variability of interface pressures, sliding velocities, temperatures, and deformation patterns generated in different operations is taken into account, the lack of agreement is not surprising. It would appear, at the present, that no direct transfer of results from one metalworking operation to another is warranted. Only when processing conditions (lubrication system, surface speeds, working pressures, surface topography, and die-workpiece combinations) are matched should transfer of results be considered at all. Otherwise, the results are likely to be invalid, even for the same process.

Validity of Simulating Tests

In view of the difficulties expounded upon above, it is not surprising that the relevance of any simulating test is always hotly debated [86]. There is no doubt that simulating tests have a legitimate use for the exploration of fundamental variables in friction, lubrication, and wear. Direct application to metalworking operations, however, is always doubtful and is usually successful only if some further qualifying limitations are set. Thus, for example, Vojnovic et al. [87] found that an evaluation of steel rolling lubricants on a modified four-ball (Roxanna) tester gave a correlation with rolling performance only if saponification value and free fatty acid content of the

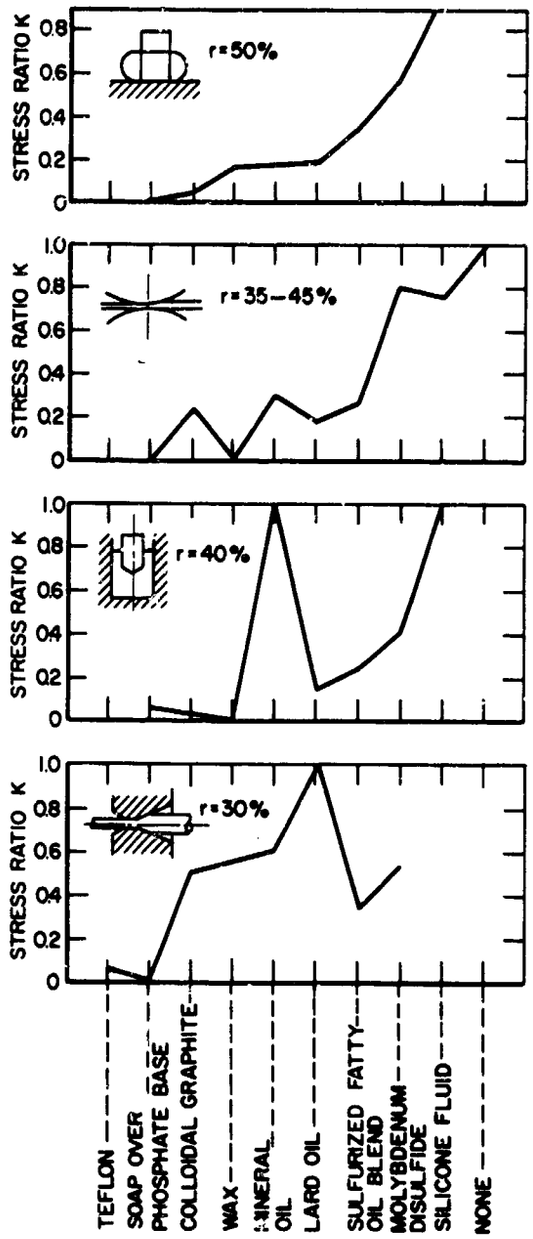

Fig. 5.12. Relative performance of selected lubricants in axial upsetting, rolling, piercing, and drawing [84].

lubricant was kept within certain limits. Obviously, this limited the comparison to fatty oils and derivatives.

The suitability of various bench-type boundary lubricant testers for rolling lubricant evaluation was systematically and critically evaluated by Saeki (reported by Funke [88]). Palm oil, rapeseed oil, and turbine oil were tested over a temperature range from 20° to 200°C in a four-ball tester and

in two "pendulum oiliness testers." The actual values of friction were different even in the two models of pendulum testers, and both friction and wear followed a different relationship with temperature in the three different bench tests. The only common feature was that palm oil was the best, and turbine oil the poorest. Subsequent rolling experiments on a production size 4-high mill proved palm oil to be the best lubricant; however, this in no way means that results from the bench test are directly transferable to rolling. For example, palm oil gave a friction coefficient of 0.11 on the pendulum oiliness tester, 0.05 on the four-ball tester, and 0.015 in the rolling mill. In view of the great variability of lubricant behavior with temperature, it is very doubtful that bench tests would give sufficient distinction between lubricants of less obviously differing performance. Results obtained with a twist-compression test in the elastic range (Fig. 5.10e) by Haverstraw [69] gave only very moderate correlation with the performance of lubricants in the hot extrusion of steels.

Best correlation is usually achieved when plastic deformation is not too severe—as in, for example, sheet metalworking. Thus, Ebben [89] reported on the evaluation of some twenty lubricants in the ironing test (Fig. 5.8b) and in actual ironing operations. Plant performance was rated on a scale from 0 to 10, with 0 being assigned to failure and 10 to the best, smoothest draw. Correlation between laboratory ironing at 15% reduction and plant performance was very satisfactory.

It would appear, therefore, that even though the case for simulating tests is not hopeless, results should be transferred to actual practice only with extreme caution. On the basis of available evidence, it would be dangerous to assume the validity of any simulating test without corroborating evidence from comparative experiments with the same lubricant under production conditions or, at least, from a suitably scaled-down laboratory variant of the full-size metalworking technique.

Reporting of Friction Test Results

The foregoing discussion has amply demonstrated the need for a careful selection of test techniques for friction measurements. Until such time that universally acceptable tests are developed, a multitude of tests will be used. It is important, though, that results be presented in a form suitable for subsequent independent evaluation and, if possible, correlation with results

obtained from other sources. The value of all work, whether basic or applied, would be greatly increased if some basic standards of reporting experimental variables were accepted, as suggested by DePierre [90]. Such a description should include at least: (1) die and workpiece material (composition, condition, hardness, dimension); (2) method of preparing die and workpiece surfaces (chemical and mechanical, including coating); (3) surface topography of die and workpiece; (4) heating of die and workpiece (method, temperature, time, atmosphere); (5) lubrication system (lubricant composition, method of preparation and application, thickness); (6) process conditions: die geometry, amount of deformation, surface and/or deformation speeds, working pressures; (7) surface condition of dies and workpiece after deformation.

The data will often have to be reported in the briefest possible form, such as coefficient of friction values; nevertheless, the method of deriving these data must always be clearly shown. Unless the original measured data can be recalculated from the published friction values, it is certainly preferable to present the measured data as well.

5.3 MEASUREMENT OF LUBRICANT FILM THICKNESS

Valuable information regarding the effective lubricating mechanism may be obtained by measuring average or instantaneous film thicknesses generated during the deformation.

If care is taken in the handling of the product emerging from the deforming die or rolls, an average lubricant film thickness can be determined by simple solvent techniques, measuring the weight change of the sample before and after degreasing. This method has been used successfully and repeatedly for the determination of oil film thicknesses in strip rolling and also for soap films in wire drawing.

Direct electrical measurement of oil film thickness during the deformation process itself is possible only if lubrication is predominantly hydrodynamic. In predominantly boundary contact, resistance is practically nil because a number of metallic contacts in the deforming zone provide a direct current path. As the thickness of the mixed film increases, it could be expected that the asperities lift off and the resistance between die and workpiece increases. This has indeed been confirmed by Ranger and Wistreich [91]. Film resistance measurement is facilitated by connecting a high fixed resistance in series with the lubricant film (Fig. 5.13a); this keeps the

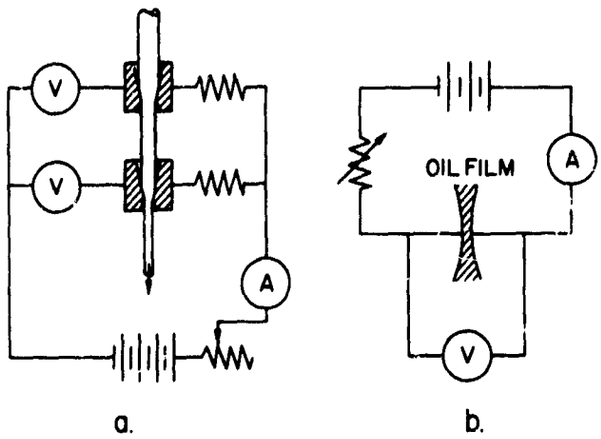

Fig. 5.13. Principles of measuring lubricant film thickness by electrical methods: (a) resistance, (b) electrical discharge.

current flowing through the film sensibly constant and makes the system more sensitive to variations in film resistance, generally in the range of 0.1 to 3 ohms when drawing with a soap. Even though rapid variations indicate periodic metallic contact, an estimate of film thicknesses may be derived from the average voltage.

In principle, the discharge voltage method frequently used in investigations of elastohydrodynamic lubrication between gears and disks should also be applicable. The circuit for such measurement is very simple. A heavy current of the order of 1 to 5 amps is passed across the oil film causing an arc discharge. The voltage necessary to maintain continuous discharge is measured with a voltmeter connected across the oil film (Fig. 5.13b). The discharge voltage is usually taken to be a linear function of oil film thickness. However, Dyson [92] found by capacitance measurements carried out under identical sliding conditions that the linearity does not necessarily hold. He considered that the technique may be useful for relatively thick films (of the order of 40μ in. or thicker) and for high slide/roll ratios. These conditions are attained in a number of metalworking operations, especially in wire drawing and, to a somewhat limited extent, in rolling; the technique could be useful, although no information relating to its application to metalworking could be located.

Optical interferometry (Section 5.62) can give detailed information on oil film thickness variations in the contact zone, but at least one of the contacting materials must be transparent. Therefore, the technique can serve only for simulation.

Radiotracer techniques are most useful. For example, Golden and Rowe [93] measured the thickness of glass films by a radioactive glass added to the glass pads and coatings used in extrusion. Radiotracer techniques relevant to glasses have been described by Peyches [94]. Komura [95] incorporated tracers into the phosphate coating preapplied to the workpiece surface. The reaction of E.P. compounds with the surface of the die and workpiece may be followed with labeled chlorine, phosphorus, or sulfur compounds.

5.4 MEASUREMENT OF DEFORMATION PATTERNS

The effect of friction on deformation patterns within the deforming body can be traced in several ways.

Macroscopic changes are best followed by the grid line technique, but microscopic changes that affect recrystallization on subsequent annealing or changes in material properties from the surface to the inside of the workpiece can be more readily revealed through microscopic observations of the structure. The problem is often how to prepare the specimens without destroying the edges. This difficulty is readily overcome by depositing—for example, by electrodeposition—a layer of material of similar hardness so that the edge is fully protected. The severe shear deformation occurring on surfaces worked without a lubricant is readily discerned, whereas mostly uniform deformation is normally visible in specimens deformed with lubricated dies, and shear is limited to the interface. The difference in deformation may also be confirmed by microhardness measurements.

Deformation patterns in bulk deformation processes may be traced in a number of ways. Thus, the workpiece may be composed of different materials that either contrast in color or may be etched to show up the deformation of individual elements. Such techniques have been frequently used for rolling, forging, and extrusion investigations. Pins of a different material may also be driven into strategic positions, and their deformation revealed by sectioning or by radiography. Grid lines etched, cut, or printed on planes of symmetry have, however, become the most popular techniques. They have been applied to rolling slabs in the horizontal as well as vertical plane of symmetry, and to axially symmetrical forging, extrusion, and drawing in the plane passing through the axis. Normally, it is necessary to machine two cylindrical specimens so that when the two remaining halves are matched they form a perfectly circular cross section. The grid needs to be marked on only one of the contacting surfaces.

The lines may be produced by a scriber, by accurately controlled tools on a milling machine or shaper, or by printing. More recently, etching techniques have come to be extensively used. In the photo-etch technique, the workpiece is coated with a light-sensitive emulsion, covered with the mask (positive) bearing the desired grid lines and exposed. On developing the light-sensitive layer, places shaded from light are left unprotected and can be etched in a suitable solution.

Electrochemical techniques use a stencil that bears the outlines of the grid [96, 97]. The stencil is placed on the metal surface, which is then submerged in an electrolyte specific to the material to be etched, and alternating or direct current is applied for a few seconds. With alternating current, metal is etched from the surface in one half-cycle and the resulting cavities are filled in the second half-cycle by the deposition of the base metal oxide, in the form of a black coherent complex which contrasts sharply with the original metal surface. With direct current, a permanent impression of a depth of 0.001 in. is produced, which may then be pigmented to high-light contrast. The d-c technique is applicable to all metals, the a-c technique to all common ferrous and nonferrous metals with the exception of aluminum. Current is typically supplied at 25 volts and 100-200 amps. Lines can be very fine, allowing resolutions of 100 lines to the inch or producing grid circles of 0.050 in. diameter. The stencils may be reused.

It is often desirable that surface deformations be followed in similar detail. Scratched or machined lines act as lubricant pockets and could interfere with the lubricating mechanism and thus with the basic deformation mode; therefore, techniques that produce lines of minimum depth are preferable.

5.5 MEASUREMENT OF WEAR

It has been repeatedly emphasized that wear may be more important than friction itself in metalworking. Nevertheless, information concerning wear is rather scarce, at least in the published literature.

The wear of a die is most readily assessed. Many plants keep records to show the quantity (tonnage, number of pieces) produced with any given set of work rolls, drawing, forging, or extrusion dies, or sheet metalworking tooling before regrinding or refinishing of the surface is necessary, and before the die has to be discarded or finished to the next larger size because the dimensions of the product would no longer fall within the tolerance limits.

More detailed measurements of die dimensions themselves are needed if the course of wear is to be followed in any detail. Since such measurements call for greater effort and may also disrupt production, most data relating to localized die wear are the result of special investigations. Usual engineering measurement techniques are sufficient for rolls and larger dies, but special mechanical and optical devices have been developed for inspecting and measuring changes in the surface dimension of wire drawing dies [98-101]. In the absence of such instrumentation, the profile and exact dimension of draw dies and forging dies may be more readily followed on replicas, cast of lead or, more frequently, of an acrylic resin. For worn profiles, rubberlike dental compounds are useful [102].

One of the most powerful tools for measuring wear of either the workpiece or the die material utilizes radioactive tracer techniques. A radioisotope may be incorporated in the die or workpiece material, either during the preparation (melting, powder metallurgical compaction, etc.) of the metal, or the product may be exposed to radiation for activating some of the elements. Transfer of radioactive material onto the nonradioactive contacting surface may then be followed either by autoradiography or by counting techniques. Details of these processes may be found in some excellent monographs (Kohl, Zentner and Lukens [103]; Cook and Rabinowicz [104]). It should suffice to say here that practical limitations usually arise from the strict safety precautions that must be followed in handling radioactive materials.

The total permissible activity often limits the size of the die or workpiece material that may be handled without expensive precautionary measures. When the experiment is to take place on larger size metalworking equipment, isotopes of reasonably short half-life are preferable because they will become harmless even if contamination is not fully detected and immediately removed. Too short half-life could, however, curtail the experiment. Total activity may be reduced by choosing materials that contain only a minute amount of active elements. The total activity of large workpieces may be further diminished if the bulk of the workpiece is nonradioactive, and the material containing the radioisotope is applied as a cladding to the nonradioactive body [105]. A minimum total activity is, nevertheless, needed to assure sensitivity of detection.

The wear of drawing dies has often been followed by activating the die material; the position of wear particles on the drawn product is then readily

detected by autoradiography. Visual examination can be misleading, and densitometer readings are advisable. Golden and Rowe [106] have warned that great care must be exercised in preparing the experiment and interpreting the results, and they also recommend alternative means of examination, such as electron microscopy, for an unequivocal interpretation.

Radiotracer techniques have been more frequently used in general friction and lubrication research; however, the same techniques could be applied profitably to metalworking. Metal transfer has been studied, among others, by Bowden and Tabor [107]. Average wear may be followed by activating one of the contacting metal surfaces and measuring the accumulation of radioactive debris in the lubricant.

Localized wear or pickup is often clearly visible, particularly when a color contrast exists (e.g., copper on steel). The scanning electron microscope, further discussed in the following section, offers often dramatic views of damaged surfaces, as shown by Johnson [108] for the abrasion of aluminum surfaces.

Other techniques [109], used in general wear investigations, could serve equally well for research on deformation processes. In particular, X-ray and electron diffraction, spectrography, and the electron microprobe analyzer may be drawn upon for identifying pickup and wear debris.

5.6 SURFACE FINISH AND SURFACE PREPARATION

The shape, size, and distribution of irregularities on both the die and workpiece surface are of particular importance in friction and lubrication because they determine the extent and nature of contact between the two bodies and profoundly influence the lubricating mechanism. For this reason, the surface topography is and has been a subject of fundamental importance. Various techniques have been devised to measure and record surface features, most of which amplify the height of asperities so as to make their shape more readily discernible to the eye. The abundance of such surface profile traces in the literature has led to the misleading impression that asperities are usually sharp peaks.

In a review of the subject, Williamson [110] points out that asperities are typically from 10 to 300 μ in. high, and spaced from 50 to 3000 μ in. apart. The slopes usually lie between 5° and 10°, although occasionally steeper slopes up to 25° are encountered. The summits are seldom peaked, but are more likely to have a large radius typically of 400 to 800 μ in. Large, worn

plateaus are likely on worked surfaces. On many surfaces, the heights of asperities follow a Gaussian distribution. Therefore, contact is likely to occur first over only a very small number of points, and the detailed topography of the surface would have to be known if a complete understanding of lubricant breakdown at critical points and the shape of trapped films between the two contacting surfaces were to be considered in detail. Such knowledge is very limited, especially for conditions of sliding contact under high interface pressures. As a minimum, an approximate description of the surface characteristics is essential for the interpretation of frictional and lubricant phenomena. In the following, a brief survey of inspection and measurement techniques will be given.

5.61 Surface Roughness Measurement

Commercially available instruments offer the quickest way of obtaining a suitably magnified surface profile [110, 111]. A fine-pointed diamond stylus is drawn slowly across the surface, and its up-and-down motion is converted into electrical signals, which may then be used, after suitable amplification, to obtain a direct recording of the surface irregularities. The accuracy of the trace is ultimately a function of the stylus radius (typically, 500 μ in. in industrial instruments, down to 45 μ in high-resolution instruments). If loads are light enough, plowing of the surface will be minimized and repeated traverses may be taken on the same line.

A direct observation of surface irregularities may be made with an optical microscope. Amplification of asperity height is again desirable and may be achieved by preparing a tapered section. Surface features are preserved by first electroplating the specimen with a thick film of nickel (Moore [112]) or even with solder (Wright and Scott [113]), and a cross-section is then carefully polished at an angle to the original surface. A magnification of at least 10 times is readily obtained.

A profilometer trace, or a photograph of a tapered microsection, presents a good general indication of surface topography. In fact, although it is not generally recognized, profilometry provides exact data on the general distribution of asperities, because each traverse or tapered section has the same information as any number of parallel tracks or sections [110], even though the die as well as workpiece surfaces frequently show marked directionality resulting from a machining or grinding operation. It is usually

desirable, however, to measure two profiles, one in the direction of the machine tool traverse and the other approximately perpendicular to it.

The traces may be used to derive quantitative measures of surface roughness (Fig. 5.14). The maximum peak-to-valley height is the only relevant figure when an estimate is required of the depth that needs to be removed for producing a fine finish. In most friction and lubrication problems, some average value may be more useful. The average peak-to-valley height is expressed in microinches and gives the vertical distance between the average elevation of peaks and the average depression of valleys. More frequently, roughness is expressed as an average deviation from a mean surface. The mean surface is taken to cut off the asperities at such a level that the volume removed would fill in the valleys. The arithmetical average of a large set of height measurements from this mean surface leads to the value described as arithmetical average (AA) or—in Britain—centerline average (CLA), with dimensions in microinches or microns. By squaring each value and taking the square root of the average square, the root mean square (rms) value is arrived at. The difference between the two methods of calculation is usually small, and seldom exceeds 10%, which is negligible for all practical purposes.

The above averages could, in principle, be arrived at from calculations based on direct measurements of surface roughness traces, or they may be obtained directly through suitable electronic circuits. For research purposes, numerical analysis and processing in a computer are valuable [110]. A number of industrial profilometers dispense with recording altogether and indicate AA or RMS values directly; although such instruments are suitable for controlling the consistency of any one surface finishing process, their

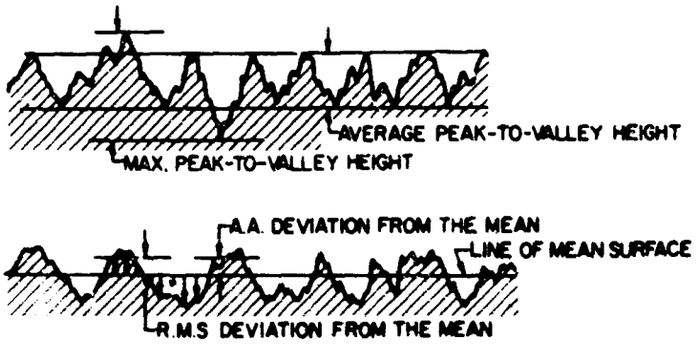

Fig. 5.14. Terminology used in describing surface roughness (vertical magnification greater than horizontal magnification).

value for friction and lubrication studies is greatly limited because detailed information on surface topography is lost. Average roughness can be particularly misleading if the surface is composed of a large number of uniformly small imperfections interrupted by some exceptionally large ones. Such large imperfections can determine service performance (e.g., initiate pickup).

The above averages are widely used, but other numerical characteristics such as the number of peaks per unit distance, bearing area, and volume of trapped valleys may be more relevant for particular applications and may be derived from profilometer traces.

A tapered section, although much more costly to prepare, often yields information that is invisible on a stylus trace. Sharp, jagged edges are revealed (and also exaggerated) by a taper section, while the corresponding stylus trace is rounded because of the arc-like motion of the stylus of finite radius over a point-like peak and its inability to reach the deepest or partially obstructed portions of troughs (Fig. 5.15).

5.62 Optical Microscopy

A metallographic microscope with its vertical illumination yields only limited information on surface topography. Nevertheless, it has been used for the identification of lubricating mechanisms from evidence of rolled and drawn surfaces and, coupled with auxiliary techniques, it can be a

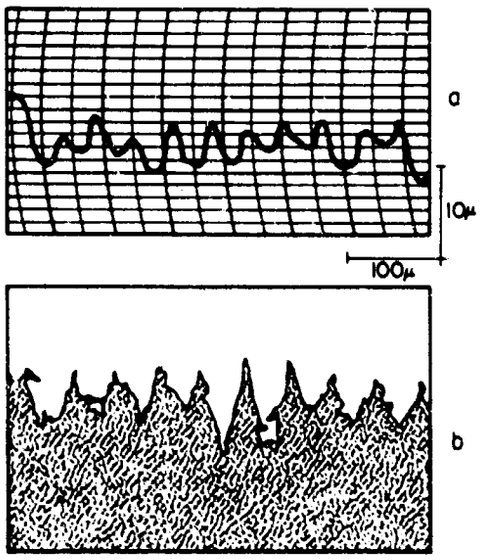

Fig. 5.15. Comparison of surface features (a) recorded by stylus instrument and (b) revealed by taper section [114].

powerful tool in controlling lubricating processes. Stereo microscopes are especially useful for a rapid assessment of surface features.

The usefulness of the optical microscope may be greatly increased by choosing the proper mode of illumination, as reviewed by Scott [114]. Dark-field and, especially, oblique illumination gives some three-dimensionality to the observed image; dark-field illumination shows clearly, against a dark background, irregularities—in particular, scratches—that cause a diffraction of light. Phase contrast, available on many modern microscopes, reveals details not visible under normal illumination. Polarized light may be useful in specific instances (e.g., when there are inclusions of copper oxide on a surface).

Quantitative analysis of surface topography is possible by interferometry. A monochromatic beam of light is split, and the images formed by the light waves reflected from the surface of the specimen and from an optically flat reference surface are superimposed. All waves reflected from loci of equal height have the same phase relation to the light reflected from the reference surface: when in phase they appear bright, when out of phase they annul each other. The resulting bright and dark fringes thus represent contour lines, adjacent fringes corresponding to a level difference equal to half the wavelength of the light used. As an example, Fig. 5.16 shows a trace produced by traversal of a hemispherical slider over an electrolytically polished aluminum surface characterized by a large number of randomly distributed asperities. In contrast, a mechanically polished surface is quite smooth, as shown by the even and parallel spacing of interference fringes; the heavy distortion due to the passage of the slider is clearly visible. Sometimes, white light is used with advantage to form interference fringes in color.

5.63 Electron Microscopy

The resolution of the optical microscope is often insufficient to reveal minute yet important details of friction and wear processes. The electron microscope has proven a powerful tool in such studies. Until relatively recently, direct surface examination was limited to small specimens and most work was carried out on replicas. Various techniques have been surveyed by Scott and Scott [115]. Negative (single-stage) replicas may be difficult to interpret, even if they are shadowed for heightening contrast. Interpretation is somewhat facilitated by a reverse printing of the photographs. Even positive replicas, made by a two-stage technique, may pose

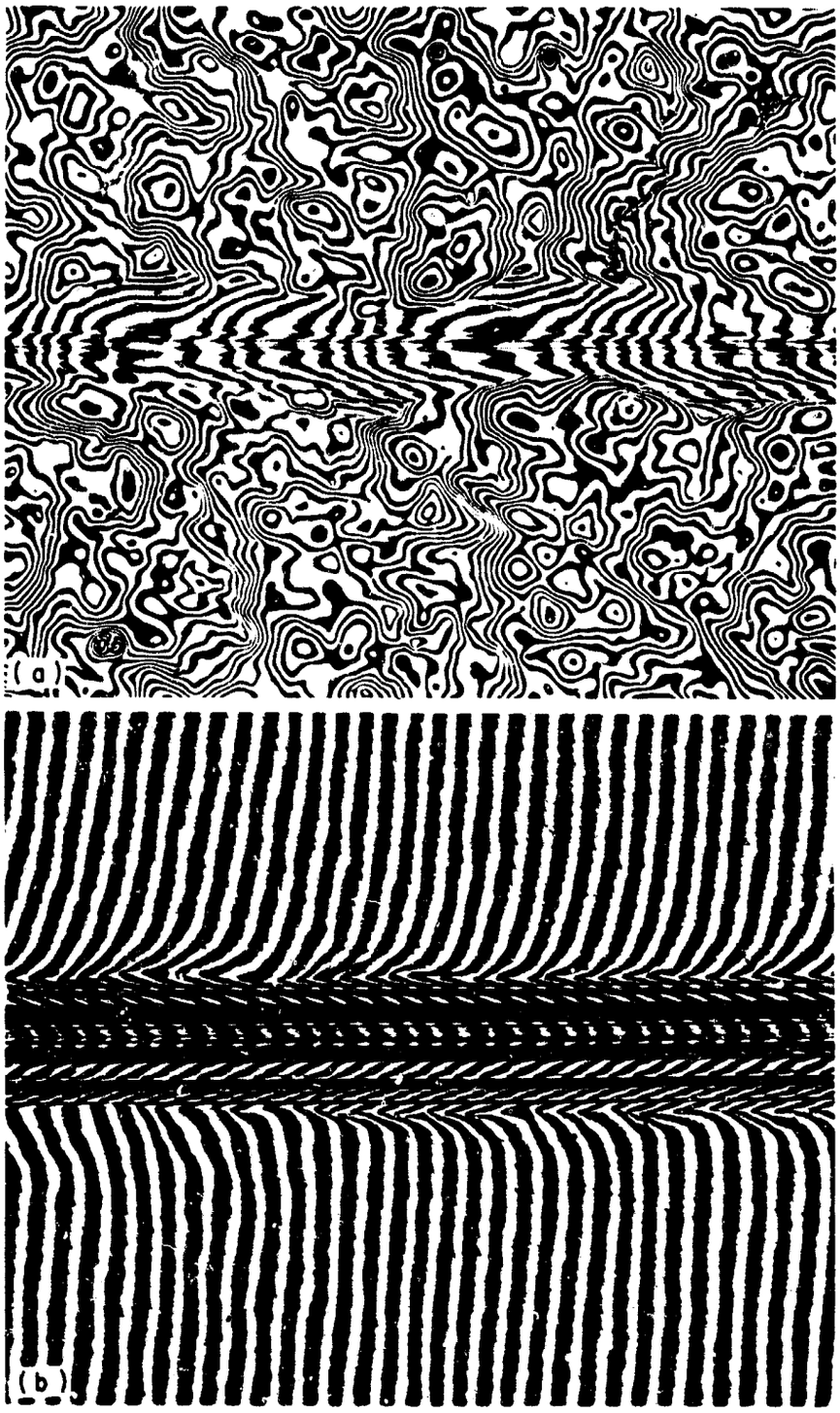

Fig. 5.16. Friction traces across aluminum surfaces polished (a) electrolytically and (b) mechanically (x65) [114].

difficulties in interpretation, and latex particles normally used for magnification checks and calibration may be incorporated to determine the direction of shadowing. Since replicas also pick up wear debris, they have been found extremely useful in wear studies [116].

With the appearance of the scanning electron microscope, direct examination of surfaces has become more practicable, and this tool will no doubt become one of the mainstays of friction and wear studies. The great depth of focus combined with adequate resolution (of the order of 150 Å) creates a three-dimensional effect unobtainable by any other means, and eliminates the need for replication of the surfaces. An example is shown in Fig. 5.17, in which an optical micrograph and a scanning electron microscope image of the same rolled surface is compared [117]. Experiments with large pieces are simplified if inserts are placed in the die or workpiece, and removed for examination after deformation; this technique also avoids heat generation during cutting.

5.64 Preparation of Replicas

It is often inconvenient and sometimes impossible to obtain a stylus trace or to perform a microscopic examination of the surfaces in situ. A number of techniques are now available that allow the preparation of replicas of surfaces; these replicas may then be examined by any convenient means. Plastic replicas may be prepared in a range of hardnesses, making them suitable for either microscopic or stylus instrument examination.

The technique described by Pearson and Hopkins [118] uses a liquid mixture of a monomeric and polymeric methyl methacrylate. A representative area of the surface is surrounded by a plasticine dam, and the mixture is poured onto the metal surface, where it flows into the smallest irregularities without entrapping air. After irradiation with ultraviolet light, the polymerized solid replica may be removed. Tributyl citrate is used as a stripping agent. The strength of the replica may be increased by backing it up with an unplasticized transparent Plexiglas sheet, which adheres firmly to the replica.

More recently, a number of self-curing resins have become available. Originally developed for dental work, they reproduce surfaces faithfully. They are simply prepared as a liquid from a resin and a hardener and require no ultraviolet irradiation. Thin, but equally faithful replicas may be

obtained by pressing a softened, thin, cellulose acetate sheet onto the surface. Sheet of 0.05 in. thickness and moistened with acetone has been found

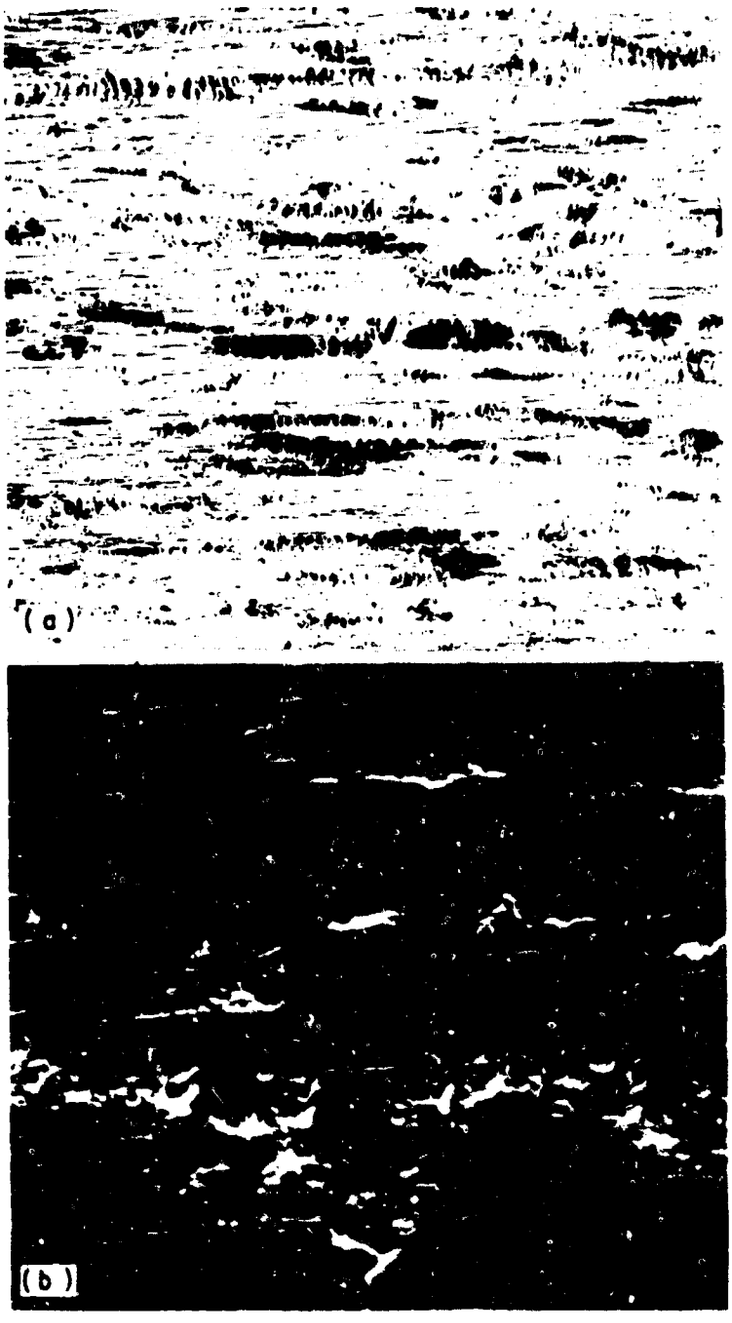

Fig. 5.17. Comparison of rolled aluminum strip surface observed with (a) optical microscope (x100) and (b) scanning electron microscope (x1000) [117].

satisfactory [119]. There are also proprietary brands of plastic sheets available for the purpose.

Thin replicas may be viewed in transmitted or reflected light, or a highly reflecting surface may be produced by vacuum coating the replicas with a thin film of aluminum or chromium. In this form, interferometry may also be applied.

5.65 Visual Inspection

While the above techniques offer quantitative or semiquantitative methods of analyzing surface topography, the human eye is the most critical judge of surface finish. Minor variations in reflectivity make surface defects or other surface features visible even when they are undetectable by instrumental techniques. The drawback of visual inspection is that it is highly dependent on the nature, direction, and intensity of the incident light and subjective elements always enter judgment. Visual inspection is, nevertheless, the most widely practiced method of assessing surface quality during the actual deformation process at present; optical methods, reviewed by Reynolds [120], could be used for detecting at least the macroscopic changes in surface appearance but have found only limited application in deformation processing.

The luster or reflectivity of finished products, especially that of rolled sheet, is extensively checked with commercially available or specially built devices. Reflectivity of aluminum surfaces and the ratio of total to specular reflectivity is often measured by the Guild photometer [121]. Examples of recent developments in surface texture measurement will be found in Section 6.27.

Specially built devices (endoscopes) find widespread use for the visual examination of the internal surfaces of hollow parts, tubes, and dies.

Closed circuit television has solved problems of inspecting inaccessible, hot or dangerous areas and—by arresting the image on a persistent screen—it also offers a means of inspecting the surface of moving workpieces at any selected point.

5.66 Surface Preparation

All efforts at generating relevant information may be rendered futile if the quality of contacting surfaces is uncontrolled. In the preparation of die

and workpiece surface for experimental purposes, two philosophies are usually followed.

If the experiments are designed to evaluate practical lubricants or the effects of process variables, or are otherwise practically oriented, the main criterion is that of reproducibility. Dies are given a preparation typical of good work practices. Thus, all lubricant residues are removed and the surface is reconditioned to a practicable, acceptable roughness. This may cover a wide range from a ground or shot-blasted surface of 40-180 μin. AA roughness (for some rolling operations and for draw dies for thick sheet) to a mirror finish of sometimes better than 2 μin. AA roughness (for bright finished rolls, draw dies, and cold extrusion dies). It is important that the direction of the surface finish be in the right relation to the material movement, otherwise the relevance of the test may be lost.

If oily residues are to be removed, only nonpolar liquids such as mineral spirits, methanol, or benzene should be used. Organic solvents such as trichlorethylene and alcohols have polar properties, and adsorbed films of sometimes substantial lubricating ability may be left behind. Rubbing of the surfaces with a cloth immersed in the solvent only helps to build up these boundary and E.P. films. Moisture adsorbed from the air is also an excellent lubricant for some materials. Since most production dies heat to temperatures in excess of 100°C even in cold working operations, no experiment should really be conducted with dies at room temperature. If the dies are heated to 120°-150°C from the beginning, no [illegible] will be found for a "break-in" period.

During experimentation, a close check must be kept on the condition of the dies. Very minor scoring of a polished die may sufficiently interfere with lubrication to raise the coefficient of friction and may render futile even the simplest attempts at ranking lubricants. Removal of die pickup and reconditioning of the surface is never an easy matter. Some materials, such as aluminum, may be etched off the steel surface with a caustic solution, but others can be removed only by mechanical means. In the process the surface is likely to be changed and, in many instances, the only acceptable solution is a complete redressing of the surface.

Much the same considerations apply to the workpiece material: some technique must be found which assures reproducibility of surface quality. If the test pieces are machined, surface finish must be strictly controlled,

because slight changes in surface topography may cause a marked change in the lubricant quantity trapped and transported into the die-workpiece interface. Although very clean surfaces may possibly be produced for fundamental work [122], there is no such thing as a clean workpiece surface for practically oriented research; as a minimum, however, the surface must be of a consistent quality. Annealed surfaces carry an oxide film and are best left alone; if the oxide must be removed by some suitable pickling technique, this should be followed with a cold and hot water rinse and rapid drying in blown air. The water for the final rinse must be of constant quality and, preferably, deionized, because deposits due to water hardness may inadvertently provide lubricant carriers. Prior deformation processing leaves residues that resist removal by conventional solvent cleaning techniques [123]. If they are unlikely to interfere with the lubricants used in the experimental work, removal of the excess with a nonpolar solvent may suffice. If, however, the lubricant residues could mask the effect of lubricants in the actual test, more powerful methods are needed. Alkaline degreasing followed by a water rinse and drying may be adequate for less critical purposes, or a thin layer of the workpiece material may have to be removed electrolytically, or by some chemical etching (pickling) process. It is imperative, though, that no polar solvents be used for a final rinse, because they will again leave a lubricating residue. Prepared specimens should not be touched by hand.

Hot working experiments need similar careful preparation, especially if preheating temperatures are only of the order of 400° -500°C. Lubricant residues may oxidize, polymerize, and form tenacious films. At higher temperatures, the residues may influence the course of oxidation. Heating practices themselves may introduce an often undetected variable. Oxidation in a small experimental furnace may be substantially different from that occurring in practice, and careful control of heating rates, holding times, and furnace atmospheres is necessary if relevant results are to be obtained.

The same precautions apply, but much more rigorously, to experiments conducted within the framework of fundamental studies. All steps of preparation and handling become critical. In general, it is desirable that prepared workpieces be handled only with tongs or gloved hands and that the experiments be conducted in rooms of suitably controlled temperature and humidity. Storage of workpieces and dies after preparation for uncontrolled periods of time is usually a source of random variations in results.

While mechanical preparation is often undesirable for practically oriented experiments because the resulting surface may be different from that normally encountered in production practice, grinding has often given satisfactory, well reproducible surfaces for basic experiments. Usually, the specimen is abraded on silicon carbide papers with standard metallographic techniques. Menter and Tabor [124] abraded under water and followed up with alumina-alcohol polishing, electrolytic degreasing, and a water rinse; it is conceivable that the alcohol left a boundary film behind. Golden and Rowe [106, 109] abraded under a flood of methanol or benzene, and removed the residual surface film by a chemical etch. For copper, a continuous flood of a 1:1 solution of concentrated HCl in distilled water for 30 sec, followed by a distilled water rinse gave reproducible results. The mechanical aspect of surface preparation is important, too: scratches trap lubricants and may lead to erroneous results. Sandblasting or lapping probably assures the best reproducibility.

It would appear that many of these precautions have not been observed in a great many experiments conducted in the past. This would make many of the results suspect. Fortunately, some obvious weaknesses of practice are readily identified and can be taken into consideration when evaluating the results. Furthermore, much of the past and present work has sought to establish orders of merit, which are not affected by minor variations in surface preparation practices, provided that the lubricants investigated are powerful. Nevertheless, the value of research into metalworking lubrication would be greatly enhanced if some general guidelines in regard to surface preparation were developed and adhered to.

5.7 MEASUREMENT OF TEMPERATURE

The average and local interface temperature prevailing during deformation is significant because it affects lubricant viscosity, reaction rates, and breakdown of lubricants and gives an indication of the frictional conditions prevailing in the zone of contact.

Chapter 2 has demonstrated how frictional energy raises the surface temperature of the deforming metal. The surface can become much warmer than the bulk of the metal in cold deformation processing. In hot working, the die temperature is often well below that of the workpiece. The interface temperature is not likely to reach that of the workpiece (otherwise die

materials would be destroyed in most metalworking operations), and it is probably above the mean of die and workpiece temperatures. Even though the importance of knowing the interface temperature is well recognized, no generally applicable measurement technique has been developed yet.

5.71 Calorimetry

For any metalworking operation, the total heat generated is a measure of lubricant efficiency, provided that all other process variables are kept constant. This principle permits the use of calorimetric measurements for judging frictional phenomena.

Rosenhain and Stott [125] measured the temperature increase of an oil bath through which the drawn aluminum or copper wire was led immediately upon leaving the draw die. This technique is valid only if the oil bath temperature is equal to that of the wire temperature; however, this can be true only if heat insulation of the bath is perfect and if the wire is run long enough to establish thermal equilibrium. Eichinger and Lueg [126] measured the temperature of the drawn wire with an iron-Constantan thermocouple while the heat content of the thermally isolated draw die was measured by calorimetric methods. The technique used by Lewis and Godfrey [127] represents considerable refinement. On emerging from the draw die, the wire runs through a copper tube that is heated externally with a wire heater. The temperature of the tube is varied until heat exchange between the drawn wire and the heated tube ceases. At this point, the temperature is read from a thermocouple embedded in the copper tube. The accuracy of this measurement is no doubt satisfactory, but long lengths of wires must be drawn to establish equilibrium.

5.72 Thermocouples

Fast-responding thermocouples could be used for the direct measurement of the exit temperature of wire; however, sliding between the thermocouple and the wire could induce rubbing and thus give erroneous temperature indications. This difficulty is overcome by the rider constructed by Zastera [128]. The thermocouple hot junction is housed in a saddle to insulate from heat and electricity; the saddle itself is pressed against the wire, and the radiating heat from the wire is recorded by the thermocouple.

Belansky and Peck [129] were successful in measuring the surface temperature of hot rolling mill rolls with two wire brushes (one iron, the other Constantan) pressed against the roll surface. It would appear that calibration against a rotating, heated disk eliminated friction as a disturbing factor. Two rollers of different material are pressed against the drawn wire which completes the circuit in the "Addison" temperature meter, described by Sturgeon [130]. This was found to give reliable readings provided that the pressure was high enough to prevent skidding of the rollers and that thick lubricant films were removed with suitable felt wipers before the wire reached the rollers of the instrument.

In some processes, such as extrusion, it is possible to measure the temperature of the deforming body by thermocouples embedded in the workpiece [131]. While such techniques are reliable for following temperature changes in the bulk of the specimen, the hot junction must always be at a finite distance from the actual interface and, therefore, measures only subsurface temperatures. Moreover, the thermocouples will take only a limited strain before breaking.

The two thermocouple wires may also be embedded in the die, close together, in two holes perpendicular to the surface, so that the contacting workpiece surface creates the hot junction. Any lubricant films interposed will invalidate such measurements. Such surface thermocouples have been used, apparently successfully, under dry friction conditions.

Frequently, especially in hot working operations, only the free surfaces of the specimen may be observed. Thus, the exit temperature of an extrusion may be taken as indicative of the heat balance existing between initial heat input, heat of deformation, heat of friction, losses to the dies and, by radiation, to the surrounding atmosphere.

Direct thermocouple measurement is usually impractical, although a technique of driving thermocouples into the surface of large workpieces by gun action has been developed [132].

Spot checks of surface temperature may also be made with prod-type thermocouples; in these, pointed, rigid thermocouple leads protrude and establish contact when stabbed onto the hot surface. If the oxide film is penetrated, a true surface temperature is measured.

5.73 Dynamic Thermocouple

A rather attractive method of temperature measurement utilizes the die and the workpiece as the two elements of a thermocouple and is thus, in principle, suitable for instantaneous measurement and recording of interface temperatures. This technique was apparently first used some forty years ago for measuring temperatures in metal cutting. Reichel [133] applied it to thread rolling, while Thompson and Dyson [134] introduced the technique for wire drawing. It was later used by a number of investigators; a typical experimental arrangement, due to Lueg [135] is shown in Fig. 5.18. The carbide die insert A, isolated by the disk D from the die support E, forms one arm of the thermocouple, whereas the drawn wire wound onto the drum H forms the other. A lead, attached at F_1 to the end of the wire, connects to a mercury-wetted contact J attached to the shaft of the drum H. From this, the emf generated in the die throat is recorded on a fast-responding optical recorder V. In the course of the experiment, the distance between the cold junction F_1 and the die throat increases; however, according to Ranger and Wistreich [91] this does not impair the accuracy of the measurement. It is recognized, of course, that the recorded voltage is a low average of the emf generated by a number of thermocouples formed at asperities making metallic contact with the dies. The high-temperature spots are short-circuited by the low-temperature junctions and the average is pulled down; but this should in no way impair the validity of comparative measurements.

Reichel [133] proposed that a more localized temperature may be measured if the die is made up of two disks of different compositions. At the

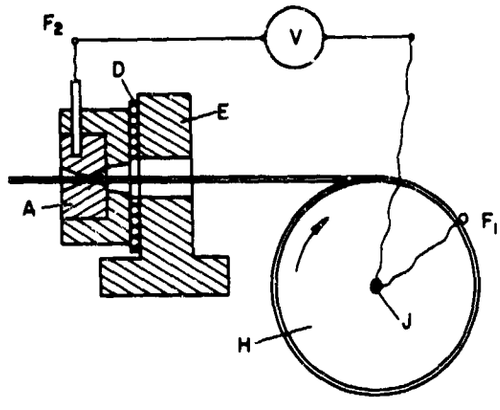

Fig. 5.18. Principle of dynamic thermocouple used in wire drawing experiments [136].

plane of contact, the drawn material forms a conducting bridge between the two thermocouple elements, and thus the temperature at a selected point of the draw cone may be obtained. Reichel also suggested that instead of two die halves, two dies may be used in tandem, with the drawn wire between them forming the electric contact.

The temperature recorded by the dynamic thermocouple could be influenced, of course, by interface films. However, Ranger and Wistreich [91] found that soap films had no effect in wire drawing. Similarly, Lueg and Treptow [136] found that a sufficient number of metallic junctions existed (at least in a static calibration test) to allow the formation of couples. Of course, as soon as fully hydrodynamic lubrication is achieved, such a relationship breaks down.

The basic problem with all dynamic thermocouples is that of calibration. It may be accomplished by immersing the die and a short piece of partly drawn wire into lubricant baths held at varying temperatures. Alternatively, a hollow wire may be part-drawn and internally heated by some means. All of these procedures assume that lubrication in static calibration and during dynamic drawing conditions is similar enough not to affect the validity of calibration.

A critical evaluation by Lueg and Treptow [136] of the various temperature-measuring systems led them to conclude that the dynamic thermocouple is the most suitable for sensing rapid variations due to frictional conditions. The die composed of two disks was considered to offer advantages if various materials are to be drawn, since the thermoelectric force is governed by the choice of the two die components. In contrast, the output of the dynamic thermocouple is a function of the die-workpiece material combination. A comparison of the dynamic and of embedded thermocouples was given by Furey [137].

5.74 Surface Temperatures

Crayons, lacquers, and inks that change their color or change from a solid to a liquid could offer a simple way of measuring surface temperature. Unfortunately, they must be applied after the workpiece leaves the die, and begins to cool. Since the phase or color change is a function of time as well as of temperature, these methods can claim only very approximate accuracy and their usefulness is doubtful even for comparative purposes

unless their application and the cooling rate of the workpiece can be strictly controlled, or if they are used to measure die temperatures.

The maximum temperature a material was subjected to during deformation may be judged from the structure if the material undergoes a phase change or transformation of exactly known temperature, such as the martensitic transformation in steel [138]. The underlying assumption—that the temperature of the phase transformation is not affected by simultaneous deformation—is not proven and measurements of this kind can be only approximate.

Measurement of the surface temperature by some optical means is more practicable (see, for example, Cook and Rabinowicz [104]). Of the available pyrometers, those measuring total radiation or brightness are susceptible to large errors because of variations in surface emissivity. The two-color pyrometer offers substantial improvement, since measurement at two temperatures introduces the ratio of two emissivity values. Therefore, the indicated temperature is dependent only on the slope of the emissivity vs. wavelength curve. Comparative experiments by Burk [139] showed the two-color pyrometers suitable for measurements on rolling mills for steel and stainless steel, even though possible interference from ambient lighting, flames, or loose scale must be considered. An overall improvement is assured if the product is enclosed. Difficulties increase when emissivity is very low and temperatures are relatively low, too. Such is the case in the deformation processing of aluminum and its alloys. Infrared radiation pyrometers with lead sulfide [140], silicon [141], lead selenide, or similar detectors have been used and, if calibrated against a surface of known temperature, give high accuracy. The reproducibility of the surface condition is the only limiting factor.

Radiant heat could also be registered upon infrared-sensitive photographic plates and compared with workpiece surfaces held at a known and controlled temperature, as was done by Boothroyd [142] in a study of temperatures during orthogonal metal cutting. The infrared television camera could serve a similar purpose. No record of using this technique for plastic deformation processes was found.

5.8 STAINING PROPENSITY AND CORROSION

Most lubricants leave a residue on the surface of the deformed material. Sometimes there is no other choice but complete removal, as is the case with glass used in the hot extrusion of steel and other materials. In most instances, however, lubricant residues are left on the surface partly out of necessity and partly for economic reasons. If such residues are exposed to heat—for example, in subsequent annealing—organic residues may oxidize, polymerize and, especially if the vapors are retained, form a highly viscous or even solid, dark colored ("brown") stain. Brown stains are sometimes soluble in organic solvents or may burn off at higher temperatures. The lubricant or its residues may also interact with the metal surface and form unsightly reaction products, or corrode the metal surface itself ("white stain"). Similarly, corrosion may occur on holding the deformed workpiece at ambient temperatures for a prolonged time, especially with aqueous lubricant residues. In some materials, residual carbon may lead to embrittlement.

There are no strictly quantitative tests available for measuring the staining and corrosion propensity of lubricants. A number of simulating tests have been reported in the literature, indicating that no fully accepted, generally valid test has been developed yet. Staining is of particular concern on rolled products which tend to show up discoloration more clearly because contrasts on the large flat surfaces are readily discernible. For this reason, most tests were developed for rolling lubricant applications. There is, however, no reason why the same test should not be applied for all metalworking lubricants. For convenience, tests will be described in groups according to the workpiece material.

The largest number of tests refer to aluminum rolling lubricants, because the high reflectivity of this material and the low annealing temperatures make the staining problem particularly severe. All tests agree that a small measured quantity of lubricant is placed on a standardized sheet surface; differences arise from the shape of the sheet surface used, and from the degree and technique of limiting the evaporation of the lubricant.

The only test designed for hot rolling emulsions has been described by Snow [143]. Test plates with a central depression of 1 1/2 in. diameter are used. One or two milliliters of the emulsion is placed in the depression, and the plate is inserted into an open furnace at a predetermined temperature (for example, 350°C). The plate is removed and examined periodically.

The emulsion dries out after the first few minutes of heating, leaving a residue which may then become brown or black depending on the composition of the emulsion and the temperature of the test. On further heating, the residue may become charred, turn into a white powder, or disappear altogether.

Guminski and Willis [144] report on two tests. Yellow or brown oil stain tendency is checked by placing three drops of the oil in 70 mm diameter, 15 mm high capsules, the lid of which is perforated by three holes of 1 mm diameter. After heating for 1 hr in an air-circulating furnace heated to 350°C, the inner surface of the boxes is examined. In the test for white stains, two drops of the lubricant are placed on a 3.5 in. square aluminum container sheet of 0.08 mm thickness, and covered with a sheet of the same size. The edges of this sandwich are covered with aluminum foil, and the foil is secured at the four corners with paper clips. The completed sandwich is then heated slowly (in 30 to 40 min) to 350°C in an air-circulating furnace and held for 1 hr; subsequently, the temperature is raised to 450°C and, after holding for 2 hr, the specimens are cooled on air. The separated specimens are then inspected for white stains.

In the test described by Sargent [145] a small (0.8 ml) sample of the oil is applied by pipette to one side of a degreased "Standard Stain Plate." These "plates" are 5 5/8 in. diameter and 0.064 in. thick, and specially fabricated for uniformity of surface flatness and brightness. The oiled plate is placed on the floor of an electric muffle furnace held at 345°C. After heating with the door closed for 30 min, the specimen is removed and the stain compared to a graded series of standardized plates. The test is sensitive to the surface condition and flatness of the test plate, draft through the furnace, temperature, and oil composition. Periodic calibrations must be made using standardized oils and comparison plates. Used oils are tested in an undisclosed modification of the standard test.

The effect of annealing temperature, oil quantity, and excess of air on brown staining during the annealing of aluminum sheets was systematically investigated by Zlotin et al [146]. Sheets of 1.2 x 100 x 250 mm size were coated with the lubricant, clamped into piles and heated at a rate typical of industrial practice. The effect of the form and size of the gap between adjacent sheet surfaces was investigated by using one sheet at a time, dense

packs and loose packs, packs made of sheets with a mirror surface and with rough surfaces.

Staining tests for steel rolling emulsions, described by Nekervis and Evans [147] were performed in an electric tube type furnace. Plant annealing conditions were followed by heating from room temperature to 680°C in 30 min, with subsequent cooling to 120°C by means of an air jacket around the hot zone of the furnace. The atmosphere consisted of oil pumped nitrogen and 4% hydrogen. One drop of the lubricant was placed in a ball indentation in the middle of a single sheet. Stains formed in this method were heavier than observed in practice, but believed to be representative. Correlation with plant experience was not available.

The staining propensity of steel rolling lubricants was checked by Griffin [76] with a test strip annealer, originating with U. S. Steel Corporation. It consists of a test strip holder positioned in a glass tube which can be purged and filled with the annealing atmosphere to be used. The 1 x 12 in. test strip is coated with a lubricant and resistance heated to the annealing temperature; after cooling, it is examined visually for cleanliness.

Brown stains ranging from thick varnish deposits to thin, slightly colored films may also develop on annealed brass and copper strip. Reynolds [13] described a test in which strips of 2 in. width, 5 in. length, and 0.015 in. thickness were coiled loosely over a 3/8 in. diameter arbor, immersed in the oil to be tested, and then coiled tightly (under unspecified tension) and bound before removing the arbor. The coil was placed in a furnace at 500°C for a period of 45 min, using a neutral gas as an atmosphere. The coils were examined, after cooling, for staining. The stains were generally heavier than in production practice but gave the right order of merit for various lubricants.

Water stains may be caused by emulsions or even moisture condensations from the atmosphere. Belfit and Shirk [148] described two types of tests. For the laboratory tests, a sandwich of four brass strips (3.5 in. long, 2 in. wide, 0.015 in. thick) is made up with a 1/2 mm gap between the strips. The sandwich is then submerged in the emulsion, and the strip surfaces are observed after one, two, and three days' exposure at room temperature or after short intervals at elevated temperatures. The second test is also performed in the laboratory, but is a simulation of production conditions. Lengths of 2-3 in. wide and 0.02 to 0.04 in. thick strip are

rolled on a two-high laboratory mill with the test emulsions; after rolling, coils are wound, strapped, and stored for ten days. The test coils are rated for staining in the as-rolled condition and after annealing and pickling.

All staining tests are, by necessity, qualitative and become meaningful only if control experiments are carried out on lubricants of known staining propensity in production practice.

5.9 LUBRICANT COMPOSITION AND TECHNOLOGICAL PROPERTIES

Metalworking lubricants may be rather well defined, relatively pure substances, a mixture of relatively pure starting materials, a naturally occurring mixture of more or less reproducible quality, or a proprietary combination of any of the foregoing groups. Specification of certain physical and chemical properties is a practice that has found increasing acceptance in more recent years; even though exact compositions are not necessarily known or disclosed, factors essential for the control of the lubrication process can often be specified without violating proprietary interests.

Standardized methods of determining most physical and chemical properties are available in the publications of the American Society for Testing and Materials, Committee D2 [149], the American Petroleum Institute and the (British) Institute of Petroleum. Corresponding standards exist in other countries. The most frequently encountered specifications are defined in the Appendix.

A review of test methods has been given by Bastian [150], and some details of the significance of chemical properties will be found in texts dealing with fats [151] and fatty acids [152].

An almost endless variety of tests specifically designed for a particular lubricant application exist. They are sometimes a modification of some existing standard tests or may be developed entirely without precedent.

Emulsions and aqueous dispersons are the subject of many technological tests. The stability of emulsions is believed to be an indicator of lubricating quality and is also an important factor in judging the suitability of a particular composition for recirculating systems with given heating, cooling, filtering, and agitation characteristics. Stability is usually determined by the amount of cream or free oil separating during a specified period of time, while holding the emulsion of the desired concentration at close to ambient (typically 20-35°C) or at a slightly elevated (up to 70°C) temperature. Very

stable emulsions may have to be subjected to separation by centrifuging. Such tests cannot give an indication of what will happen in production under the effect of contact with fresh metal surfaces.

An apparatus, developed by the Standard Oil Company of Indiana has been reported [76] for the measurement of the cooling ability of solutions. A thermocouple is suspended in a guillotine, heated, and then dropped into the lubricant. The cooling rate, recorded on a fast-response instrument, is a measure of quenching ability.

Wetting properties of lubricants are of considerable concern when complete coverage of the working surface with a preapplied film has to be relied upon. In flood applications, too, it is often believed—usually without clear substantiating evidence—that good wetting is a desirable feature of a lubricant. Most wetting tests are qualitative or semiquantitative. In the simplest from, the lubricant is placed on a prepared test plate which is then inclined at an angle to allow the fluid to run. Slightly more quantitative is the method where a measured quantity of lubricant is placed on a prepared horizontal metal surface and the rate of spread of the drop is measured. This technique has found widespread use in testing the wetting ability of glasses on metal surfaces for hot working purposes. A more accurate measure of wetting is, of course, obtainable from measurements of the contact angle, and equipment is now available to do this at both room and elevated temperatures.

A technological test for wetting has been described by Snow [143] for aluminum rolling emulsions. An emulsion sample is placed in a trough, and a roller, partially submerged in the emulsion, is rotated. After stopping rotation, the pattern and rapidity of dewetting of the surface is observed. Snow also describes the use of the Draves test originally used by textile mills for the evaluation of wetting and detergent solutions. The time required for a skein of cotton to become wetted and sink in the emulsion is a measure of wettability. Since milky emulsions will prevent direct observation, the test is slightly modified by attaching a lightweight thread to the skein which, hooked into a plumb-line, gives an indication of the time wetting takes place.

In some instances the wetting of the workpiece with the lubricant occurs through a surface reaction, which may cause rapid erosion or corrosion of the surfaces. Experiments for the determination of such tendencies have

been devoted mostly to hot-working lubricants of the glass or ceramic type. Rate of reaction may be determined by weight loss, dimensional loss of a sheet, or by taking microhardness measurements close to the reacted edge so as to determine the depth to which reaction between lubricant and workpiece material occurred. More sophisticated techniques—such as radioactive tagging—are usually necessary for cold working lubricants, since reaction rates are slower.

5.10 SUMMARY

The preceding sections have shown that, in almost all applications, the lubricant is expected to fulfill a great number of requirements. While measurements can be made to attach some numerical values to lubricant quality, the meaning of these measurements is by no means always clear.

As evident from the array of techniques available for measuring friction, the ability of the lubricant to reduce friction has been and is still most frequently investigated. Yet, apart from the use of coefficient of friction values in calculations of forces and power requirements, the great reliance placed on the knowledge of an absolute friction value is not always justified. Tests that yield a precise coefficient of friction often operate under idealized conditions that are inapplicable to the real process; relatively simple tests, designed to permit merely a ranking of lubricants, could often serve a more useful end. It is very unlikely that a single test would suffice, but a few well-chosen tests could certainly yield meaningful data for lubricant development. Tests and experiments of a more fundamental nature, including those aimed at deriving friction coefficients, are justified mostly by the hope that they will shed some light on operative mechanisms and define the role of various parameters.

Fortuitously, tests primarily designed for the measurement of friction often reveal important information on pickup, wear, and ability of the lubricant to maintain a continuous parting film separating the die and workpiece surfaces. Quantitative observations on pickup and wear are relatively scarce, however, compared to the vast literature available on measured friction values. The problem lies in finding a satisfactory method of describing the phenomena under widely ranging conditions and in the long times required for running experiments before relevant information can be derived. In particular, there is no direct proof that any of the small-scale tests can

adequately simulate the conditions created by multiple passes, widespread in all deformation processes. Nor do they incorporate changes occurring during prolonged use—the gradual deterioration of lubricants due to contamination, oxidation, bacterial attack, and thermal effects or the gradual improvement due to transformation of some components into more powerful lubricating agents.

Somewhat more successful have been the attempts to study the effect of lubricants on surface finish, corrosion, staining on annealing, and other side effects of industrial importance. Although much remains to be done, semiquantitative indication of lubricant quality in these respects represents a beginning.

The ultimate judgment as to the suitability of a lubricant still remains its performance in production practice. This does not mean that observations in full-scale production are the best guide to absolute lubricant quality. Once a lubricant is accepted in a production unit, surface preparation, lubricant application, and process variables are gradually tailored to yield optimum performance with that particular lubricant. Whenever a new lubricant is tried, work practices developed for previous ones may adversely affect its performance, and superior lubricants may be condemned through a failure to optimize production conditions. It may happen, of course—especially if production practices are less than optimum—that an experimental lubricant may perform better because greater care is exercised during its testing. The effects of process conditions on lubricant performance are still inadequately understood, and this leads all too often to the frustrating experience of a lubricant performing satisfactorily in one plant while failing completely in another. For all these reasons, attempts at evaluating lubricants in a more controlled laboratory environment are still needed and should intensify in the future, so that a firmer, more scientific foundation for lubricant development and its integration into the whole process can be laid.

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Chapter 6

ROLLING LUBRICATION

John A. Schey

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6.1 INTRODUCTION

As discussed in Section 2.2, rolling is a rather complex deformation method with wide variations in interface conditions. Accordingly, wide variations in lubrication techniques may be expected.

Some rolling practices require little or no lubricant. Thus, many materials may be hot rolled without a special lubricant, the natural oxide taking care of separating the metal and roll surfaces effectively enough. Slow-speed cold rolling of steel and of some other more common engineering materials generates relatively little heat, and the lubricant may be periodically applied and of simple composition. Some of the simplicity is deceptive, though, because the natural fats frequently used are actually very complex and—even though unintentionally—sophisticated lubricating media. The lubricant becomes critical, however, in rolling at high speeds and heavy reductions, especially with materials that tend to adhere to the roll surfaces. Even a minor change in the lubricant may lead to a sequence of changes in the gage and shape of the rolled product, its surface finish, and in the ability to keep the mill operation under control. It is not surprising, therefore, that rolling lubrication has attracted most attention of all metalworking processes over the last 30 years.

Much of the research has been quite fundamental, inquiring into the mechanism of lubrication and seeking an understanding of governing factors, so as to permit a more scientific control of the system comprised of the rolled material, the lubricant and the rolling mill itself. This tendency has been reinforced by the appearance of high-speed tandem mills, on which an increasing amount of automation has tended to eliminate errors due to human judgment but, at the same time,

imposes more critical requirements for reproducibility of conditions in the roll gap.

The total quantity of lubricants involved in rolling perhaps outweighs the combined quantities used in all other metalworking operations; therefore, much effort has also been directed towards optimum methods of application, removal, recovery, and disposal.

Research aimed at elucidating fundamental relationships of more universal importance will be discussed first, followed by a survey of the most frequently used lubricant types, and finally, by a summary of experimental data and industrial practices pertaining to specific workpiece materials.

6.2 FRICTION AND LUBRICATION EFFECTS

Friction and lubrication manifest themselves in a great number of ways, and no systematic treatment of these could be attempted without first establishing the basic mechanisms operative in rolling. Although no general agreement exists, some working hypotheses can be developed which will serve at least as a framework for further discussion.

6.21 Lubricating Mechanisms

In discussing friction and lubrication mechanisms in Chapter 3, a wide spectrum of conditions ranging from dry friction, through boundary lubrication, thin film or mixed lubrication, to hydrodynamic lubrication were distinguished. The great flexibility of the rolling process is shown by the fact that all these mechanisms may operate under certain processing conditions.

Dry Friction and Boundary Lubrication

Rather paradoxically, rolling lays relatively modest requirements on the lubricant even though deformations may be heavy. The reason for this is to be found in the observation (Section 2.22) that interface sliding rapidly diminishes from the entry to the neutral point and, perhaps most importantly, that the area of contact between roll and strip surface is continually shifting on the roll surface. Thus, adverse effects such as roll pickup take a longer time to develop than in a process with continuous material contact such as wire drawing.

For the above reasons, dry rolling (that is, rolling without an intentionally applied lubricant) is not only possible but widely practiced, especially in the hot rolling of materials that show only moderate adhesion to the roll surface and that also form an oxide film which is either partially plastic or friable so it can follow, at least to some extent, the extension of surfaces.

The pattern of broken scale on a hot-rolled mild steel specimen surface (Fig. 6.1) reveals that some fresh metal must have been exposed [1]; however, as discussed in Section 2.24, the surface probably breaks just prior to entering into the roll gap, therefore, there may be sufficient time to allow a very thin protective oxide film to form on the freshly exposed surface. In rolling practice it is also customary to cool the rolls with water. Even though water is not a lubricant in the accepted sense, one might surmise that, as a contaminant and as a steam former, it does help reduce adhesion between the roll and the steel surface. Oxide films on stainless steel are much thinner but rather powdery and, again, provide adequate protection against seizure and pickup formation. A protective oxide forms also on nickel, copper and, to some extent, on titanium (Section 4.28).

In contrast, the oxide of aluminum is brittle and adheres firmly to the base metal; therefore, on breaking up in the roll gap, it exposes virgin aluminum surfaces that tend to weld to the roll surface, giving rise to a roll coating which could soon lead to a total seizure of the workpiece. For this reason, lubricants are mandatory in the hot rolling of aluminum.

Oxides of high shear strength lead to high frictional forces and to the development of zones of sticking in the arc of contact. Therefore, they control the uniformity of deformation and the magnitude of roll forces and power consumption. For these reasons, the value of the coefficient of friction in dry rolling has been of interest from relatively early days and has been used as a means of investigating the effects of oxidation.

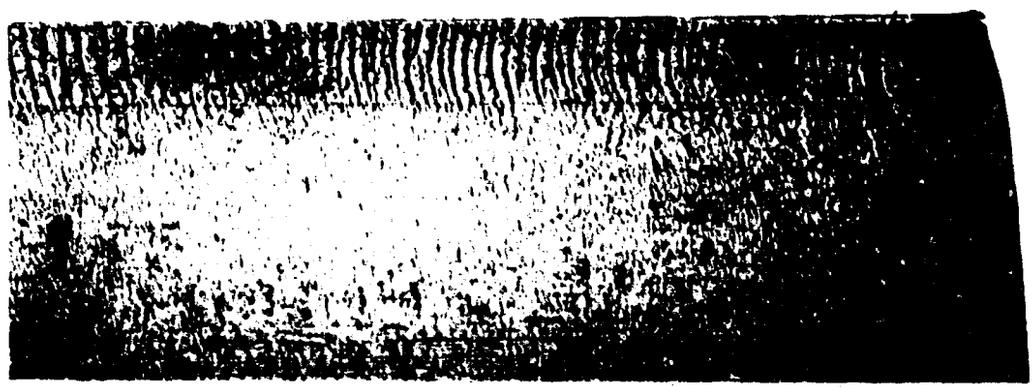

Fig. 6-1. Break-up of scale on mild steel heated to 900°C and rolled at 700°C with 30% reduction [1].

Ekelund [2] found in the hot rolling of mild steel that the coefficient of friction decreased with increasing rolling temperature, indicating that the thicker films formed at higher temperatures lubricated better. The friction value was determined from the maximum angle of acceptance (Section 5.22). This method is of limited accuracy, especially under production conditions, because the roll speed, the approach velocity and nose shape of the workpiece, and the surface finish of the rolls all have a marked effect, as shown by Kortzfleisch [3]. Invariably, the angle of acceptance (and thus the calculated friction) decreases with increasing roll speed. Laboratory investigations [4] revealed that friction decreased with increasing temperature and decreasing rolling speed on specimens with slightly rounded or tapered noses, while friction was actually higher at the higher temperatures and was independent of roll speed with specimens of sharp leading edges. Under production conditions, these tendencies may easily counterbalance each other and temperature effects on friction may be lost.

A detailed evaluation of the effects of scaling by El-Kalay and Sparling [5] has shown that heavier oxide films reduced roll force and torque by up to 25%. The effect was greater for larger reductions and with rough-ground (170μ in. AA) rolls than with smooth rolls (25μ in. AA surface finish). Friction decreased with increasing temperature on rough rolls and thinner oxide films, but increased with smooth rolls at all oxide film thicknesses. It would appear that important variables were inadequately covered in earlier work, and further evaluation of the detailed data given by El-Kalay and Sparling should prove fruitful.

It is remarkable, though, that the trends found originally by Ekelund have been repeatedly confirmed in the laboratory, irrespective of whether the coefficient of friction has been derived from forward slip or from simultaneous measurement of roll force and torque (Fig. 6.2). The latter method also allows calculation of an interface shear strength. Experiments conducted on steel in vacuum by Pavlov et al. [6] and in vacuums of various degrees and in argon by Pavlov et al. [7] show that, invariably, friction is higher when oxide formation is suppressed. This serves as direct evidence of the moderate yet significant lubricating qualities of iron oxides. Similar trends were found for nickel. In some further work of Pavlov et al. [8] friction was unexpectedly low with titanium at all rolling temperatures, and actually increased slightly with increasing oxidation. In contrast, the refractory metals molybdenum

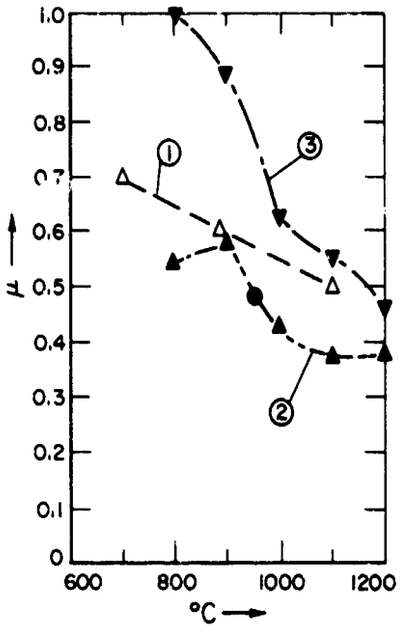

Fig. 6-2. Coefficient of friction in hot rolling low-carbon steel in air (1: Ekelund, 2: Pavlov) and in vacuum (3: Pavlov [1]).

and columbium (niobium) gave a rather high friction in vacuum, which dropped substantially when oxidation was permitted. Schey [1] found that, at typical hot rolling temperatures, friction (calculated from forward slip) decreased with temperature for stainless steel but increased slightly with aluminum. These trends are in reasonable agreement with the known properties of oxides (Section 4.28).

Intentional dry film lubrication is rather rare in rolling. Lamellar solids such as graphite or molybdenum disulfide have been used experimentally for the hot rolling of steel and will be discussed in Section 6.4. For cold rolling purposes, uniform distribution of the lubricant is of extreme importance if the desirable uniform surface finish is to be achieved, therefore, all lubricants must be applied in a carrier which assures even distribution. In this instance the carrier contributes to the lubricating mechanism; a purely solid film mechanism is maintained only if the carrier evaporates. This is only occasionally encountered, e.g., with fluorocarbon polymers (PTFE).

Cold rolling with dry rolls is very seldom practicable except for small, experimental quantities. More often than not, neither the rolls nor the workpieces are handled carefully enough to be considered really clean. Oily

contaminants from contact with fingers and cleaning rags, and even films adsorbed from the air, may act as lubricants. In fact, it is very difficult to find reliable data for true dry rolling (see also Section 6.24).

Thin Film Lubrication

With a very few and rather special exceptions, rolling lubricants are liquid. The mechanism by which they act has been a subject of extended research and often controversy. Because of the high interface pressures, the notion that lubrication must be essentially of the boundary type used to be rather widespread. This contention was often supported by experimental results that seemed to indicate a constant coefficient of friction, which could be interpreted as a sign of a constant, unchanging lubricating mechanism. The validity of this assumption was contested by the fairly early recognition that the bulk viscosity of the lubricant is of great importance and that increasing viscosity, in general, decreases friction. As a result of a number of investigations, the basic effects are now rather well clarified, even though their interpretation is not yet unanimous. However, some of the differences in views relating to the lubricating mechanism are more a matter of detail than one of overall concept.

In general, it is recognized that lubrication must be of the thin film or mixed type, with hydrodynamic and boundary elements both playing a role. Some of the most convincing evidence for the thin film mechanism came from investigations on aluminum. Because of the high adhesion of aluminum to roll surfaces, boundary contact, lubricant breakdown, and metal-to-metal contact become immediately evident in a rapid rise of friction. In the rolling of 0.080 in. thick, 6 ft long strips on 14.3 in. diameter rolls, Schey [9] observed that roll force and forward slip first rose gradually, then—after a critical reduction had been reached—rather steeply with pure aluminum and aluminum-1.25% manganese alloy strips (Fig. 6.3). Calculating average external coefficients of friction both from roll force and from forward slip by a number of methods, the derived values varied according to the chosen method, but the trends were always the same, showing a rather low (approximately 0.04) coefficient of friction in the first regime, and high values (rising to 0.2) in the second regime. He concluded that the first regime corresponded to predominantly hydrodynamic lubrication, and the second to predominantly boundary lubrication, although both mechanisms must have been operative in both regimes.

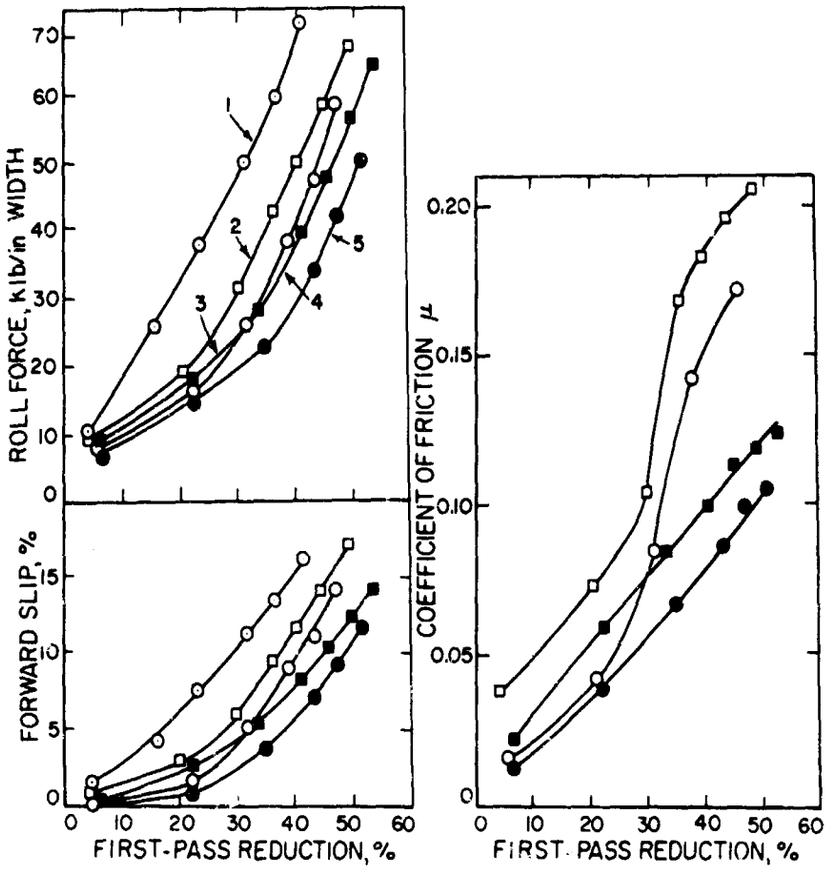

Fig. 6.3. The effect of lubrication and roll surface finish on roll force, forward slip, and calculated friction (Al-1.25% Mn strip; 1: dry rolls; 2 and 4: base mineral oil 7.3 cs at 20°C; 3 and 5: compounded oil; 2 and 3 before regrinding) [9].

Supporting evidence came from observations of rolled surfaces. At low reductions, the surface was matte and, under the microscope, revealed small impressions (Type 1, Fig. 6.4a) identified as hydrodynamic pockets. Roll grinding marks were not clearly imprinted, indicating that the lubricant film was at least locally thick enough to separate the two surfaces. Pockets were transverse to the rolling direction on strain-hardened strip and reflected the grain structure on annealed strip. With increasing pass severity the hydrodynamic pockets broke down into smaller units, conformity with the roll surface became more evident (Type 2, Fig. 6.4b and c) and, finally, in the predominantly boundary regime, most hydrodynamic pockets disappeared (Type 3, Fig. 6.4d). In the absence of a powerful boundary additive, some damaged, smeared areas appeared, which could be interpreted as points of

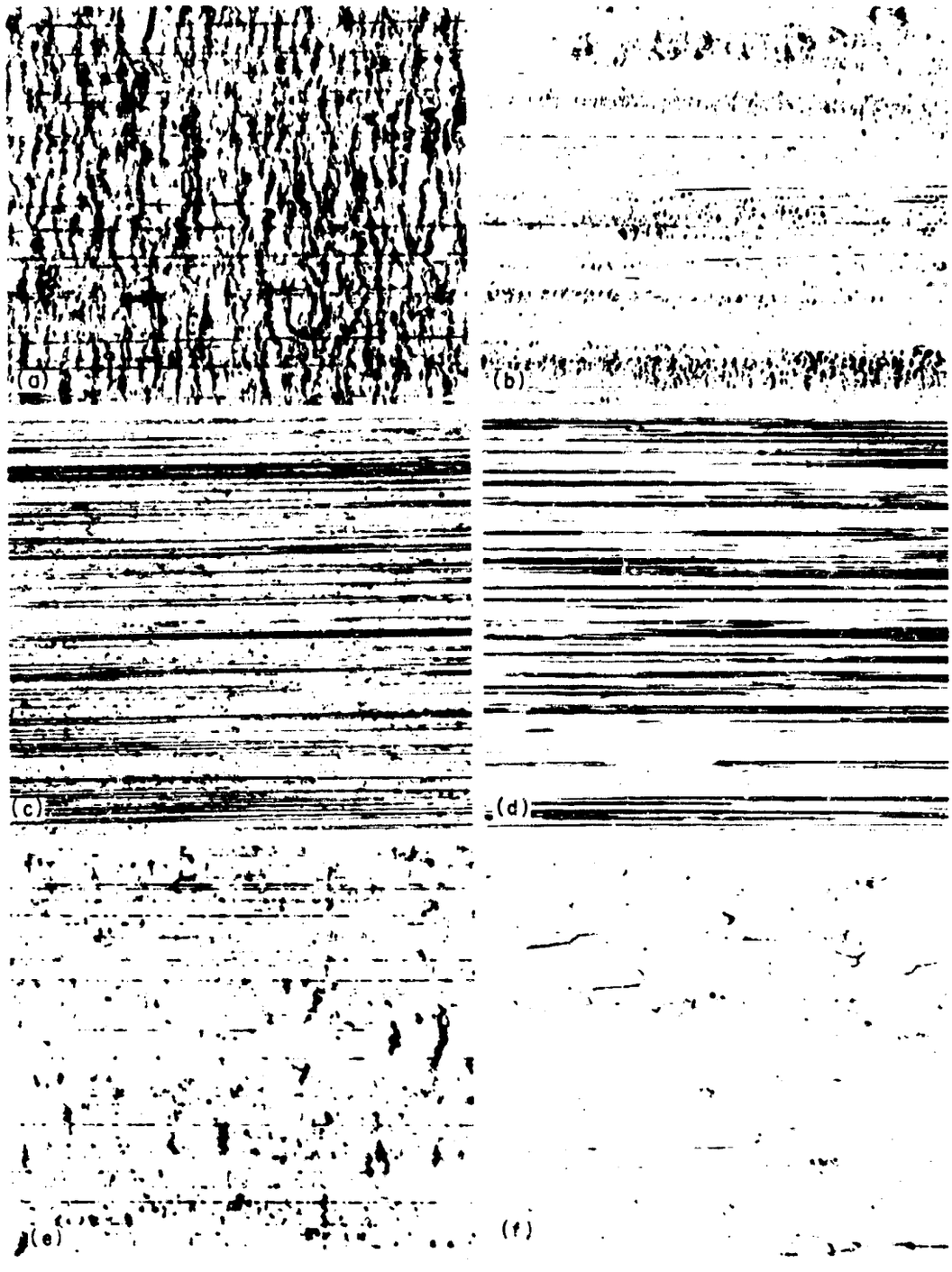

Fig. 6.4. Surface appearance of hard Al-1.25% Mn alloy strip rolled at 43 fpm [16].

	Lubricant	Pass Reduction, %	Roll Surface, μ in. AA
(a)	SAE 30 oil	23	10-12
(b)	SAE 30 oil	65	10-12
(c)	Mineral oil 7.3 cs at 20°C	21	10-12
(d)	Mineral oil 7.3 cs at 20°C	47	10-12
(e)	Mineral oil 7.3 cs at 20°C	5	2-3
(f)	Kerosene	49	2-3

metal-to-metal contact which were then smeared while the strip passed over the zone of forward slip (Type 4, Fig. 6.4f). Rolling on a roll with bright (2.8 μ in. AA surface roughness) finish with a low viscosity (7.3 cs at 20°C) base mineral oil, lubricant pockets were rather small (Fig. 6.4e) and the strip surface fairly smooth. Measured in a direction perpendicular to rolling, the surface roughness remained of the same order of magnitude as that of the roll surface until the predominantly boundary regime was reached, when surface roughness suddenly increased to values as high as 10 μ in. AA on account of the presence of smeared-over, damaged portions.

That the second regime could be identified as predominantly boundary was also proven by the observation that the addition of a boundary additive such as 5% rapeseed oil to the base mineral oil shifted the onset of sudden force rise to higher reductions and also reduced resulting surface damage even in the boundary regime. Additional evidence will be found in Sections 6.4 and 6.5.

Whitton [10] analyzed the results of friction experiments with back tension by Whitton and Ford [11] for the influence of process variables. While he did not present his results in terms of a lubricating mechanism, his conclusions confirm the above picture. Thus, the "surface damage" found with highly viscous lubricants (that registered low friction values of 0.040 to 0.046) is identical with the appearance of massive hydrodynamic pockets in the surface. With somewhat poorer lubricants, the surfaces were burnished; this was attributed to flattening over of asperities by the smooth rolls and by the action of the lubricant as a cutting fluid when slight scoring took place. Dry (but not necessarily very clean) rolls or very poor lubricants, associated with friction values of the order of 0.1 led to severe tearing of the surface. It is interesting to note that, relying on observations made in wire drawing, Wistreich [12] had already suggested that a quasihydrodynamic (thin film) lubricating mechanism could well explain these results.

Accordingly, lubrication in rolling may be imagined as mixed film lubrication in which the proportion of hydrodynamic and boundary elements is a function of process conditions. Lubricant entrapment is encouraged by the very favorable geometry (in a typical cold rolling situation, the angle between the roll surface and entering strip is of the order of 1-3°). The wedge effect is further augmented by the velocity difference (backward slip) in the entry zone, which gives rise to hydrodynamic lift. It is not necessary and, indeed, not likely that the film be entirely continuous. Electrical resistance measure-

ments have shown [9] that some metal-to-metal contact occurred even at very low reductions. Moderate roughness of the rolls and particularly that of the strip surface, however, are certainly beneficial in trapping lubricants in micro-pockets. Even though interface pressures increase and sliding velocities decrease towards the neutral point, it is conceivable—and supported by evidence of rolled surfaces—that much of the trapped lubricant is unable to escape and deformation takes place through this trapped lubricant film. With increasing pass reductions, initial boundary contact areas increase and, if adhesion between workpiece and rolled material is high, the sudden rise in friction shown in Fig. 6.3 is observed.

Less reactive materials, such as aluminum-5% magnesium alloy or mild steel did not show the same upturn of forces or forward slip values in Schey's work. However, since then LeMay et al. [13, 14] have shown in the rolling of 0.064 in. thick low carbon steel strip on 6 in. diameter rolls that at reductions of 60 to 70% a similar rise in friction may be observed on this material too. In contrast to Schey, however, they found that calculated friction may be rather high also at low reductions (see Fig. 6.20), and attributed this, in agreement with Thorp [15], to insufficient sliding speeds at the entry point at low reductions. These low velocities may not provide enough hydrodynamic lift, thus giving more boundary contact than at somewhat heavier reductions, when optimum conditions are assured. This point is certainly worthy of further investigation.

A further proof of boundary contact in the rolling of aluminum was provided by Schey [16], who found that the random variations in roll forces (Fig. 6.5) reported by most investigators working with short strips may be eliminated if an equilibrium condition is first established by running the rolls for a prolonged period against wipers or against each other. When a strip long enough to cover several roll circumferences is then rolled, a fairly steady force is indicated while rolling in the predominantly hydrodynamic regime. However, as soon as pressures are high enough to cause marked boundary contact, roll force rises in a stepwise fashion from revolution to revolution and fails to reach a maximum with an uncompounded mineral oil even after four or five revolutions. In contrast, in the presence of a boundary additive, a steady force is achieved or approached after the second revolution (Fig. 6.5), indicating that no further pickup occurs. This point was also directly confirmed by radioactive tracer experiments in which a

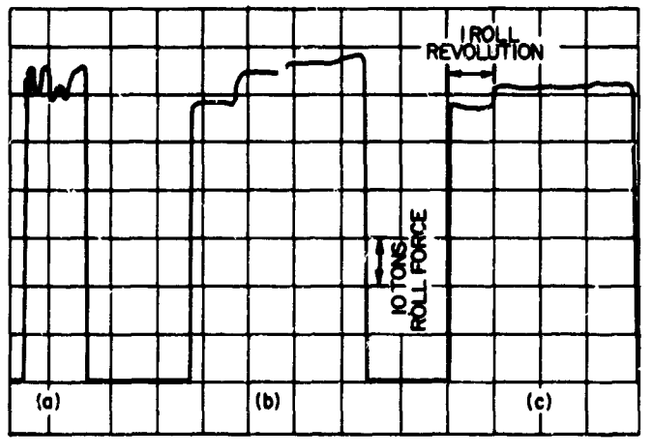

Fig. 6.5. Typical roll-force records: (a) short strip rolled at random time intervals; (b) long strip rolled with special technique and a base mineral oil; (c) as (b), but compounded oil [16].

small amount of copper incorporated in the workpiece material was activated, and thus the rate of material transfer onto the roll surface could be directly monitored.

Evidence of thin film lubrication can also be gained from rolling practice. Even though individual pass reductions are seldom heavy enough to show the rapid force changes observed in laboratory experiments and repeated contact on a long strip tends to equalize roll pickup, a faint cast of aluminum or copper may often be observed on the roll surface, indicating some metal transfer even under practically acceptable process conditions. The presence of fines in recirculating oil systems also suggests that some of the workpiece material is transferred to the rolls and is then worn away to appear in the form of finely distributed particles.

Hydrodynamic Lubrication

The very high rolling speeds used in the rolling of thin steel strip combined with the high viscosity of lubricants normally employed has led several researchers to suggest that lubrication may, in fact, be regarded as purely hydrodynamic. Roberts [17] produced a solution for perfectly rigid rolls, perfectly rigid/plastic material, and a lubricant of constant viscosity. From a consideration of the energy balance in the roll gap, he derived a solution that shows the neutral point to be close to the exit point for all practical process conditions. However, the solution predicts the neutral point to move backwards in the roll gap with increasing back tension, which is contrary to

both basic rolling theory and experience. No doubt, the simplifying assumptions are too sweeping to allow a valid solution, but at least the proximity of the neutral point to the exit point is correctly predicted.

More complex mathematical solutions have been developed by Cheng [18] and Bedi and Hillier [19]. Both recognize the presence of a friction hill; Bedi and Hillier assume a constant lubricant film thickness of constant viscosity, while Cheng allows for a variation of lubricant viscosity as a function of pressure and temperature. By solving the equations for the plastic yielding of the workpiece material and for the pressures in the hydrodynamic film simultaneously, solutions are arrived at that correctly predict the effects of tension and of rolling speed; unfortunately, all solutions indicate peak pressures close to the center of the arc of contact, whereas rolling theory as well as direct measurements of pressure distribution [20] show that, under the postulated conditions, the pressure peak should be very close to the exit plane.

Despite their shortcomings, these attempts should be regarded as promising beginnings, since there is little doubt that conditions closely approximating hydrodynamic lubrication can be obtained under a favorable set of conditions (high viscosities and rolling speed). True hydrodynamic lubrication may, however, be objectionable. With very low friction, the rolls refuse to bite; it is also well known plant experience that if the lubricant is "too good" (that is, if it lowers the coefficient of friction too much), mill control becomes more difficult because the strip tends to wander, skidding sideways in the roll gap. There is thus possibly a minimum desirable "running" friction value, although the magnitude of this has not yet been determined.

Aqueous Systems

Of all potential lubricants and lubricant carriers, water has the greatest specific heat and therefore the greatest cooling ability. It is often used in hot rolling purely for the purpose of keeping the roll surfaces at acceptable temperatures. In lubricating systems, however, it is essentially the carrier for substances that are able to reduce friction either by hydrodynamic or boundary lubrication. Unfortunately, confusion in nomenclature tends to make assessment of published data rather difficult. In this chapter, the following terminology is used: mechanical dispersions are aqueous systems in which a lubricant is dispersed by purely mechanical means, and separates very rapidly as soon as agitation is ceased. Emulsions are aqueous systems in

which the oily phase is suspended by the addition of emulsifiers as defined in Section 4.3. The dividing line between these two categories can be rather vague, as discussed in Section 6.33. Solutions are true chemical solutions of a water-soluble substance.

The mechanism of lubrication with aqueous systems is still largely unknown. With mechanical dispersions, it is usual to speak about "plating out" of the oily phase on the metal surface, and a performance close to that of the dispersed phase is normally expected. Small quantities of emulsifier may, in some unknown way, aid or hinder "plating out." For example, Whetzel and Rodman [21] found that 0.5% emulsifier added to a natural fat caused the coefficient of friction to drop noticeably in the rolling of low carbon steel, while 4% emulsifier raised it above the value registered with no emulsifier added. A measurement of the oil film thickness deposited by drawing the strip straight through the aqueous system at a constant speed showed that a maximum film thickness of close to 20μ in. was obtained with a very low (0.05%) emulsifier content; further increase in emulsifier caused the average film thickness to drop to about 10μ in. but gave a much more uniform coverage.

Some evidence of the action of aqueous systems can be derived from data reported by Lloyd [22] who rolled, presumably, steel strip (of unspecified thickness) through a standard number of passes and measured the final thickness. As shown in Table 6.1, the efficiency of neat lubricants was determined by their viscosity, even though the substances represented a wide range of chemical activities. When 5% of the same substances was dispersed or dissolved in water, performance changed greatly. Oleic acid and mineral oil formed mechanical mixtures; therefore, they plated out and lost none of their lubricating ability. The detergent was partly soluble in water, formed an emulsion, and lost some of its performance. Glycerine, which was completely soluble, became practically worthless. Thorp [22] pointed out that if it was assumed that 40% of the detergent formed a mechanical dispersion, all experimental points (both for the neat substances and the aqueous mixtures) lie on a straight line when the logarithm of viscosity is plotted against final thickness, suggesting that lubrication is essentially hydrodynamic.

Minor variations in the base oil or emulsifier, the presence of rust-inhibiting and antifoaming additives, and even incidental variations in composition greatly modify lubricant performance, and the whole subject of

TABLE 6.1

Lubricating Performance of Substances and Their Aqueous Dispersions [22]

Lubricant	Molecular Weight	Exit Thickness in.	Viscosity at 38°C, cs	Water + 5% Lubricant Exit Thickness, in.	Water + 5% Lubricant Viscosity at 38°C, cs
Water	18	0.018	0.66	—	—
Mineral Oil	250	0.013	5	0.013	1
Oleic acid	282	0.009	21	0.009	1
Detergent	750	0.007	40	0.010	1
Glycerine	92	0.007	224	0.016	1

aqueous lubricants is a rather secretive art. Information such as is available will be discussed in conjunction with a description of lubricants for various strip materials.

6.22 Effect of Lubricant Viscosity

If hydrodynamic lubrication plays a significant role—at least in the predominantly hydrodynamic regime—increasing lubricant viscosity should lower friction. Indeed, a number of results have been reported that confirm this contention. Thus, Whetzel and Rodman [21] state that in rolling steel with a variety of fatty lubricants, friction decreased proportionally with the logarithm of the viscosity increase. Unfortunately, most published data suffer from the uncertainty introduced by other incidental but by no means negligible variables. All too frequently, substances of different viscosity also had different composition and boundary lubricating components, as in the above noted example.

The most valuable data are to be found in the work of Thorp [15], who chose three members of the homologous series of paraffins: hexane (C_6H_{14}), dodecane ($C_{12}H_{26}$), and hexadecane ($C_{16}H_{34}$). At higher speeds, where predominantly hydrodynamic lubrication must have been attained, the coefficient of friction (calculated from the roll force by the equations of Bland and Ford) decreased linearly with the kinematic viscosity of the lubricants on a log-log plot (Fig. 6.6). Thorp also observed the presence of hydrodynamic pockets on the strip surface, and the "surface damage"

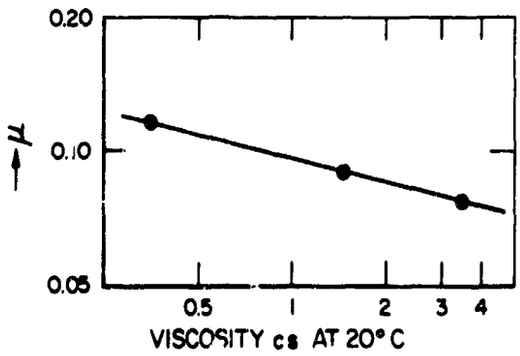

Fig. 6.6. The effect of viscosity in rolling low carbon steel strip with high purity paraffin [15].

reported by Nekervis and Evans [23] in the rolling of steel strip with various, rather viscous lubricants must also be interpreted as evidence of hydrodynamic lubrication. A comparison of hydrodynamic pockets obtained with lubricants of different viscosity by Schey [9] makes it clear (Fig. 6.4) that, for the same roll surface finish, heavy lubricant entrapment resulted in a severe distortion of the surfaces with an SAE 30 engine oil, whereas only traces of hydrodynamic pockets were found between roll grinding marks with a base mineral oil of 7.3 cs viscosity at 20°C. Some of the hydrodynamic pockets persisted with the SAE 30 oil to high reductions, but total conformity with the roll surface and absence of hydrodynamic pockets were noted with the lighter oil.

6.23 The Effect of Rolling Speed

When a long strip is cold rolled from a coil, the strip end is entered ("threaded") at a low speed, typically 50-200 fpm. On gradual acceleration to production speeds (typically 1000 to 1500 fpm for aluminum, 3000 to 5000 fpm for steel) the issuing strip thickness decreases with an unchanged roll gap setting. The effect was observed in the late 1930's on the then recently installed high-speed tandem mills, and some of the contributing causes were correctly identified. The first systematic study of the effect, however, was carried out by Ford [24] and by Sims and Arthur [25]; reviews of earlier work are given in both papers. A detailed consideration of possible influencing factors showed that yield stress increase due to increased strain rate, yield stress decrease due to increased strip temperature, or changes in the elastic characteristics of the roll and the rolling mill cannot account for the observed

speed effect. Only two possible causes remain: variation in the center of rotation of a roll supported in a journal bearing, or a change in the frictional mechanism in the roll gap itself.

Roll Neck Displacement

In rolling mills equipped with full fluid roll neck bearings, the roll-separating force is carried by a relatively thin oil film between journal and bearing at low rolling speeds. As the speed of rotation increases, a thicker hydrodynamic film is formed and the roll journals ride up on this film, occupying a new center of rotation, equivalent to closing the roll gap. This can be represented according to Hessenberg and Sims [26] by graphs of the type shown in Fig. 6.7, in which the roll separating force is plotted against the rolled strip thickness. For any given initial roll gap setting s_0 the actual roll gap increases as a result of elastic distortion in the rolls, bearings, and mill housing. The slope of this so-called elastic curve is the mill elastic constant. For a strip of a given h_1 entry thickness, the roll force rises with increasing reduction according to some "plastic" curve, as determined from rolling theory or experiment. Where this curve intersects the elastic curve, the issuing gage h_2 of the strip is found. In a mill equipped with roller bearings, the issuing gage can decrease to h_2' with increasing rolling speed only if friction in the roll gap decreases (Fig. 6.7a), provided that all other input variables are kept constant.

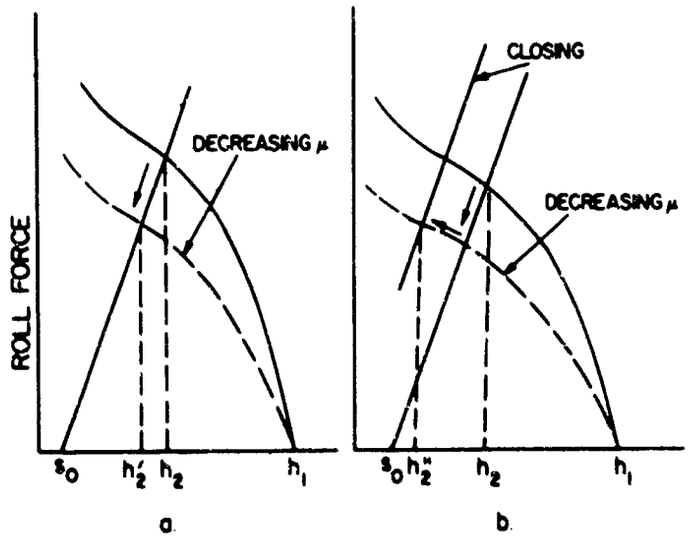

Fig. 6.7. The combined effect of friction and roll neck displacement in mills equipped with (a) roller bearings, (b) full fluid bearings [26].

In contrast, the roll journals ride up on a film of increasing thickness as speed increases; the effect is the same as if the roll gap had been set closed (Fig. 3.7b). It will be noted that this has the same effect on the issuing gage as though the coefficient of friction decreased. For this reason, the individual contributions of journal displacement and interface friction to the speed effect (as expressed by the new gage h_2'') could be separated only if all variables, including roll neck displacement were recorded simultaneously. Stoltz and Brinks [27] reported a roll gap change of the order of 0.005 in. per stand on a four-stand sheet mill while slowing down from 3000 to 250 fpm in the middle of rolling a coil. This would readily account for more than the observed speed effect (Fig. 6.8). However, the large variations in roll gap are somewhat attenuated by the decreasing efficiency of the rolling mill when reducing thin sheet; in other words, a relatively large change in roll gap causes only a small change in issuing thickness because elastic distortions absorb much of the gap change. Müller and Lueg [28] found from a simultaneous recording of roll force, interstand tensions, roll journal displacement, and gage variation that all these factors were intricately interwoven. Unfortunately, they had a displacement transducer on the top roll journal only, thus the total change of the roll gap cannot be ascertained reliably.

The effect of speed upon oil film thickness was investigated by Popov [29], who ran the rolls of a 4-high mill in contact, with copious lubricant applied, but without metal in the gap. The roll-separating force was found to rise

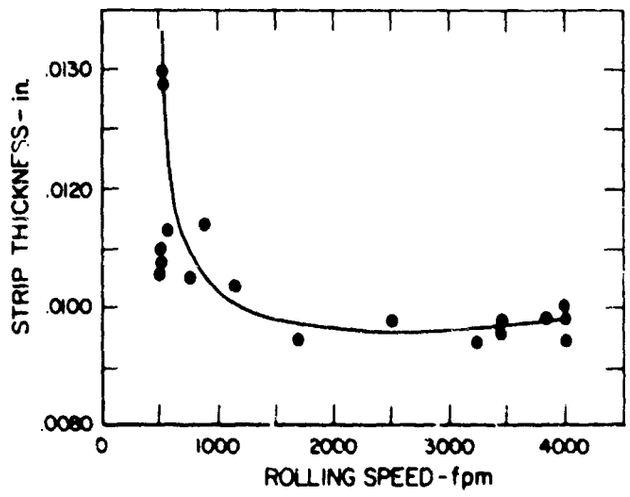

Fig. 6.8. Speed effect in rolling 0.095 in. tinplate on a four-stand sheet mill [27].

with speed according to an approximately hyperbolic relationship. A steeper rise was observed up to approximately 50-250 rpm (corresponding to a roll surface velocity of 200-1000 fpm). Since this pattern of variation is similar to that experienced in rolling practice, he concluded that the speed effect can be explained purely from film thickness changes in the journal bearings. This could be true for rolling with dry lubricants, but must be refuted in view of experimental evidence obtained on mills equipped with roller bearings when rolling with fluid lubricants.

The results of Stoltz and Brinks [27] were used by Stone [30] for calculating the variation of friction with rolling speed (Fig. 6.9). From results of more recent production-scale experiments, Pawelski [31] calculated a much more gradually changing friction (Fig. 6.9). It is reasonable to assume that the method the method of calculating μ affects the results, and it would be preferable to rely on the rolled gage as the primary indicator of the speed effect. For this, however, a simultaneous recording of the actual roll gap separation would be needed.

Speed Effect Due to Change in Friction

For reasons explained above, experiments and observations made on mills equipped with full fluid bearings must be approached with caution. Interpretation of the speed effect is much easier when the roll neck position is fixed. Ford [24] rolled at speeds ranging from 5 to 300 fpm, on a 10 in. 2-high mill equipped with roller bearings. Using an 0.2% carbon steel and high-purity copper as strip materials, reductions of 30% were taken in each pass. The speed effect was negligible in initial passes but showed up clearly in the fourth, fifth, and sixth passes when the strip became both hard and

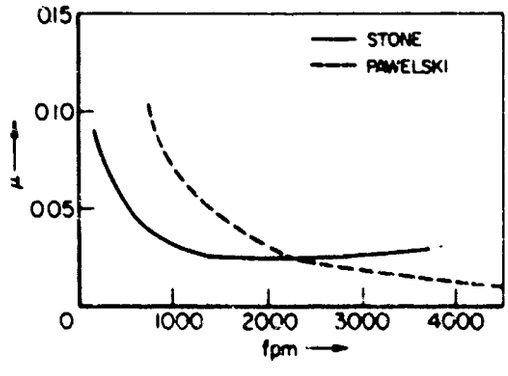

Fig. 6.9. Friction calculated from tandem mill gages [30, 31].

thin (Fig. 6.10). The speed effect was noticeable even in early passes whenever reductions were high and the starting strip thin.

Possible causes of the speed effect were investigated by Sims and Arthur [25] on the same rolling mill. With oil as a lubricant, the issuing steel strip thickness decreased from 0.035 to 0.027 in. on accelerating from 10 to 250 fpm, whereas strip rolled with dry graphite lubricant remained of essentially constant thickness at 0.038 in. The coefficient of friction calculated from Bland and Ford's theory [32] decreased correspondingly with increasing speed (Fig. 6.11). A similar variation in friction was calculated by Geleji [33], using his own rolling theory, from the experiments of Ford [24].

Experiments by Billigmann and Pomp [34] on steel and aluminum also gave clear evidence of the speed effect. In their work, initial strip thickness, reduction per pass, rolling speed (between 15 and 1300 fpm), and roll diameter were varied both with and without lubrication. They found that roll forces actually increased (correspondingly, reductions decreased) with increasing rolling speed on dry rolls. This was attributed to a gradual

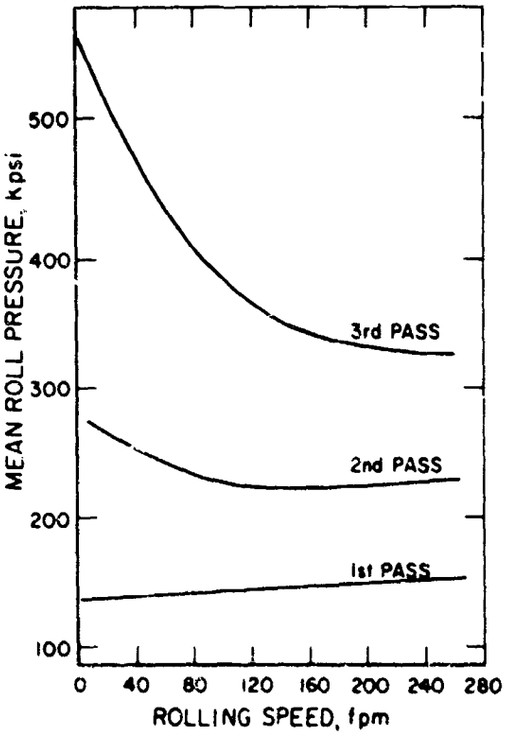

Fig. 6.10. The effect of speed on interface pressure in the rolling of 0.032 in. low carbon steel strip [24].

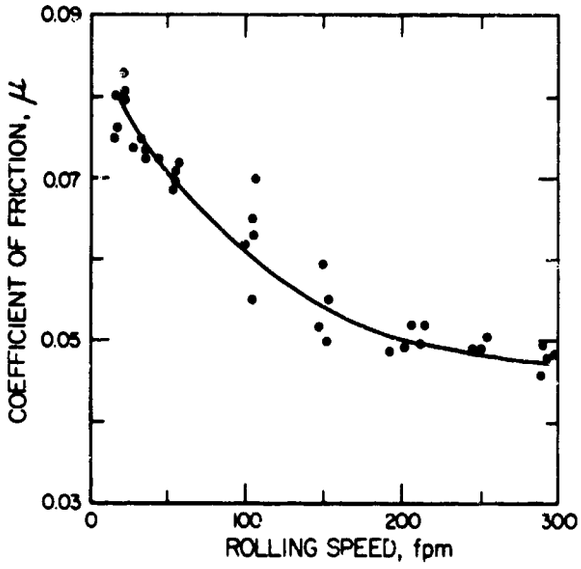

Fig. 6.11. The variation of friction calculated from experiments on low carbon steel strip [25].

deterioration of interface conditions owing to pickup and accumulation of metal and oxide particles on the rc surface. With a lubricant, the issuing gage invariably dropped with increasing speed and the roll gap had to be opened if a constant issuing gage was to be attained. In agreement with and in an extension of the observations of Ford [24], they also found that the speed effect occurred only if the ratio of issuing gage to roll diameter was smaller than a limiting value, the magnitude of which was the function of workpiece material, reduction per pass, and the surface finish of the rolls.

Whetzel and Wyle [35] found that the speed effect was almost entirely absent when a conventional "soluble oil" lubricant (probably a straight mineral oil emulsion) was used, but it became more marked with a mineral oil, and very pronounced with fatty oil (Fig. 6.12). It is reasonable to assume that the emulsion functioned as an almost purely boundary lubricant.

Mechanism of Speed Effect

Experimental evidence cited above points to the use of liquids (preferably of some substantial viscosity) as the main cause of the speed effect. This led to speculation about the possible mechanism by which a lubricant reduces friction in the roll gap. Billigmann and Pomp [34] drew on the analogy with a journal bearing, where increasing speed causes an increase in the thickness of the supporting full-fluid film. Sims [36] preferred an explanation

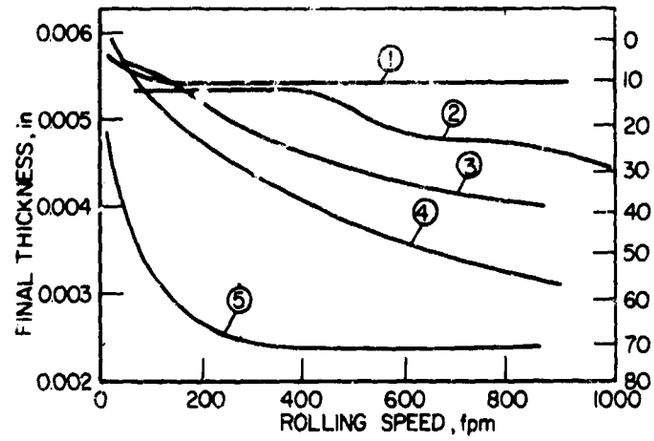

Fig. 6.12. Speed effect in experimental rolling of low carbon steel strip (1: "soluble oil"; 2: mineral oil; 3 and 5: experimental lubricants; 4: liquid fat) [35].

based on the viscous flow properties and boundary attachment of lubricants to the strip surface. He postulated that at low rolling speeds more of the attached lubricant is squeezed out, while at higher rolling speeds the time available for this extrusion effect is less and, therefore, a thicker layer remains.

A much more plausible explanation of the speed effect may be gained if it is accepted that lubrication in rolling is of the thin-film type. With a lubricant that gives predominantly boundary lubrication at low speeds, increasing rolling speeds at the same roll gap setting (or even at the same interface pressure) would cause a shift towards the hydrodynamic regime by virtue of the greater interface sliding velocities at the entry point. Thus, more asperities previously in contact with the roll surface would be lifted off, and more of the load would be borne by trapped hydrodynamic pockets. Correspondingly, the coefficient of friction would drop. This hypothesis also explains why the speed effect is more marked at lower speeds and then gradually tapers off at high speeds; the coefficient of friction should drop more rapidly in the initial stages when even a slight shift to hydrodynamic lubrication means the elimination of a greater number of contact points, while little further improvement could be expected when lubrication has already become almost fully hydrodynamic, with most of the surface separated by the trapped film [37].

All published evidence can be readily fitted into the framework of this hypothesis. Whetzel and Rodman [21] rolled steel strip precoated with controlled, uniform amounts of fatty oil lubricants, deposited from a solvent solution or by an air power spray apparatus. The film thickness thus deposited varied from very thin, ineffective, to gross excess. After rolling the strip to a constant gage at various roll speeds, the oil film thickness on the rolled product was determined by a solvent method, and the coefficient of friction was calculated (by the method of Stone and Greenberger [38]) from roll forces.

Results for a natural animal fat and a much more viscous modified fat are shown in Fig. 6.13 for two speeds. With very thin films friction was

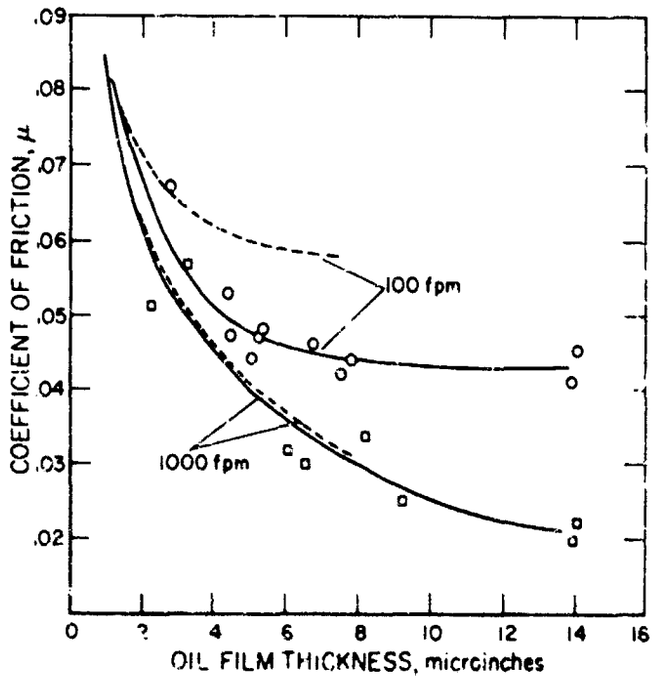

Fig. 6.13. Oil film thickness and friction in rolling steel strip (broken lines: natural fat; solid lines: high viscosity fat) [21].

high, but it decreased with increasing speeds and viscosities as the oil film thickness increased. Allowing for the elongation of the strip, they found that deposited films of thicknesses up to about 4 to 5 μ in. passed through the roll gap without change; thus, up to this thickness the coefficient of friction was governed by the available lubricant supply. Thicker oil films could be developed only by providing excess lubricant on the ingoing side, and then rolling velocities became the governing factor. It was impossible to obtain films thicker than 10 μ in. with the natural fat, but a more viscous modified fat developed a greater (14 μ in.) limiting thickness. It was also noted that the greater viscosity of the modified fat led to a markedly lower friction at the low speed, whereas both the natural and the viscous fat produced identical friction at the high speed. This indicated that the greater interface velocity developed at high speeds in the entry zone generated sufficient hydrodynamic drag to make viscosity a secondary factor. Similar conclusions were reached by Iwao et al. [39] on both steel and aluminum.

In a detailed examination of the speed effect Thorp [15] normalized rolling conditions by repeating experiments at various speeds and different roll settings so that, irrespective of mill spring, the roll force for a constant reduction could be plotted as a function of rolling speed. The most unusual feature of his results is that roll force dropped rather abruptly around a critical speed with the pure hydrocarbons, while the more normal gradual decrease in forces was noted with palm oil.

The validity of these results has been debated in the subsequent discussion. The steel strips were only 2 ft long; thus, truly representative equilibrium conditions may not have been reached, especially at heavier reductions. The strips were electrocleaned and then washed, including an alcohol rinse which, as pointed out by Rowe [40], leaves a boundary film. This could be especially disturbing when very pure hydrocarbons are tested as lubricants. Also, when the results were replotted for constant roll forces, the drop in exit thickness was more gradual (Fig. 6.14). It would appear, therefore, that even though the speed effect may be more sudden on very pure substances than on natural mixtures, basically the same changeover from predominantly boundary to predominantly hydrodynamic conditions must exist.

From pilot runs on a production aluminum foil rolling mill, Yokote and Nomura [41] calculated the variation in friction with rolling speed and found that μ dropped from 0.07 at 300 fpm to 0.03 at 1200 fpm. The drop was fairly gradual, again suggesting a thin-film mechanism.

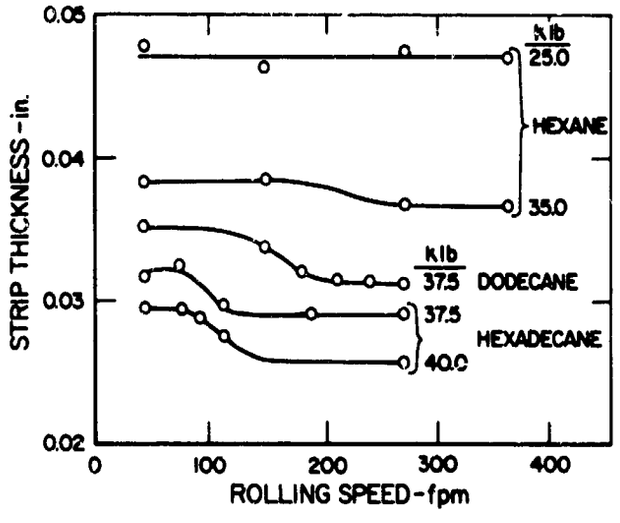

Fig. 6.14. Speed effect in rolling steel strip with high purity paraffins [15].

Experiments by Christopherson and Parsons [42] in drawing aluminum, copper and mild steel strip through freely rotating rollers (equivalent to Steckel rolling) provided some indirect evidence of increasing hydrodynamic lubrication with increasing speed. Using a "vaseline grease" as a lubricant, the surface finish of the strip was roughened with increasing speed (Table 6.2), no doubt because increasingly heavy layers of lubricant caused marked hydrodynamic indentation of the surfaces.

An interesting explanation of the speed effect has been proposed by Pawelski [31]. He suggests that on entering the roll gap, the lubricant film between the roll and the strip is subjected to very high strain rates, causing it to behave in a viscoelastic manner. However, relaxation times of lubricating oils are two to four orders of magnitude shorter than stressing times calculated for the rolling mill and—in the absence of data on viscoelastic properties under conditions of high interface pressures, temperatures, and shear rates—it is difficult to determine the validity of this suggestion.

6.24 The Coefficient of Friction

We have seen in Section 2.2 that the absolute magnitude of the coefficient of friction is of interest both from the theoretical and practical point of view, because of its importance in the determination of forces, power requirements, and limiting reductions.

TABLE 6.2

Effect of Speed on Surface Roughness of Pull-Rolled Strip [42]

Material	Reduction, %	Drawing Speed, fpm	Surface Finish, μ in. AA
Aluminum	21.7	0.25	8
	21.7	140	90
	21.7	550	175
Copper	17.2	0.25	6
	17.2	140	30
	17.2	550	55
Mild steel	13.1	0.25	9
	13.1	140	36
	13.1	550	76

Method of Deriving Coefficients of Friction

Coefficient of friction values are found in great abundance in the literature. However, as discussed in Section 5.22, the absolute magnitude of friction cannot be determined directly under truly relevant conditions; therefore, almost all published data are based on indirect derivations. It should also be emphasized that the coefficient of friction normally quoted is a mean value over the contact arc.

Even though the true yield stress of the rolled material is seldom known for conditions prevailing during the rolling operation, friction values were frequently calculated from measured roll forces. Many investigators used the theory of either Bland and Ford [32] or that of Stone and Greenberger [38]. While the former entails the use of graphs, it probably gives somewhat more reliable solutions than the latter which, though more convenient to handle, is based on rather broad simplifying assumptions. As suggested by Browning [43], the major discrepancies stem from disregarding the inclination of the converging roll surfaces in the Stone and Greenberger theory.

On the whole, friction values calculated from forward slip could be regarded as more reliable and, as shown by Schey [9], most accepted calculating methods give very similar values for steel. Agreement was still acceptable for aluminum, except for the heaviest reductions that approached purely

boundary contact. Friction values calculated from roll force and from forward slip agreed reasonably well when Ekelund's equations (Eq. 2.12 and 2.14) were used.

Of the other techniques of determining friction, the limitations of the method of maximum angle of acceptance have already been discussed in Section 6.21 in conjunction with dry friction. The method of increasing back tension until the strip begins to skid is generally regarded as the most reliable, although Dahl [44] has found that the friction coefficients derived by this technique are consistently higher than those found from forward slip. The difference may well be attributed to the natural material flow in uninhibited rolling as opposed to the artificially unidirectional material flow obtained when the strip is arrested. The lubricating mechanism must also be disturbed. The two techniques employed for arresting the strip (Figs. 5.1d and 5.1e) give practically identical results, as found by Müller and Funke [45] in the rolling of 0.1% carbon steel at reductions ranging from 10 to 60%. The rust-preventing oil preapplied to the strip served as lubricant; roll force, torque, and back tension were measured at the point where the strip began to skid, and the coefficient of friction was determined according to Whitton and Ford (Eq. 5.1) and Pavlov (Eq. 5.5). The agreement between the two sets of results was very close, the coefficient of friction being typically 0.15 for all reductions.

Typical Coefficient of Friction Values

Despite all of the above reservations, it is still useful to survey the range of coefficient of friction values normally found, as an aid to calculations of roll force and power requirements.

The discussion in Section 6.21 has shown that the calculated average coefficient of friction ranges from 0.3 to 0.5 (complete sticking) in most unlubricated hot rolling operations, and is primarily a function of the oxidation of the workpiece material. It is to be expected that friction is also a function of the roll material. In the experiments of Ekelund [2], steel rolls gave higher friction than cast iron rolls, and these observations have been later confirmed by others, for example, by Stone [46]. In a survey of published friction values, Lucas [47] reports friction coefficients of the order of 0.2 for the hot rolling of copper, magnesium, and aluminum alloys with kerosene as a lubricant. The condition of the roll surface is of obvious

importance. For copper and aluminum, Pavlov [48] quotes friction values of the order of 0.25-0.30 for clean coarse-ground rolls, 0.42-0.45 for crazed rolls, and 0.55 for rolls coated with the metal.

In unlubricated cold rolling, coefficients of friction of the order of 0.1 to 0.2 are usually reported for various materials. MacGregor and Palme [49] calculated $\mu = 0.17$ from the measured friction hill in the rolling of aluminum on dry rolls, while Pavlov [48] calculated $\mu = 0.25$ from the maximum angle of acceptance. Such low friction values may be realistic for materials (e.g., steel) that show little adhesion to the roll, but it is likely that they should be around 0.4 [9] for materials (e.g., aluminum) with marked propensity to form roll pickup. Brass and copper are unique in that friction remains low (0.11-0.14 in Pavlov's experiments) even though the rolls become coated; this peculiarity has already been mentioned in Section 3.25. Smith et al. [50] found $\mu = 0.2$ for the hot and $\mu = 0.12$ for the cold rolling of copper on dry rolls, by matching the directly measured friction hill with a calculated one.

Most published experiments were conducted with rolls carefully degreased with trichlorethylene or a similar solvent, which actually leaves a boundary film on the surface (Section 5.66). The films can be removed only by rolling some dummy workpieces prior to commencement of the actual experimentation [9].

In lubricated rolling of steel and nonferrous materials, coefficient of friction values ranging from 0.08 to 0.15 have been repeatedly reported. These values appear to be too high in the light of more recent research. As pointed out by Ford and Ellis [51], pressures and thus the effect of friction will be overestimated if interface pressures are calculated from the measured roll force by dividing merely by the plastic arc of contact. For correct results, the elastic arc of contact must be taken into account. It should be added that much of the earlier work concentrated on relatively low-speed laboratory- or plant-scale experiments, with rather inadequate lubrication. Disregarding the variations due to the method of deriving friction coefficients, it seems reasonable to say that, on the average, friction coefficients ranging from 0.03 to 0.05 should by typical of predominantly hydrodynamic lubrication, and values around 0.1 should occur only with materials that are difficult to lubricate, or at high interface pressures and low sliding velocities that cause lubrication to shift into the predominantly boundary regime.

Effect of Interface Pressure

It must be emphasized that the use of a single average coefficient of friction value for any given roll and workpiece material combination and lubricant should be discouraged. Since the operative mechanism in lubricated rolling is mostly of the thin-film type, it is very sensitive to rolling speed and pass reductions and, one would expect, also to interface pressures. This has indeed been indicated by a number of experiments. Thus, in Fig. 6.15, friction values are plotted as a function of interface pressure for a number of aluminum alloys and for mild steel according to Schey [9]. The rapid rise of friction with increasing pressure when rolling with an uncompounded oil is no doubt due to the widespread boundary contact and welding of asperities, uninhibited because of the absence of suitable additives. As referred to earlier, LeMay and Vigneron [13] found increasing friction with increasing interface pressures even for steel. Similarly, the coefficient of friction was found to rise with initial strip thickness and with work hardening

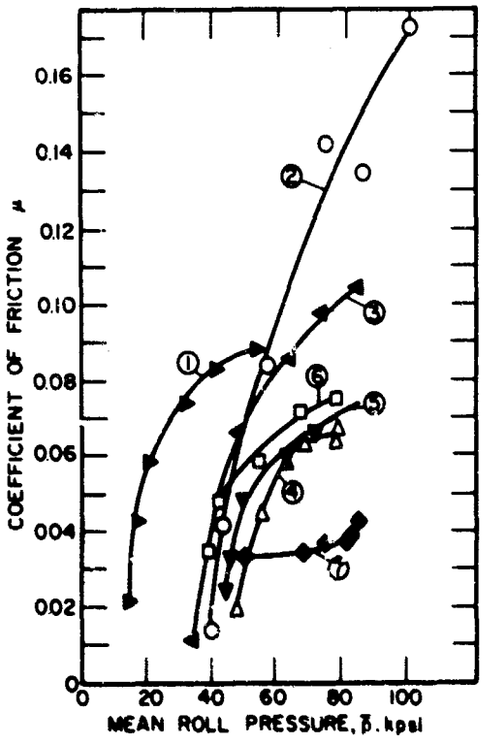

Fig. 6.15. Friction as a function of interface pressure: (1) 99.99% Al; (2) and (3) Al-1.25% Mn; (4) Al-5% Mg; (5) Al-Cu-Mg-Si; (6) Clad Al-Cu-Mg-Si; (7) low carbon steel, (2) Rolled with base mineral oil, all others with compounded oil [9].

in the work of Zhuchin and Pavlov [52], who derived friction from simultaneous measurement of roll torque and force in the rolling of magnetically soft iron alloy on a commercial 4-high rolling mill. Roberts [53] found that friction was higher on full-hard 0.015 in. thick "black plate" than on annealed material, although the difference disappeared at speeds above 300 fpm (see also Section 6.26).

Experiments often failed to reveal the role of interface pressure simply because conditions did not cover a wide enough range to show an indisputable effect. This was, for example, the case in the work by Whitton and Ford [11]. On the other hand, it could also be argued that pressure cannot be changed without affecting other variables; clearly, this is a problem in need of further work.

Variation of Friction Along the Arc of Contact

If the coefficient of friction is a function of interface pressure, it must also vary along the arc of contact (Singer [54]). Indeed, direct measurements of friction variation by the oblique pin technique (Fig. 5.1h) tend to confirm this point. Unfortunately, very few successful measurements have been reported.

In the hot rolling of 3/4 in. thick and 3/4 in. wide steel specimens at 1050°C with reductions of 20%, Grishkov [55] found friction to increase from 0.17 at the middle of the bar to 0.30 at the edges. Obviously, the narrowness of the workpiece allowed considerable spread and thus reduced the zone of sticking, giving rise to lower friction values. Van Rooyen and Backofen [56] measured a friction coefficient of 0.55 near the strip edges and at the entry plane in the cold rolling of aluminum at 15% reduction on sandblasted roll surfaces. Friction gradually decreased towards the flow-dividing plane and reached a value near zero. These experiments seem to contradict the view that friction should rise with interface pressures; however, it must be considered that as the product of the coefficient of friction and of interface pressures exceeds the yield stress of the material in shear, sticking friction prevails (Section 2.12). Consequently, movement of the material over the pins is arrested and a coefficient of friction cannot be meaningfully determined.

Simultaneous measurement of longitudinal and transverse frictional forces, with a total of four pressure-sensitive transducers built into the roll surface, by Grosvald and Svede-Shvets [57], revealed similar variations

(Fig. 6.16) in the cold rolling of aluminum and in the hot rolling of iron. Again, the absence of a transverse frictional force in the middle of the strip should not be regarded as the absence of friction, but rather as an evidence of sticking friction. Evidence of sticking zones was found by Van Rooyen and Backofen [56] from measurements of the separation of parallel marks machined into the surface of the strip, and by Capus and Cockcroft [58] from scratches produced on the strip surface by asperities.

It is interesting to note that Brown [59] arrived at a frictional force distribution similar to that shown in Fig. 6.16 from a theoretical analysis of the normal pressure distribution measured by Siebel and Lueg [20], before any of the oblique pin measurements were carried out.

A complication is introduced by lateral spread which reduces the forces acting on the oblique pin [60]. This effect is more marked in dry rolling because spread is large (Section 6.26). In fact, strictly valid measurements are restricted to the middle of the strip, because the principal flow lines (discussed later in conjunction with Fig. 6.18) prove the presence of some lateral movement even under ostensibly plane-strain conditions. Since the principal flow lines also describe the direction of frictional forces, the measured frictional forces are always somewhat lower than the real ones.

Little attention has been paid to the effect of pass geometry on measured friction. The effect becomes important when the h/L ratio is relatively large (or L/h small) and causes, as remarked in Section 2.24, marked inhomogeneity of deformation. Tarnovskii et al. [61] have shown that at h/L > 0.5,

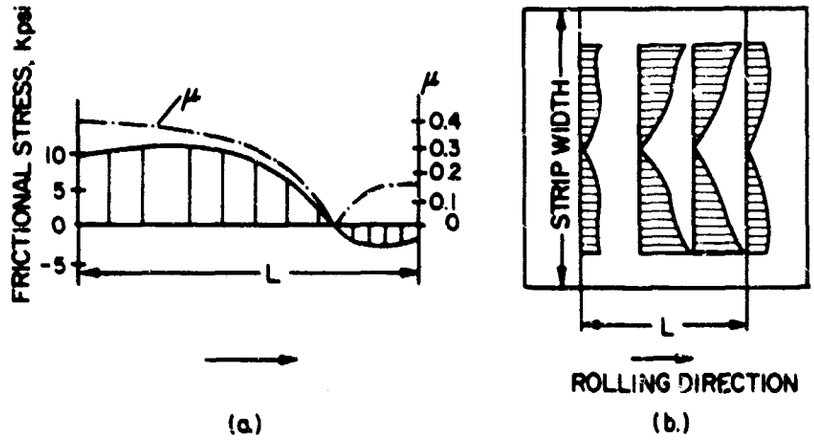

Fig. 6.16. Distribution of frictional stresses in rolling Armco iron at 950°C: (a) longitudinal stresses in strip middle, (b) transverse stresses along arc of contact L (after Ref. [57]).

a wide zone of sticking friction develops in unlubricated rolling. When the external friction coefficient is calculated from forward slip, values corresponding to sticking friction (of the order of 0.5) are obtained. These results confirm the contention of Section 2.22—namely, that the method of calculating friction from forward slip is valid even for sticking friction, because it essentially reflects the position of the flow-dividing plane in the bulk of the thick workpiece.

6.25 Friction Hill and Roll Force

The presence of interface friction accounts for the development of the friction hill (Section 2.23). The classical measurements of Siebel and Lueg [20] were the first to reveal the pressure distribution along the arc of contact by recording the pressure exerted on a radial pin embedded in the roll surface. Interface friction was varied by rolling without a lubricant, first on smooth rolls and then on rough rolls (Fig. 6.17). Interface pressures were nearly twice as high with the rough rolls as with the smooth rolls,

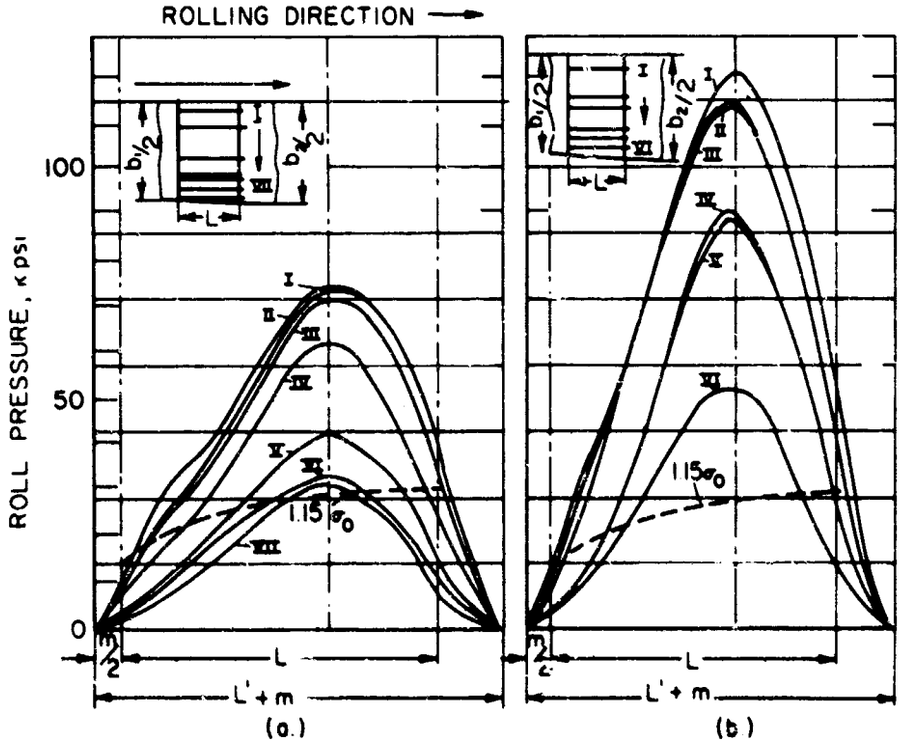

Fig. 6.17. Interface pressure distribution in cold rolling aluminum strip dry on (a) smooth and (b) rough rolls [20].

and the pressure distribution followed the trends expected from theory for sliding and partially sticking friction (Fig. 2.4a and b).

In a recent series of measurements, Vater et al. [62] used a large number of pressure transducers embedded in the roll surface along a line parallel to the roll axis. When rolling an aluminum-3% magnesium alloy at 40% reduction with a front tension equal to one-half the yield strength of the material, the use of a lubricant reduced the maximum pressure by about 30%, and the shape of the friction hill also changed in the lateral direction. Without lubrication, interface pressures were reasonably uniform from side to side, with two small maxima near the edges, after which a very sharp drop was evident toward the edge itself. With lubrication, a single maximum occurred at the center; thereafter pressures fell fairly uniformly to the edge.

Whenever the rolled slab is relatively thick ($h/L > 0.5$), sticking friction prevails along most of the arc of contact. This is a typical condition of hot rolling for most workpiece materials, and full sticking has been observed even in lubricated hot rolling of aluminum [63]. As a result of sticking friction, the friction hill flattens considerably and, as indicated in Fig. 2.4c by broken lines, a double hump often appears. This has been found by Siebel and Lueg [20], Astakhov [64], and MacGregor and Palme [49] (the latter also investigated geometries corresponding to the rolling of thick slabs). Even more suprisingly, Knauschner [65] measured a sharp pressure peak at the entry, and a continuous pressure drop towards the exit in the hot rolling of steel blooms of approximately square cross-section. Such pressure distributions cannot be satisfactorily explained from rolling theories relating to the friction hill; MacGregor and Palme attribute the initial hump to increased resistance to deformation when compressing with narrow anvils at a large h/L ratio, while Geleji [66] points to the differences in the direction of material flow when the length of the arc of contact is greater than the width of the billet. No totally satisfactory explanation appears to exist.

While the exact shape of the friction hill is important theoretically as well as for calculations of roll torque, the average interface pressure is sufficient for calculations of roll force. Increasing friction invariably raises roll force, and the effect becomes more noticeable as the ratio of the length of contact arc to strip thickness (L/h) increases. Sims [36] has calculated that in reducing a steel strip of 0.06 in. thickness by 30% on a 10 in. diameter work roll, the roll force per inch width increases from 32,000 lb to

47,000 lb while μ increases from 0.052 to 0.12. On a thinner strip of 0.030 in. starting thickness, the corresponding rise would be 27,000 to 57,000 lb. Thus, good lubrication becomes increasingly important as the L/h ratio increases (this effect is analogous to that noted in forging, Fig. 2.20b). Consistent and uniform friction is necessary for the rolling of strip with minimum gage variation.

6.26. Effect of Friction on Deformation in the Roll Gap

The simplified treatment of rolling as a special example of plane-strain deformation assumes that material flow is directed only in the longitudinal direction. In practice, all rolled material has finite width, and it is inevitable that some lateral flow, or spread, should also occur (Section 2.22). The actual directions of material flow were first experimentally established by Siebel and Lueg [20] (Fig. 6.18); lateral flow is clearly evident and resulted in an increase of width. Similar patterns have been derived by Capus and Cockcroft [60] from hook-shaped scratches left on the rolled strip by relatively large asperities. It will be noted that some lateral spread occurs even in the middle of the strip. Plane strain exists, strictly speaking, only in the middle portion of strips of a width-to-thickness ratio greater than 20. For the same pass reduction, spread is greater with a larger roll; for the

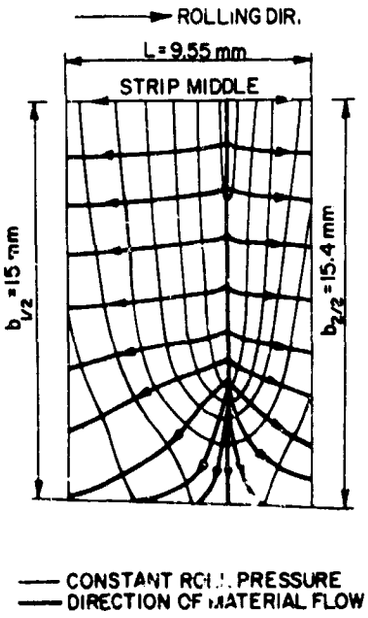

Fig. 6.18. Direction of material flow in dry rolling aluminum strip [20].

same roll diameter, spread increases with the ratio of the length of arc of contact to strip width (Section 2.24). Comparisons are valid only if these factors are kept constant. The magnitude of spread is thus a function of the roll pass geometry and, of course, of friction. Numerous observations have been made to show that reduced friction also reduces spread (among others, Pomp et al. [67] Billigman and Pomp [34], Pavlov and Gallai [68], Whetzel and Wyle [35], Chekmarev et al. [69], Tsuji et al. [70], and Chitkara and Johnson [71]). Contradictory results can usually be traced [68] to an invalid comparison between dry and lubricated experiments at a constant roll gap setting. Lubricated rolling will give higher reductions and, therefore, greater spread.

The effect of friction on the homogeneity of deformation has been noted in earlier discussion. Increasing friction leads to a more pronounced nonuniformity, as revealed by the curvature of originally vertical straight lines in the rolled slab (Section 2.24). The effect becomes most marked with sticking friction; the presence of sticking friction and its effect on deformation has been proven by many means. The spacing and deformation of transverse lines marked on the slab or strip surface, or in a vertical plane of symmetry in composite workpieces, has been frequently used. A reversal of the curvature of grid lines has also been observed very close to the surface by Crane and Alexander [72], indicating reversal of the frictional forces during the passage of the slab through the roll gap. Various techniques of establishing zones of sticking have been surveyed and applied by Tarnovskii et al. [61] and Starchenko [73].

The magnitude of friction becomes critical once conditions of limiting reduction are reached (Section 2.26), because both the rolls and the strip will then deform as elastic bodies. While the effect is well known from practice, few systematic experiments appear to have been made. Limiting reduction is usually gradually attained; that is, the interface pressure begins to rise precipitously once a certain reduction is approached. This is evident in Fig. 6.19, taken from the work of Takahashi et al. [74] in the rolling of 0.006 in. thick low-carbon steel on 10 in. diameter rolls. It will be noted that with palm oil or cottonseed oil as a lubricant, reductions are more than twice those obtained with a spindle oil (mineral oil), both in a single pass and in multiple passes on the same strip. It is noteworthy that when the

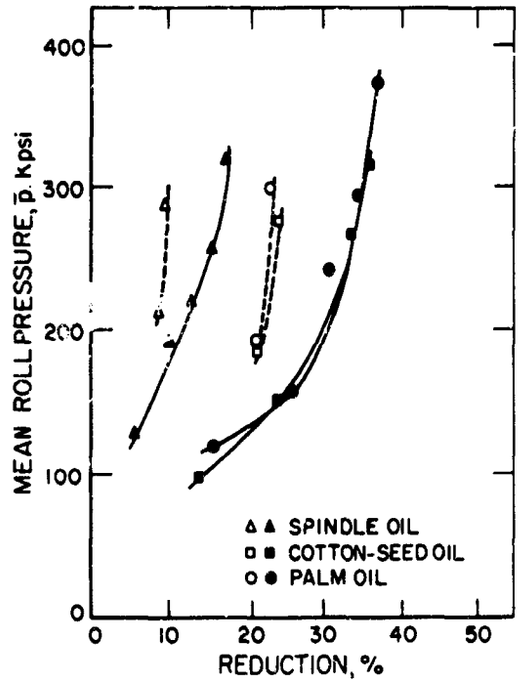

Fig. 6.19. Limiting reductions in rolling 0.168 in. steel strip on 250 mm diameter rolls (continuous lines: multiple passes; broken lines: single passes [74]).

coefficient of friction was calculated for the multiple pass sequence from Stone's formula [30], a value of 0.07 was found for the spindle oil and 0.055 for the palm oil. Because of the numerous simplifying assumptions used in developing a theory of minimum thickness, the absolute values of the coefficient of friction are not necessarily accurate; however, it is clear that even a small change in friction has a very marked effect on attainable strip thickness. The same conclusion may be drawn from an inspection of Fig. 6.26, and comparison with Fig. 6.25 will also reveal the effect of greatly increased roll flattening when full-hard rather than annealed strip is rolled.

6.27 Effect of Roll Surface Finish

Rolls are usually ground under closely controlled conditions on high-precision roll grinding machines. Surface roughness is controlled by choosing a grinding stone with a suitable grit size and by selecting the appropriate number of passes to be taken in finishing the roll with this stone. Grinding marks are invariably circumferential, and great care must be taken

to ensure that they are uniformly distributed and free of microscopic variations which may reproduce as crosshatch and other patterns on the rolled surface. Because the large flat surfaces of rolled products make even minor variations in surface patterns visible to the naked eye, much effort has been directed towards controlling the finish attained in the roll grinding process. An objective means of sensing variations of surface texture, with particular emphasis on detecting cross-hatch patterns arising from grinding wheel eccentricity or vibrations in the grinding machine, is desirable. An instrument described by May [75] accomplishes the task by finding a scatter index. Coupled with profilometric surface roughness determinations, a more quantitative assessment of surface quality may be obtained than by either method alone.

Roll surfaces are usually rough for hot rolling, in order to assure a high enough coefficient of friction for acceptance of the slab into the roll gap at heavy reductions. Surface roughnesses of 40 to 120 μ in. AA in a transverse direction are fairly typical. In the early passes of hot rolling steel on blooming and billet mills (producing rounds and sections) even the maximum reduction afforded by dry, coarse-ground rolls is insufficient for economical production. The surface can be artificially roughened by machining transverse trapezoidal, or other systematic patterns into the roll surface [76].

The surface finish for cold rolling is governed by a number of factors. A ground finish of, say, 40 μ in. AA may be desirable for sheet that is subsequently painted, enameled, or otherwise coated because the rougher finish thus produced provides some mechanical key for the coating. Smoother ground finish (of the order of 10 μ in. AA) is more common for visual appeal, and polished rolls of typically 2-4 μ in. AA are used for the production of "mirror finish" sheet or foil.

A fairly coarse (40-60 μ in. AA) random finish is often preferred for automotive body and applicance sheet, which will be subsequently painted or enameled. Such roll surfaces are usually produced by grit blasting [77, 78].

Because lubrication is of the thin-film type, the roll surface finish has a profound influence on friction and lubrication. A ground finish presents rather sharp and large ridges that penetrate the rolled material, and may break through the lubricant film. Boundary contact is likely to occur at these points at early stages; therefore, high friction values will be registered. On the other hand, more viscous lubricants are more readily trapped in the

troughs; therefore, hydrodynamic pockets may persist longer even under heavier reductions. Variations in roll surface finish therefore manifest thenselves in a number of ways. A small increase in surface roughness may cause a very large increase in roll forces, especially if metal-to-metal contact leads to junction formation—for example, in the rolling of aluminum (Fig. 6.3). Predictably, the effect is smaller on steel with its lesser tendency to adhesion (Table 6.3 and Fig. 6.20). It will be noted though from Fig. 6.20 that the effect is also a function of lubricant viscosity: tallow, which gave an almost full-fluid film, was least sensitive to surface finish.

The importance of roll surface finish in trapping lubricants was also demonstrated in experiments by Sims and Arthur [25]. On accelerating from 8 to 300 fpm in rolling 0.037 in. thick copper strip, the coefficient of friction dropped from 0.056 to 0.039 with mirror finish (4 μ in. AA) rolls; a much larger drop from 0.080 to 0.048 was calculated for the matte finish (22 μ in. AA) rolls. Thus, even though the absolute value of friction is higher with the rougher roll finish, the improvement due to increased lubricant put through is more marked.

Mechanical entrapment of lubricants should be promoted by rolls that are transversely ground (parallel to the roll axis). Some experiments conducted at the BISRA laboratories, and referred to by Thorp [15] showed promising initial results, but rapid wear of the as-ground finish made the technique impracticable.

TABLE 6.3

Effect of Speed and Roll Surface Finish on the Coefficient of Friction in Rolling Low-Carbon Steel Strip [15]

	Coefficient of Friction*			
	Mirror-Finish Roll (0.8 μ in. AA)		Medium-Finish Roll (8 μ in. AA)	
Lubricant	Low Speed	High Speed	Low Speed	High Speed
Benzene	0.16	0.13	0.22	0.17
Dodecane	0.12	0.10	0.16	0.11
Stearic acid	0.068		0.075	

*Calculated according to Bland and Ford [32].

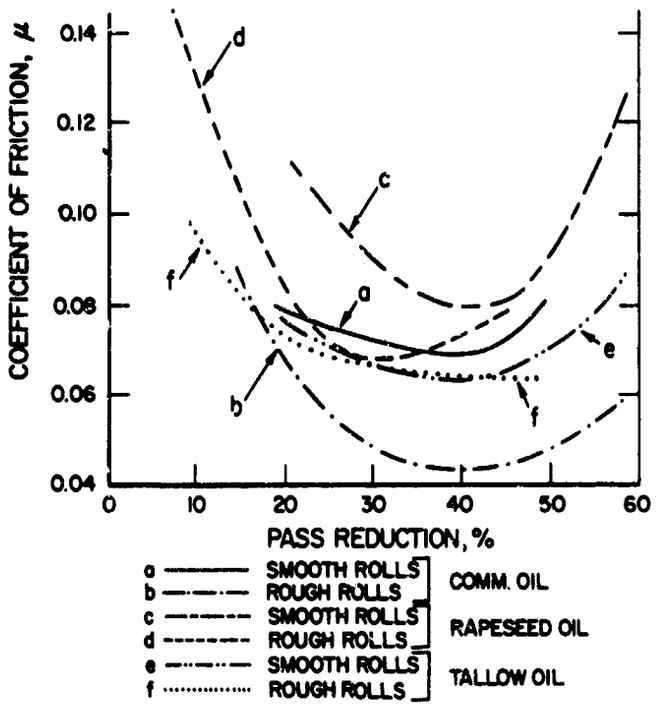

Fig. 6.20. Effect of roll surface roughness and lubricant on friction in rolling low carbon steel strips [14].

6.28 Effect on Product Quality

The magnitude and distribution of interface friction and the mechanism of lubrication are potent factors in controlling the quality of the finished product. Surface appearance is the most obvious variable, but shape and mechanical properties are also affected.

Strip Surface Finish

The discussion of lubricating mechanisms (Section 6.21) has shown that the finish of the rolled product depends not only on the surface finish of the roll but also on the lubricant itself. With predominantly hydrodynamic lubrication, the imprints of hydrodynamic pockets make the surface appear dull. In a detailed evaluation of rolled surfaces, Thomson [79] showed that the surface pattern reflects the grain boundaries and slip lines in initially soft material. Differential plastic deformation of the surface produced channels in the rolling direction at lower reductions, while transverse channels (similar to Fig. 6.4a) initiating at slip bands were dominant at heavier reductions.

As conformance to the roll surface increases with a shift towards boundary conditions, the surface brightens. Brighter strip is obtained with

purely boundary contact not only because hydrodynamic pockets are smaller and fewer (Fig. 6.4) but also because higher friction forces the neutral plane further back from the exit plane and forward slip increases, causing a burnishing of the strip surface by the more rapidly moving roll surface. It is for this reason that, in practice, the lubricant is intentionally degraded when bright finish is desired. Brighter material is rolled on large-diameter rolls (long arc of contact) of bright finish, at low rolling speeds (in order to discourage hydrodynamic lubrication) with a very light lubricant (high friction and forward slip). Even the brightest strip is often damaged on a microscopic scale, as illustrated by Fig. 6.4f, but the damage is uniform and does not appear to penetrate to a great depth, at least in the few samples investigated, especially if the rolling process is properly controlled.

Surface defects of a larger scale and more undesirable nature have been studied by Thomson and Hoggart [80]. Damaged or heavily worn or corroded rolls were prone to pick up material from the workpiece, and caused tearing and extensive damage in the rolled surfaces. Damage was more severe on aluminum and steel and less so on copper.

Rolled surfaces occasionally exhibit more or less periodic variations in surface brightness. Thomson and Hoggart [80] found that alternating duller and brighter bands formed perpendicular to the rolling direction on copper strip rolled with a very viscous lubricant; the alternation of these surfaces was associated with periodic forward movement of the strip in the rolls, apparently as a result of excessive lubricant viscosity. Transverse bands were also observed under severe conditions with relatively poor boundary lubrication. These were attributed to stick-slip motion, which was suspected to initiate torsional oscillations in the rolls and drive. A small periodic increase in strip thickness was attributed to material built up in the sticking part of the cycle. At heavier reductions (of the order of 85%) bands occurred at a higher frequency and were ascribed to transverse vibrations in the mill.

A detailed evaluation of transverse ripple has been reported by Moller and Hoggart [81]. In the rolling of 1.5 or 2 in. wide aluminum alloy strip on a rolling mill equipped with roll force and torque measuring devices, they found that the ripple originated from torsional vibration of the rolls. Vibration could be initiated by any sudden change in torque—for example, by the entry of the strip into the roll gap or by gage variations—but the vibration

was stable and self-sustaining only when the coefficient of friction decreased with increasing speed. In contrast, vibrations were damped out if friction rose with increasing speed. The amplitude of vibration depended on the slope of the descending portion of the friction vs. speed curve. Since lubricants of lower viscosity developed more positive speed effect, they were also prone to give more ripple. The torsional vibration showed up clearly on the torque recordings and was always in phase for the two spindles; no corresponding variation was found in roll force. The period of torque variation and the frequency determined from the spacing of the ripple coincided with the natural frequency of the rolls and shafts considered as a torsional pendulum.

Transverse bands of brighter and duller appearance are, in practice, often described as gear ripple even though it is not certain that the gear drive is really responsible for the phenomenon. Ripple occurring at an angle or in a symmetrical pattern is frequently referred to as herringbone and is most predominant on aluminum. Although its cause has not been identified, it is definitely affected by lubrication, and may often be made to disappear by increasing either lubricant viscosity or rolling speed. This suggests that, at the onset of the defect, changeover from predominantly hydrodynamic to predominantly boundary lubrication may take place in a periodic fashion. A defect of similar appearance sometimes found on temper rolling steel mills is no way connected; temper rolling is usually conducted dry, and the ripple is a sign of periodic yielding of the strip material.

Apart from the visual changes in the appearance of the rolled product, the effect of lubrication on surface finish can be followed also by surface roughness measurements. From the discussion of the thin-film lubricating mechanism (Section 6.21) it is evident that the as-rolled surface finish will be a function of the initial surface finish of the strip, the surface finish of the rolls, and the lubricant and process conditions that determine the extent of boundary and hydrodynamic contact. High viscosities and high rolling speeds cause a roughening of the surface (see also Sections 6.22 and 6.23). Thus, Ford and Wistreich [82] reported the surface finish of a copper strip deteriorating from an initial 14 μ in. AA value to 23 μ in. AA as a result of rolling on smooth rolls (of 9 μ in. AA roughness) with castor oil as a lubricant. Similar observations were made by others [15, 16, 42, 79]. Roughening due to hydrodynamic pockets has often been referred to as surface damage, and is sometimes attributed to a tearing of particles out of the surface. This

interpretation is obviously erroneous, and while hydrodynamic pockets certainly change the appearance and roughness of the surface, one cannot speak of surface damage.

Whitton and Ford [11] found that the surface of the rolled strip remained unchanged in the longitudinal direction but worsened in the transverse direction with lubricants of moderate friction ($\mu = 0.055$–0.070). This is probably typical of slower speed rolling at moderate reductions. True damage to the surface occurs when lubrication is predominantly boundary and the strip material tends to adhere to the roll surface (Fig. 6.4f). Such strip may nevertheless by very bright, even though surface appearance and measured surface roughness reveal the presence of smeared-over junctions. The optimum finish, defined as the brightest strip with minimum surface damage, would be obtained at the changeover point from predominantly hydrodynamic to predominantly boundary lubrication, corresponding to the knee in the curves of Fig. 6.3; but, as mentioned, this is the zone suspected to be most prone to the herringbone defect.

Strip Shape

A flat product is rolled only if reductions—and, consequently, elongation—are uniform across the whole width of the sheet. This may be attained on a strip of uniform cross-section only if the roll gap is parallel. Since the roll force causes the rolls to bend, they are ground to a barrel shape and this "ground camber," combined with the barrel shape developed during rolling on account of heating ("thermal camber"), must be of the exact magnitude to counteract bending by the roll force and thus present a parallel gap with the rolls deflected. In practice, the strip is usually rolled with a slightly thicker middle ("crown") to prevent it from wandering sideways in the roll gap; the roll gap must then conform to this thickness variation.

Poor lubrication manifests itself in a number of ways. Increasing friction means increasing heat generation, and the rolls are likely to assume a greater thermal camber then would be normally allowed for. Consequently, the middle of the sheet is elongated more and poor shape (long middle) develops. The edges of the sheet become tight in rolling with tension, and edge cracking or splitting may occur. Localized poor shape may be the result of a blocked coolant nozzle, which allows local heating and increase in roll diameter. On starting up the mill, or when the cooling effect of the lubricant is excessive, proper thermal camber does not develop and the

strip is rolled with a long (wavy) edge. For these reasons the control of shape is intricately interwoven with lubricant and coolant distribution and application practices. A discussion of this complex subject has been given by Pearson [83].

Mechanical Properties

Friction and lubrication may influence the properties of the finished product in two ways.

Firstly, the temperature of the rolled strip depends on the lubricating and cooling capacity of the lubricant. Some materials that soften at relatively low temperatures (such as aluminum and some of its alloys) may show a lower as-rolled hardness if friction is allowed to rise or cooling is inadequate. In hot rolling, of course, the cooling efficiency of the lubricant may be a decisive factor in determining the properties of the as-rolled sheet through its influence on finishing temperatures.

Secondly, friction can also cause variations in properties within the rolled workpiece. If sticking friction is attained over part of the arc of contact, deformation becomes inhomogeneous and, at small L/h (large h/L) ratios, marked differences may be found in the hardness of a cold-rolled product or the recrystallized grain structure of a hot-rolled product in the thickness direction. Hundy and Singer [84] rolled 0.2 in. thick specimens on a 10 in. diameter mill with various lubricants. An "inhomogeneity factor" was derived as the difference in hardness between the core and the surface, as a percentage of the core hardness. Inhomogeneity decreased as friction dropped (Fig. 6.21), in agreement with expectations (Section 2.24). With very light reductions, inhomogeneity was evident even with the best

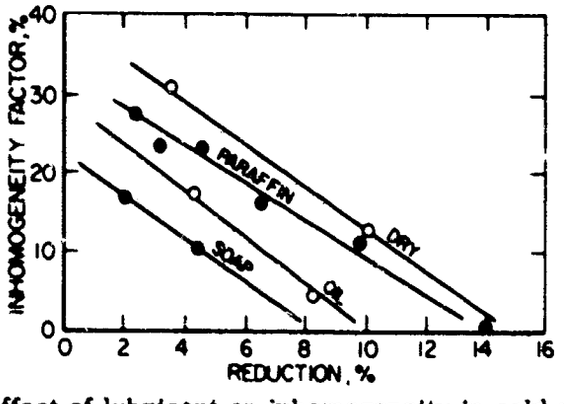

Fig. 6.21. Effect of lubricant on inhomogeneity in cold rolling copper [84].

lubricant, because the L/h ratio was small. At L/h values of the order of unity (approximately 6% reduction if roll flattening is ignored) the effect was most marked. At high L/h values more typical of production rolling of sheet, deformation becomes homogeneous irrespective of the lubricant used (reductions in excess of 15% in these experiments).

Varich et al. [85] sought to determine the effect of lubricants on the texture of cold-rolled sheet; however, interpretation of their results is difficult because pass reduction was not kept constant.

6.29 Roll Wear

The importance of a closely controlled and reproducible roll surface finish has been discussed in Sections 6.27 and 6.28. Wear of the rolls gradually changes this finish and also leads to unacceptable dimensional changes which finally cause the rolls to be withdrawn and dressed (reground, occasionally also shot peened). Localized pressure changes at the edge of the rolled strip lead to localized wear; therefore, it is customary to start a rolling program with the widest strip and to change gradually to the narrower ones (although a narrow strip is usually rolled first to develop thermal camber after a shutdown).

Wear and its causes have been the subject of extensive investigations [86-88]. While this work has been directed toward wear in the rolling of steel, some of the conclusions are of universal validity and will be discussed here.

In hot rolling, abrasive wear is initiated by the oxides of most metals. This wear is rather uniform and gradual. Thermal fatigue caused by rapid heating on contact with the hot workpiece, followed by quenching from the cooling water or lubricant, results in cracks (crazing), while fatigue due to high contact stresses leads to a separation of surface layers (spalling). The same mechanisms contribute to wear of rolls when the workpiece material adheres to the roll surface, except that abrasive wear now plays a subordinate role.

Abrasive and adhesive wear are important in cold rolling too, and are controlled primarily by the choice of lubricant. A good lubricant minimizes wear and also assures its uniformity. This results first in a smoothing of the originally rough ground surfaces but, gradually, localized wear patterns on the smoothened or originally smooth rolls appear. A worn roll is likely

to present more points at which lubricant breakdown may occur, thus wear becomes more severe and a sumes an accelerating trend. With a poorer lubricant, roll pickup may also occur, which in turn ruins the strip surface, and may also accelerate the rate of wear both on the roll and on the workpiece. Skidding or accidental damage such as indentation of the roll surface may be severe enough to cause immediate withdrawal of the rolls. Apart from such damage, however, spalling is the most likely cause of severe roll wear. Spalling is controlled primarily by the magnitude of contact stresses, and roll life may be extended by removing the heavily strain-hardened surface layer.

Few reported attempts have been made at increasing the life of the roll by choosing a roll surface of low adhesion or high wear resistance. Spenceley [89] found lower wear rates and a more consistent strip surface finish when the work rolls of four-high and cf Sendzimir mills were electrolytically coated with a hard chrome layer of less than 0.001 in. thickness. Plating apparently delayed the wear of rough-ground finishes also, thus extending useful roll life. It is believed, however, that repeated elastic deformation of the roll may cause separation of plated layers, and diffusion coatings may be preferable in this respect. Newnham and Shey [90] observed that boronized roll surfaces gave lower friction in hot-rolling 7075 aluminum alloy and a nickel-base superalloy, but the laboratory experiments were obviously inadequate to judge wear resistance under production conditions.

6.3 ROLLING LUBRICANTS

In principle, all lubricants discussed in Chapter 4 could serve as rolling lubricants. However, in practical applications there is always a simultaneous need for cooling the rolls and/or the rolled product. Consequently, lubricants are chosen as much for their cooling ability as for their lubricating function or, if the two cannot be obtained in the same material, the lubricating agent is applied with or in a cooling medium.

6.31 Neat Lubricants

Occasionally—for example, in laboratory or small-scale industrial rolling of strip and sheet—control of the heat balance is of minor concern, and then the lubricant choice may be entirely governed by the specific needs of the process. Thus, highly viscous or even solid lubricants may be used to

reduce friction, or a poorer lubricant may be chosen for improved surface finish. In either case, friction must be high enough to allow entering the workpiece into the roll gap; chamfering or pointing the nose end of the billet or strip will help acceptance. The following lubricant classes may be considered:

Mineral Oils

These are suitable lubricants for workpiece materials that show only moderate adhesion to the roll surface. A lower viscosity oil will be chosen for a bright surface finish, a heavier oil for lower friction but duller finish. Mineral oil compounded with boundary or extreme pressure additives are useful when more reactive materials are rolled.

Fatty Oils and Derivatives

Members of this group, especially palm oil, rapeseed oil, cottonseed oil, and castor oil have been extensively used partly because of their ready availability and partly because of their favorable combination of viscosity and boundary lubricating action. Friction is usually low and the rolled surface matte.

Extreme Pressure Compounds

Undiluted compounds, especially chlorinated paraffins are popular for the rolling of reactive materials that do not respond to boundary additives, for example, stainless steel. Sulfochlorinated hydrocarbons and sulfurized fatty oils (e.g., sperm oil) are also used for metals not sensitive to sulfur staining on annealing.

Solid Lubricants

The only solid lubricant that has found some acceptance is polytetrafluoroethylene (PTFE), applied to the strip surface prior to rolling from a trichlorotrifluoroethane dispersion. After the evaporation of the solvent, a thin continuous film remains which then serves as a lubricant over a number of passes.

Lamellar solids such as graphite and molybedenum disulfide are used to a limited extent in the hot and cold rolling of some difficult-to-form materials. Mostly they are applied in a carrier consisting of a mineral oil or a grease; occasionally, they may be applied to the workpiece surface in a volatile carrier prior to heating.

Some refractory metals and difficult-to-form materials are rolled after canning, but the canning material is seldom soft enough to lower interface friction.

6.32 Oil-Base Systems

When the lubricant is required to cool as well as lubricate, the greatest benefit would obviously be derived from an aqueous system. However, undesirable side effects, mainly that of staining or corrosion on some materials, have led to the widescale adoption of oil-base systems. While these do not provide the same cooling capacity as aqueous lubricants, freedom from corrosion is readily attained and lubricating qualities, surface finish of the product, and staining tendencies are more easily controlled.

Oil-base lubricants usually contain a small quantity of boundary or extreme pressure additive incorporated into a mineral oil of carefully defined quality. Lower viscosity oils are easier to apply, recirculate, and filter, and the surface finish is brighter. Heavier lubricants, however, assure lower friction because lubrication becomes predominantly hydrodynamic; therefore, lubricant viscosity is usually chosen at the maximum that is compatible with ease of application and with freedom from staining at the annealing temperatures typical of the rolled material. Small quantities of chemicals are usually added for greater oxidation stability and reduced corrosion propensity.

6.33 Aqueous Systems

All aqueous systems are composed of an oil phase and a water phase. Terminology is rather diffuse and often misleading; the following terms will be adopted throughout this chapter.

Direct application: the strip is precoated with the lubricant, usually a fatty oil, and the water is applied at the rolling mill. There is, of course, no purpose in recirculating the water, and the collected water-fat mixture is either put through a reclaiming process or, after skimming the separated oil, the remnant is dumped into a river or lake. Because of the serious pollution it causes, the latter method is rapidly dwindling.

Mechanical dispersions: the lubricant, again typically a fatty oil, is mixed into water and broken up into globules by continuous mechanical agitation. The dispersed phase separates immediately on standing, and may

present problems in recirculating systems. Frequently, the ready-mixed lubricant is applied to the mill and the collected used mixture is disposed of (total loss system); it then presents the same problems as the direct application method. In fact, this technique is also referred to as direct application.

Unstable Emulsions: a small amount of emulsifier added to the lubricant (whether a fatty oil or a mineral oil) causes the oil to break up into relatively large globules, which form an emulsion that can be kept reasonably homogeneous with only a moderate amount of agitation, such as may be provided by the pumping action of a recirculating system. Such emulsions, like mechanical dispersions, are believed to become effective through "plating out" of the lubricant phase on the strip and roll surface, thus providing essentially the lubricity of the dispersed phase.

Stable emulsions: a carefully prepared concentrate containing the lubricant (mineral oil, fatty oil, or wax) and emulsifier is diluted with water in the lubricant system of the rolling mill, to form a stable emulsion that remains homogeneous for a prolonged period of time even when allowed to stand in a settling tank. Additives designed to prevent corrosion, foaming, bacteriological attack, and oxidation are frequently incorporated. Such emulsions are provided with the necessary lubricating additives and need not be "aged." The rather ill-defined term "aging" is used to describe changes taking place after running for some period of time. Some emulsions develop their best performance after decomposition has produced more active constituents or, possibly, changed the stability toward faster "plating out."

Solutions: true solutions made of water-soluble compounds are rarely used for lubrication purposes; however, they fulfill a very important function as coolants, especially in hot rolling, when merely the addition of a corrosion inhibitor is necessary to prevent rusting of the mill equipment or of the rolled product. They also serve as lubricants for resin-impregnated fabric bearings.

It will be noted that the above nomenclature is in agreement with that adopted in Chapter 4 and that the term "soluble oil," which has sometimes been used indiscriminately for mechanical dispersions as well as true emulsions, has been avoided. It will be used in discussing experimental

work and plant practices only when it is impossible to determine from the original publication whether the lubricant was a mechanical dispersion or true emulsion.

6.34 Lubricant Application and Treatment

Lubricant Application

In experimental work and pilot-scale production on sheet or strip it is often adequate to apply the lubricant by a brush, cotton swab, or rag to the roll surface and/or strip surface. Even for the lowest speed strip rolling, however, it is essential that the lubricant should be distributed evenly. This could be accomplished simply by passing the strip through felt pads (press wipers) which are saturated with the lubricant; lubricant may be replenished by drip feed onto the wiper. The press wipers may be replaced with felt or foam rubber (plastic) rollers, particularly if rolling speeds are somewhat higher. Felt, bristle, or wood wipers may also be applied against the roll surface under a controlled pressure. This helps to spread the lubricant evenly and also catches loose debris that may be otherwise rolled into the strip surface.

It should be emphasized that uniform and reproducible lubricant application is crucial for experimental work of any value. A simplified form of recirculation or total loss system (Fig. 6.22)--incorporating a pump P, a heater H, and a mixer M—is often desirable. The preparation of the strip surface (as discussed in Section 5.66) is, of course, equally important.

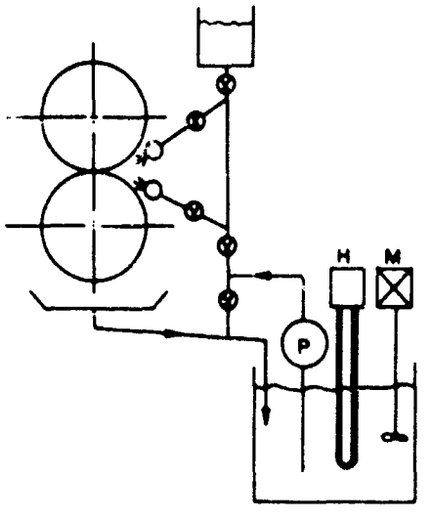

Fig. 6.22. Experimental lubricant application system.

If the heat generated during rolling is high enough to cause unacceptable temperature rise in the roll gap, the lubricant (whether oil- or water-base) must be applied through a suitably designed system of jets. A large number of jets is normally arranged in banks, parallel with the roll axis. Jets can be directed either onto the roll surface, into the roll gap, and/or onto the surface of the entering strip. A second bank of jets is frequently located on top of the roll (or back-up roll in four-high mills) in order to cool it. It is desirable that flow through each jet should be individually adjustable so that lubricant flow may be modified to provide control over thermal camber and thus facilitate the rolling of flat strip.

The lubricant is supplied to the jets by pumps at pressures ranging from a few pounds to several hundred pounds per square inch. There appears to be no general agreement on the most desirable pressures. Proponents of high pressure application claim that impingement of the high-velocity jet on the roll and strip surface helps to break up a stagnant layer of the lubricant or of steam and thus increases heat transfer. Adherents of the low-pressure school regard quantity of lubricant and wetting as more important for optimum cooling. No rigorous study of the variables appears to have been published.

The lubricant quantities available for cooling purposes were rather inadequate on older mills, but newer mills are usually built with lubricant systems that can carry away 75 to 100% of all heat generated in rolling. The simplest way of determining the necessary heat capacity is to take the thermal equivalent of the maximum horsepower that the drive motors can deliver continuously. This usually leads to a lubricant supply rate of several hundred to several thousand gallons a minute per mill stand. Tselikov and Smirnov [91] proposed a simple empirical formula for the determination of emulsion consumption Q (in liters/min) in cold rolling steel strip mills:

$$Q = vbz$$

where v = maximum rolling speed in the last stand (m/sec); b = maximum width of the rolled strip (cm); z = number of stands. They also quote experimental work according to which 65-75% of the total heat generated is carried away by the emulsion, 18-25% by the strip, while only small fractions are transmitted from the strip and the rolls to the surrounding atmosphere. The temperature rise in the emulsion is taken to be 12° to 15°C.

Recirculating Systems

A suitably constructed, readily cleanable pit is provided under the mill for catching the coolant and, except for total loss systems, the lubricant is then returned into a tank (reservoir).

The size of the tank is determined by the requisite flow rate and retention time. The longer the retention time, the more of the metallic and nonmetallic fines and contaminants entering the system will have time to settle out. Too long a retention time, however, becomes uneconomical because of the cost of the tank and because smaller particles will not settle out even on prolonged holding; also, relatively unstable emulsions and, particularly, mechanical dispersions would break. Thus, Wettach [92] quotes 6 sec as the time taken by a 0.5 mm diameter sand particle to settle 1 ft in still water. Fine sand of 0.05 in. diameter takes 2 min, while silt of 0.005 mm diameter takes over 2 hr. While retention times of up to 30 min are often allowed in oil-base systems because of the higher viscosity of the lubricant, retention times of 10 to 20 min are typical for stable emulsions, and only 5 to 6 min for mechanical dispersions.

Decantation and skimming [93] of contaminants rising to the tank surface is practiced even in modern systems. Dumping of skimmings and of filter cakes is normally objectionable, and reclamation of the trapped oil for some secondary purpose is economical.

Frequently, the tank is also equipped with a heat exchanger, which facilitates rapid preheating of the lubricant for a cold start and cooling of the system once heat input from the rolling operation exceeds heat losses. The temperature at which the bath is operated depends on the lubricant: temperatures of 60° to 70°C are usual for mechanical dispersions, 50° to 60°C for unstable emulsions, and 35° to 55°C for stable emulsions. The temperature of mineral oils is usually held around 30°C to 35°C although higher temperatures may be desirable for higher viscosity lubricants, and lower temperatures for very light mineral cuts (kerosene) of low flash point. The heat exchanger usually utilizes water or, in areas with limited water supply, air.

Particles too small to separate by gravity accumulate gradually in the system and, coupled with undesirable contamination from tramp oils (hydraulic and bearing oils), will make the lubricant rejectable after a few weeks of use even in the larger systems. The lubricant must then be changed and the used bath reclaimed or dumped; neither course is very economical, and dumping can also present a pollution problem.

When the mill is shut down for any reason, lubricant circulation is usually maintained to preserve homogeneity and temperature control. All systems are designed so that there should be no dead corners and difficult-to-reach parts, but the piping is usually designed for turbulent flow to assure complete mixing especially in unstable emulsions or mechanical dispersions. Some systems designed for mechanical dispersions incorporate baffles in the tank to assure maximum turbulence, but it would seem that cleaning must present problems.

Some mills are equipped with two or three separate systems that serve the purpose of either providing different lubricants to various stands of a tandem mill, or allowing rapid changeover of lubricants for different duties [94]. Combination total loss and recirculating systems have also been installed [95] for tinplate and double reduced tinplate rolling. For direct application tanks are of 1000-25,000 gal size. Recirculating systems incorporate reservoirs of 5000-50,000 gal capacity. The used solution is pumped to a process tank equipped with oil skimmers and sludge scrapers.

Filtration

Most modern mills and many of the older ones are now equipped with filtration systems. The complexity of the system is usually dictated by the maximum size of fines that can—according to experience—be tolerated, and by the particle size of the dispersed phase in an aqueous system. A typical system is shown in Fig. 6.23.

The lubricant returning from the mill is first passed through mechanical filters, which may take the shape of a flat filter bed or tubular or sacklike filters. A positive pressure (or vacuum on the underside of the filter) is often applied partly to increase filtering rates and prevent retention of the dispersed phase of unstable emulsions or mechanical dispersions, and partly to effect some cooling by breaking up the stream [96]. Filtration to a particle size of approximately 100 microns is possible with continuous filtering bands made of some durable material such as stainless steel, cotton, or nylon mesh, and the sludge cake is then blown off by steam or air. Nonwoven fabrics of cellulose or other fibrous materials are used only once and are disposed of when clogged, either by changing the cartridges or bags, or by advancing the filtering medium from a roll over a flat filter bed. Filtration down to particle sizes of 10-20 microns is possible. As noted by El Hindi [97], a filter rated for 100 microns removes finer particles by first building

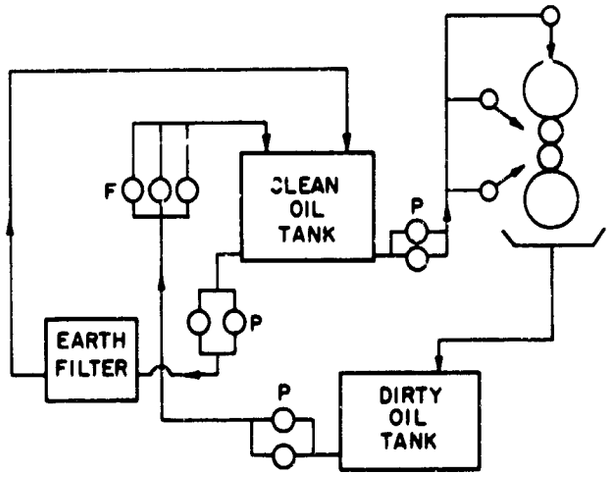

Fig. 6.23. Typical recirculating system for oil-base lubricants.

up a sediment cake of larger particles. A pressure drop of 0.5 to 2 psi is recommended because pressures as high as 6 psi will extrude gelatinous contaminants through filter papers or fabrics. Even particles smaller than 10 microns may be removed by depth filtration through the filter cake. Suggested flow rates are 20-25 gpm/sq ft filter area.

Filtration to the micron size and below is possible with diatomaceous and fuller's earth filters which are normally applied over a perforated or woven metal screen [98]. They may be of the disposable cartridge, bulk pack, or precoat type. The latter is a complex but economical system in which the filter medium (precoat) is mixed with a measured quantity of clean oil, then circulated through the filter so that a uniform precoat bed is deposited on the tubular element. The used lubricant is then circulated from the storage tank through the filter bed, often with the addition of "filter aid" (powdered earth) which increases the length of the filtration cycle by maintaining porosity in the bed of impurities that gradually deposits on the precoated element. When the pressure drop in the filter increases to 30 psi, lubricant supply is cut off and the sludge is blown off the filter element. Since emulsifiers would adhere to the filtering medium, emulsions cannot be treated in this way. Mineral oil base lubricants also tend to lose some of their surface-active additives by adsorption on the filtering medium. Modern plants are automatically operated, filtering cycles being controlled by pressure drops, temperatures, and other critical indicators.

Centrifuges and magnetic separators are a useful addition to many filtering plants, and often assure adequate cleanliness of lubricants that could not be treated in earth filters [93].

Filtration was first applied to aluminum rolling lubricants [99] and is increasingly used on steel mills [100, 101, 92-94]. Special care is exercised in treating lubricants for Sendzimir and other mills in which the lubricant, whether mineral oil or water base, also serves as a bearing lubricant [102-105].

The complexity of the system is a function of the material rolled. Steel and brass mills often find a mechanical filter or centrifuge adequate even in a 15-20% bypass flow. The full flow is passed through mechanical filters on mills rolling stainless steel and aluminum, and an earth filter in a bypass circuit is added for mineral oil base lubricants.

Possible contaminants are of a great variety [97]—among others, tramp oils, metallic soaps (developed through reactions with the rolled metal and with the water hardness), inverted emulsions, solid metallic particles, non-metallic particles (wood slivers, paper shreds, and cigarette butts, especially with filter tips), and water hardness. Solid particles (wear debris) may range from 10 microns to submicron size. Tramp oils from bearings, hydraulic systems, etc., are probably the most troublesome because they enter emulsions and mineral oil base lubricants, changing their composition and lubricating ability, and may lead to staining. Great care is now taken in designing rolling equipment as a system, with due regard to dangers of contamination [106, 107]. Bearing seals have been improved, and roller bearings are often mist-lubricated, allowing the rolling oil or the neat emulsion concentrate to be used.

Recirculating systems may represent substantial capital investment, yet are found economical by extending the life of the lubricant bath over several months or years. It is then only necessary to provide makeup in the form of water, emulsion concentrate, or mineral oil and additives. A well-run rolling lubricant plant is usually carefully controlled, and samples are taken at regular intervals to assess viscosity, composition (including fatty oil and free fatty acid content), wetting, ash content, stability, pH, and other applicable criteria.

6.35 Lubricant Removal

While the cooling and lubricating properties of the rolling oil are indispensable, excess oil left on the strip surface is not only wasteful but also creates problems with staining or corrosion. Therefore, every effort is

made to reduce the residual oil quantity. Air jets directed away from the strip center ("air knives") are commonly installed at the exit side of the mill and, occasionally, wipers or squeeze rolls are also used. The amount of dirt left on the strip is tested either by simply wiping the surface with a white paper or, after stopping the mill, by pressing adhesive cellophane tape on the surface to strip off the dirt particles for examination under the microscope [108].

For special applications, the residual oil may be removed from the surface by some degreasing procedure or, in aqueous lubricant systems, the last stand may be supplied with a detergent solution for the production of so-called "mill clean" sheet. Nonferrous sheet subjected to subsequent annealing is seldom cleaned; rather, the lubricant is chosen to evaporate or decompose at the annealing temperature without leaving objectionable residue.

Lubrication practices change from plant to plant even for the same nominal duty. Although improved lubricants are always sought, changes cannot be made lightly because of the large quantities involved and because of the danger of ruining a substantial quantity of rolled product or causing a complete stoppage. Some of the defects may be rather subtle, causing only a slight change in the rate of dirt generation, which can be sufficient, however, to cause a dirty strip surface and impose extra requirements on the filtration system. While some lubricants may be very successful in reducing friction, separation of a heavy phase could cause uncontrollable sideways skidding of the strip, skidding of the work rolls on the strip surface, or skidding of the backup rolls on the work rolls during startup and stopping. Emulsions that are unstable in the presence of tramp oils or do not tolerate certain waters may age or break prematurely. Invert emulsions (water in oil emulsions) may form that behave like free oil; they pick up dirt and float on the surface of the tanks. They are good lubricants, but cause skidding if they find their way into the lubricant supply jets. Because of the many factors involved, the selection and changeover to a new lubricant must be preceded by a careful evaluation of all ramifications [109].

6.3 LUBRICANTS FOR FERROUS MATERIALS

Steel is still produced in the largest quantity of any metallic materials. The majority of steel is rolled into flat products, with cast ingots or continuous cast slabs or billets serving as the starting material. Heavy plates

(thicker than 1/2 in.) weighing sometimes up to 80 tons are hot-rolled on reversing mills as are slabs for further rolling into wide strip. Most strip is hot rolled at wide widths (typically, between 24 and 100 in.) on mills comprising 6 to 10 stands arranged in line, with the last stands forming a continuous (tandem) rolling mill in which the strip is passing through several stands at the same time. The finished product is a hot-rolled coil (also called "breakdown") weighing 8 to 25 tons, in thicknesses ranging from 0.040 to 0.120 in. If a thinner gage, better surface finish, or strain-hardened material is required, cold rolling is practiced on single stand or tandem mills.

The cold finished product is classified according to its use. Wide strip (over 12 in.) that is going to be used in a thicker gage and will probably be cut up into shorter lengths is called sheet, typically in gages between 0.024 and 0.064 in. Thinner gage material (to a minimum gage around 0.008 in.), destined for subsequent tinning, is properly called black plate. Terminology is confusing though, because "tinplate" is often used as an alternative description for the untinned sheet. In recent years, even thinner gages (down to 0.003 in.) have been produced for the canning industry, and it is then usual to refer to double reduced or extra thin tinplate. The second cold rolling step takes place after annealing and usually before but sometimes after tinning; therefore, the lubricant may now have to lubricate a tin surface. Strip thinner than 0.002 in. is referred to as foil. For economy of production, cold rolling mills are run at high speeds, in excess of 1000 fpm and approaching 6000 fpm. Narrower strip is either slit from wide strip, or rolled in narrow widths on specialty mills if small quantities, special compositions, or rolling difficulties warrant it.

Stainless steel is rolled essentially with the same techniques, although quantities are smaller. The hot band is likely to be thicker and more cold reduction, coupled with appropriate process anneals, is customary. Mills with small work rolls, primarily the Sendzimir mill, have found wide acceptance. Four-high, cluster (six-high), and multiroll (12 and 20-roll) mills as well as special mills are now also being built with comparably small work-roll diameters.

Sections amount to a smaller proportion of the total steel output, but they still represent a significant tonnage. Almost invariably they are hot rolled from prerolled or cast billets. Special sections are frequently extruded.

6.41 Hot Rolling Lubricants

As discussed earlier in Section 6.21, ferrous materials are hot rolled dry, that is, with the oxide fulfilling the role of a lubricant. Cooling water is applied to the rolls and, if the finishing temperature of the product is to be controlled, also to the workpiece. Carefully designed jets and sprays are used on the runout table of hot strip mills, and the water flow is closely controlled [110]. Two-color radiation pyrometers are the most reliable for measuring strip temperature on the finishing stands, with dials placed in view of the cooling water operator. At rolling speeds of 2000 to 3000 fpm, water is supplied at rates of several thousand gallons per minute at 60-75 psi pressures. Enough coolant is applied to cool a 0.080 in. strip by 280°C.

Lubricants are not used industrially in the rolling of solid shapes, but graphite in various carriers is applied to the piercing plug in tube-piercing operations. It has been pointed out, however, that some benefits of lubrication could be expected in the rolling of thin-walled, lightweight sections, particularly in the finishing passes, where roll pressures are high, relative sliding velocity is high and variable, and roll wear becomes severe. The suitability of various lubricants was tested by Chekmarev et al. [69] by rolling on 8 in. diameter chilled cast iron rolls at 60 fpm. Lubricants included a commercial window (soda-lime) glass with a softening point of 700°C, alone and with flake graphite, an experimental glass of 500°C softening temperature, and common salt (sodium chloride). Preheated specimens were descaled, covered with the lubricant powder, returned to the furnace for 5 to 10 min, and then rolled. The efficiency was judged by a number of methods; compared to dry rolling, lateral spread of the billets was reduced 30% by the window glass, 22% by the graphited glass and the experimental glass, and 12% by the salt. Interface pressure was reduced 40, 27, 29, and 33%, respectively. Since the common salt generated objectionable fumes, window glass appeared to be the most promising material. Further tests showed that it reduced forward slip from 7% in dry rolling to 0% with glass lubrication, while the angle of acceptance decreased from 13° to 9°. Although the latter value is rather low, it does not preclude rolling in finishing passes, where the section thickness is relatively small compared to the roll diameter. There is no indication that lubrication by glass or any other lubricant has been introduced into industrial rolling practice; advantages and difficulties associated with glass lubrication are discussed in Section 8.34.

6.42 Experiments on Cold Rolling Lubricants for Steel

Since the introduction of palm oil (see Chapter 1), most lubricant evaluation has been made with reference to this lubricant, and it will serve as a convenient standard basis of comparison for this discussion, too.

In view of the economical significance of steel strip, it is not surprising that substantial effort has been devoted to lubricant research. Some of the work was directed toward a more fundamental understanding, other researchers were interested in evaluating the relative merits of lubricants, while a large group devoted itself to developing improved lubricants. A difficulty of presentation arises from the fact that reported results were obtained by different techniques and on widely varying equipment. Quantitative comparisons would be entirely misleading; obviously, results obtained by any given technique must be compared within a single group, and only an order of merit of lubricants may be established. Therefore, the following discussion, based on data reported in Tables 6.4 to 6.17, will be divided according to lubricant groups, and will then be followed by a reasoned appraisal of industrial practices.

Valid conclusions may be drawn only if the conditions of experiments are taken into account; therefore, the method of deriving the numerical data is briefly indicated in Tables 6.4 to 6.17. Some further explanation is needed for Tables 6.11 to 6.17. The technique used was always that of repeated rolling of the same strip with a predetermined roll gap setting sequence (Fig. 5.1b). In the work reported in Tables 6.11 to 6.15, the total reduction obtained in a predetermined number of passes on dry rolls (RED_d) was taken as a base-line and the reduction attained with the lubricant (RED_ℓ) was taken as a measure of lubricant quality:

$$\frac{(RED_\ell) - (RED_d)}{(RED_d)} \times 100\%$$

Billigmann [111] pointed out that reproducibility is much better when lubrication with water is chosen as a base line. He obtained a second reference line by rolling with palm oil precoated onto the steel strip, with water cooling applied at the roll. If water is assigned 0 and palm oil 100 efficiency, other lubricants may be related to this arbitrary base scale by linear interpolation and extrapolation (as in Fig. 6.27)

TABLE 6.4

Coefficient of Friction Measured in Rolling Steel Strip [11]

Lubricant	Pass No.	Reduction %	Coef. of Friction (μ)
Dry	1	15.0	0.085
Paraffin (kerosene)	1	16.5	0.080
	2	17.0	0.068
	3	22.0	0.060
Paraffin + 1% stearic acid	1	16.7	0.075
Paraffin + 1% palmitic acid	3	22.0	0.043
Paraffin +1% lauric acid	2	18.8	0.052
	3	24.3	0.053
Paraffin + 5% lead oleate	2	17.4	0.058
Graphite in SAE 30 oil	1	15.5	0.072
Olive oil	2	18.1	0.057
Castor oil	4	23.0	0.045
Lanolin	4	26.5	0.041
Camphor flowers (natural)	4	27.2	0.038

Back tension increased until strip skids; 4 in. diameter rolls of 10 μ in. AA roughness at 32 fpm, 0.070 in. x 1.5 in. annealed 0.08% C strip.

Mineral Oils

All practical observations and experimental results agree that mineral oils are of only moderate lubricating value. While coefficients of friction of the order of 0.08 to 0.10 reported for dry rolling by Whitton and Ford [11] (Table 6.4) and by Yamanouchi and Matsuura [112] (Table 6.5) are almost certainly too low, the slightly lower friction measured for various mineral oils seems to be realistic. There is complete agreement that viscosity is the dominant factor, friction decreasing with increasing viscosity (Tables 6.6 and 6.7). Chisholm [113] also reported that in the rolling of 0.011 in. thick mild steel strip at 85 fpm, reduction increased from 20.5% with a low viscosity (40 SUS at 100°F) compounded oil to 26.5% with a higher viscosity (160 SUS at 100°F) straight mineral oil, at a constant roll force. The detailed investigation of Iwao et al. [39] revealed that predominantly naphthenic oils are less efficient than their paraffinic counterparts of the same viscosity (Table 6.6).

TABLE 6.5

Coefficient of Friction in Rolling Steel Strip [112]

Lubricant	Pass No.	Reduction, %	Coef. of Friction (μ)
None	1	13.5	0.101
	2	19.1	0.087
Paraffin (kerosene)	1	1.9	0.081
+ 5% stearic acid	1	5.9	0.065
	2	7.5	0.066
Dynamo oil	1	10.2	0.059
	2	6.7	0.069
	3	4.3	0.066
Graphite in oil	1	6.6	0.056
	2	11.2	0.058
	3	11.2	0.062
	4	9.9	0.057
Coconut oil	1	12.0	0.036
	2	5.5	0.043
	3	3.5	0.047
Lanolin	1	8.9	0.046
	2	5.7	0.044
	3	10.9	0.043
Castor Oil	1	7.3	0.034
	2	5.2	0.038

Back tension increased until strip skids; 6 in. diameter rolls at 56 fpm; 0.040 x 1.35 in., annealed 0.5% C steel strip, TS = 83 kpsi.

The evidence on the efficiency of additives in mineral oils is somewhat contradictory. Boundary additives such as lead oleate (Table 6.4), oleic acid (Tables 6.6 and 6.11), but particularly stearic acid (Tables 6.5, 6.11, and 6.13) have been shown to be moderately effective, especially if added to mineral oils of low viscosity. Other investigators found the fatty acids ineffective (Table 6.7); it is likely though that—as suggested by Iwao et al. [39]—the effect of additives is masked when the base oil is of sufficient viscosity to assure predominantly hydrodynamic lubrication.

TABLE 6.6

Lubricant Performance in Rolling Steel [39]

Lubricant	Strip Thickness, in.	Speed, fpm	No. of Passes	Viscosity at 37.8°C, cs	Total Elongation, $(\ell_1 - \ell_o)/\ell_o$
C100 (paraffinic) mineral oil	0.08	21	5	21.8	2.43
D100 (naphthenic) mineral oil	0.08	21	5	21.0	2.33
C450 (paraffinic) mineral oil	0.08	21	5	99.3	2.47
D500 (naphthenic) mineral oil	0.08	21	5	111.0	2.36
C100	0.04	77	7	21.8	1.65
C100 + 50% lard oil	0.04	77	7	—	1.77
100% lard oil	0.04	77	7	—	2.00
C40 (paraffinic) mineral oil	0.04	21	6	4.0	0.82
C40 + 1% oleic acid	0.04	21	6	—	1.03
C40 + 5% oleic acid	0.04	21	6	—	1.07
C100	0.08	130	8	21.8	1.80
Oleic acid	0.08	130	8	20.6	1.92
Lard oil	0.08	130	8	41.7	2.07
Olive oil	0.08	130	8	42.3	2.08
Palm oil	0.08	130	8	44.1	2.15
Castor oil	0.08	130	8	286.3	2.30

0.040 x 1.8 in. or 0.080 x 2.7 in. mild steel strip.

TABLE 6.7

Effect of Lubricant on Reduction Obtained in Steel Rolling [21]

Lubricant Type	Characteristics	Reduction, %
Mineral oils	70 SUS at 100°F (38°C)	16.0
	600 SUS at 100°F	24.0
	600 SUS +5% stearic acid	24.0
Fatty oils	Typical animal fat	32.5
	More viscous fat	39.0
	Stearic acid	32.5
	Oleic acid	30.0
	Palm oil	32.5
	Tallow oil (0.25% free fatty acid)	32.5
"Water soluble"	Experimental	28.0-59.0

0.0063 x 0.250 in., cold rolled SAE 1010 strip; 4 in. diameter rolls at 300 fpm, 38°C; rolls and strip flooded, roll force 3800 lb.

There is almost general agreement that extreme pressure additives such as zinc thiophosphate and chlorinated paraffin [39] are totally ineffective (Table 6.13) even though some compositions have been patented (see literature cited in Ref. 122). It should be borne in mind, however, that most experimental work was conducted at low speeds. In the high-speed experiments of Starchenko et al. [114] a sulfur-containing mineral oil became more effective with increasing rolling speeds (Table 6.8 and Fig. 6.24) suggesting that the higher temperatures that were bound to develop had activated the sulfur.

Fatty Oils and Derivatives

Palm oil, originally used as a flux in the tinning process, was introduced as a rolling lubricant by inspiration. Preapplied to the strip surface in a thin film it provided both the required lubricating capacity and corrosion protection. However, its performance was often found variable, it had to be removed before annealing because of heavy staining, and it proved to be a scarce commodity in wartime and in countries with limited access to prime sources. Substantial effort has been devoted to understanding the variables that affect the lubricating ability of various fatty oils and their derivatives,

TABLE 6.8

Lubricants Used in Cold Rolling Steel [114]

No.	Designation	Characteristics
1	Emulsion 2.5% conc.	Fluid, milky color at 30-40°C
2	Emulsion 5% conc.	As 1
3	Emulsion 10% conc.	As 1
4	Water	
5	Industrial oil type	Mineral oil viscosity 3°E at 50°C, flash point 170°C, solidification temperature 20°C
6	Sulphoresol	Min. 1.7% S content, viscosity 3°E at 50°C
7	Castor oil	Saponification No. 182, acid No. 1.14, viscosity 20.3°E at 50°C

0.120 in. thick, hot-rolled, pickled 0.08% C steel strip; 12 in. diameter work rolls. Lubricant No. is the same as in Fig. 6.24.

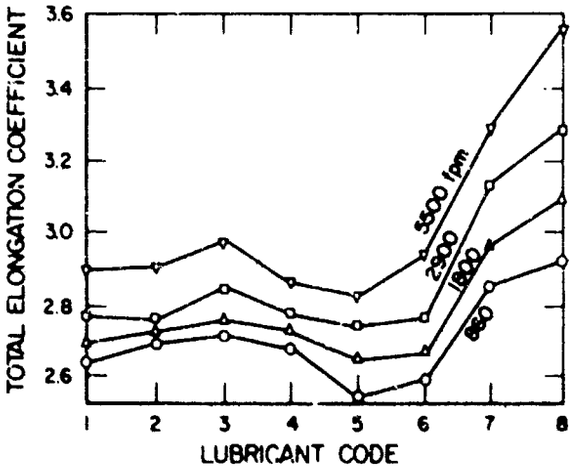

Fig. 6.24. Lubricant efficiency in cold rolling 0.120 in. low carbon steel sheet (lubricants described in Table 6.8) [114].

TABLE 6.9

Reduction Obtained in Rolling Steel Strip [115]

Lubricant	Sap. Value	Free Fatty Acid, %	SUS at 210°F (99°C)	Average Reduction, %	Rolling Load for 50% Reduction, klb
Methyl palmitate stearate	200	0.8	32.6	42.1	30.8
Lauryl alcohol	0.2	0.1	35.1	42.7	34.4
Diethylhexyl sebacate	262	0.1	38.3	44.1	25.5
Lauric acid	280	100	37.0	45.2	27.1
Palm oil	199	9.5	54.0	49.3	17.9
Tallow	196	1.3	56.8	50.2	20.4
Mineral oil	0	0	123.3	53.0	16.4
Lubricant 344	245	5.0	190.2	59.7	11.9

1 5/8 in. diameter rolls at 215 fpm; 0.010 x 2 in. low-carbon steel strip, YS = 43 kpsi, cleaned with trichlorethylene, dipped in lubricant at 65°C.

TABLE 6.10

Roll Force Developed in Rolling Low-Carbon Steel [121]

Oil	Sap. Value	Free Fatty Acid, %	SUS at 150°F	Timken psi max.	Amsler μ	Roll Force at 40% Reduction, klb/in.
Palm oil	198	12	96	8,000	0.043	30.5
Soybean oil derivatives	—	—	—	—	—	21.3
Glyceryl trioleate	—	—	—	—	—	29.0
Rolling oil 1	199	3.5	102	7,000	0.039	27.0
Rolling oil 2	76	6.0	160	12,000	0.046	29.5

0.010 to 0.020 in. x 2 to 10 in. full hard C1017 steel, YS = 128 kpsi, 6 in. diameter rolls at 100 fpm, front tension 620 lb, back tension 600 lb per inch width; 4% "solution" (mechanical dispersion) at 65°C (150°F) 5 psi spray into roll gap.

TABLE 6.11

Lubricant Efficiency in Rolling Steel Strip (Nos. 1-34 [116]; 35-59 [124])

No.	Type	Free Fatty Acid, %	Viscosity at 50°C °E	Improvement over Dry Rolling, %
1	Palm oil	3	4.0	60
2	Rapeseed oil	1.5	4.3	56
3	Castor oil	13.0	7.0	60
5	Rapeseed oil + 6% rapeseed oil acid	6.0	3.8	60
6	Tallow + 3% tallow fatty acid	3.2	4.0	64
7	Mineral oil	0	6.0	39
9-12	No. 7 oil + 3 to 10% oleic acid	3-10	5.8-6.1	37-39
13-16	No. 7 oil + 3 to 6% saturated fatty acid	3-6	5.1-6.1	38-39
17	No. 7 oil + 30% stearic acid	30.0	3.8	48
18	No. 7 oil +25% palmitic acid	25.0	4.0	43
19	Tallow	—	4.4	62
20	Lanolin	—	38.0	55
21-24	No. 19 oil +3% fatty acids	3.0	4.4-5.0	62-63
25-26	No. 20 oil + 3% fatty acids	3.0	35-41	56-58
27-28	1/2 tallow, 1/2 lanolin + 3% fatty acids	3.0	4.3	62
29-31	Tallow and lanolin emulsions 2%	20.0	4.0	47
32	No. 7 oil + emulsifier (2%)	—	11.2	48
33-34	Commercial emulsions (2%)	12.0	4.5-5.2	48-52
35	Neutral fat emulsion (5%)			63
36-38	Mineral oil emulsion with additives (5%)			45-48
40-43	Mineral oil emulsion (5%)			44-47
41	Palm oil	17.0		54
42-49	Pickle oil (mineral oil + rust preventive)			36-38
	Pickle oil (2%) in water			40
44-45	Palm oil emulsion (3%)			56-57
46-47	Mineral oil (4°E at 50°C) emulsion (5%)			42-43

TABLE 6.11 (Continued)

No.	Type	Free Fatty Acid, %	Viscosity at 50°C °E	Improvement over Dry Rolling, %
48	Mineral oil (6°E at 50°C) emulsion (5%)			49
50	Mineral oil ("petroleum")			35
52-55	No. 50 oil +0.4 to 5% stearic acid			37
56-59	Tallow-lanolin emulsion with wetting and frost-protection agents (5%)			57-61

0.040 x 2 in. cold rolled 0.064% C steel strip; 7 in. diameter rolls at 22 fpm, 6 passes of 0.00475 in. roll gap setting each; viscous liquids brushed on strip, emulsions recirculated.

TABLE 6.12

Lubricant Efficiency in Rolling Steel Strip [126]

Lubricant*	Improvement over Dry Rolling, %
Water	12
Palm oil (neat)	40
Mineral oil emulsions	15-22
Rapeseed oil-mineral oil emulsions	14-23
Wax emulsion	36-37
Palm oil emulsion	36.5
Animal oil emulsion (No. 5)	17
No. 5 + TCP (or Pb stearate, or n-butyl stearate or oleate)	18
No. 5 + 5% octadecyl amine	26
No. 5 + 30% wax	29
Rapeseed oil emulsion + 2.5% wax	41
Rapeseed oil emulsion + 30% wax	45

*5% emulsion unless otherwise stated.

0.040 x 2 in. annealed 0.07% C steel strip; 10.2 in. diameter roll at 57 fpm, 3 passes, 44% total reduction in dry rolling.

TABLE 6.13

Total Reduction Obtained in Rolling Steel Strip [127]

No.	Lubricant	Total Reduction, %
0	Water	57
1	Castor oil	83
2	Rapeseed oil	81
3	Mineral oil	57
5	Mineral oil with 0.4% stearic acid	73
8	Mineral oil with 30% Cl compound	67
11	Mineral oil, 1°E at 50°C	64
12	Mineral oil, 2.5°E at 50°C	67
16	Sperm oil emulsion (5%)	73
17	Sperm oil emulsion with phosphoric acid ester (5%)	69
20	Tallow emulsion (5%)	68
22	Tallow-lanolin mixture (solid)	86
24	Synthetic fatty acid (anoxidized paraffins) emulsion (5%)	85
25	Synthetic fatty oil emulsion with mineral oil (5%)	72
26	Mineral oil emulsion (5%)	64

0.040 x 2 in. strip, 0.19% C cold rolled; 6 passes of 0.00475 in. roll gap setting, 8.3 in. diameter rolls at 70 fpm.

and to find the lubricants that can not only substitute for palm oil, but even improve on its performance.

All evidence indicates that the bulk viscosity of the fatty lubricant is a major factor, as shown by the systematic work of Iwao et al. [39] (Table 6.6). The same trends may be found in Tables 6.4, 6.5, 6.7, 6.9, and 6.11.

Viscosity, however, is only one of the significant indicators of lubricating performance. In practice, it was found that neutral fats are inadequate and the opinion was soon formed that slightly aged palm oil, in which 7 to 14% free fatty acid was present, was desirable. This view was confirmed by the work of Nekervis and Evans [23] who found that Nigerian palm oil with 16% free fatty acid gave higher reductions (and a lower calculated coefficient of friction in rolling

TABLE 6.14

Reductions Obtained in Cold Rolling Steel [70]

Steel Composition, %	Tensile Strength, kpsi	Lubricant	Total Reduction, %
0.064C	90	Mineral oil (6°E at 50°C)	46
		Rapeseed oil	53
		Emulsion*	59
1.35C, 0.70Cr	95	Mineral oil	54
		Rapessed oil	64
		Emulsion*	66
1.36C, 0.67Cr	140	Mineral oil	72
		Rapeseed oil	80
		Emulsion*	84

*64% mineral oil, 10% fatty alcohol C_{12}-C_{18}, 26% mineral oil sulfonate, anionic emulsifier.

0.040 x 2 in. strip, mill and drafting as in Table 6.11.

TABLE 6.15

Efficiency of Lubricants in Rolling Steel [123]

Identification	Lubricant	Total Reduction (6 passes), %
—	Dry	53
D	(1/2 calcium phosphorus stearate, 1/2 stearic acid) dissolved in toluol	89
F	(1/2 Fe phosphonostearate, 1/2 neutral soap) 5% emulsion	90.8
—	Tallow (3% free fatty acid) (neat)	87
P	Glycol distearate (neat)	89
S	Fe salt of dodecylphosphonic acid dissolved in toluol	91
—	Rapeseed oil (neat)	86

Conditions as in Table 6.11.

TABLE 6.16

Efficiency of Emulsions in Rolling Steel [111]

Lubricant	Free Fatty Acid, %	Efficiency (8th pass)
Water	0	0
Conventional emulsions	1	20-45
Improved emulsions	1-8	50-75
Palm oil emulsion	5	72
Tallow emulsion	9.5	85
Experimental emulsion	22.7	80
Mineral oil (preapplied, water cooling)	0	60
Palm oil (preapplied, water cooling)	10	100

0.020 in. thick, 0.05 to 0.08% C cold rolled steel, degreased; 8 passes on 3.5 in. diameter rolls at 250 fpm, 5% emulsions in water of pH 6, 30°C, flood application.

than the same oil refined until its free fatty acid content was reduced to 0.55%. In their experiments, the acid extracted from the same oil was also more efficient than the fatty oil itself. Later work, however, showed that this is by no means a universal rule, since very efficient lubricants have been found with relatively low (around 1%) free fatty acid content [21, 115]. The detailed work by Lueg et al. [116] indicated that free fatty acids added to a neutral fat increased the lubricating potential only slightly (see rapeseed oil, tallow, and lanolin in Table 6.11). Johnson et al. [117] used a wire drawing test for evaluation of palm oil substitutes and, therefore, the strict relevance of their results to rolling is rather doubtful (see Section 5.28) but it is interesting to note that they also found free fatty acid added to tallow to be either ineffective or even harmful, depending on the drawing temperature.

A further observation relates to the structure of the fatty acid molecule. Generally, the longer the chain length, the higher the viscosity, and this would be in line with the previously discussed effect of bulk viscosity. For identical chain lengths, unsaturated acids are less viscous than their saturated counterparts (for example, oleic acid and stearic acid in Table 6.7). It has also been observed that predominantly saturated animal fats such as tallow are successful substitutes for palm oil (Johnson et al. [117], also Table 6.7), while fish oils higher in unsaturated fatty acid esters are

TABLE 6.17

Efficiency of Emulsions in Rolling Steel [125]

Lubricant (5% emulsion except where shown)	Free Fatty Acid, %	Efficiency in Pass No. 3	6	12
Palm oil (neat)	10.0	100	100	100
Synthetic palm oil (neat)	9.0	128	135	124
Pickle oil (neat mineral oil)	—	48	53	65
Mineral oil with fatty additives	0.5–23.6	30–80	34–71	40–72
Mineral oil with E. P. compounds	0.8–7.1	56–106	60–90	65–90
Palm oil	7.7–10.3	80–90	82–90	88–90
Tallow	1.1–6.8	88–110	75–97	72–82
Tallow and rapeseed oil	1.1–2.1	112–126	88–112	90–105
Rapeseed oil	0.7	44	54	56
Linseed oil	1.3	128	97	87
Castor oil	2.0	128	93	77
Codliver oil	0.3	147	95	73
Spermaceti (raw)	0.8	108	85	76
Spermaceti (refined)	1.1	162	108	100
Synthetic products (polymerized)	—	73–76	70–72	62–73

Conditions as in Table 6.16, but 12 passes.

generally less satisfactory. This has led to the view that a good rolling lubricant should have a low iodine value and a high titer (for definition, see Appendix). It would be a mistake, however, to take these limitations too rigidly. As discussed in Section 4.22, even nominally identical oils have different compositions depending on the exact source of supply and on changes introduced by extraction and refining. Tallow is usually fairly reproducible; on the other hand, lard oil is variously reported as unsaturated or comparable to palm oil in saturation.

The tallow-based "synthetic palm oils," also called palm oil substitutes, were developed after World War II [23, 117]. They are still among the best lubricants available (Fig. 6.25 and 6.26) [118, 119] having found widespread acceptance [120] after the initial production trials. Of the vegetable fatty oils, castor oil has been found either superior (Table 6.6) or equal (Table 6.11) to palm oil. Cottonseed oil has been judged equally good. The less viscous rapeseed oil is somewhat poorer (Table 6.11 and Fig. 3.20) although experiments with various proportions of rapeseed oil and tallow [13, 14] have shown promise. Linseed oil and similar oils containing higher unsaturates are normally undesirable because of their oxidative instability. The reader interested in greater detail will find it worthwhile to study the data given in

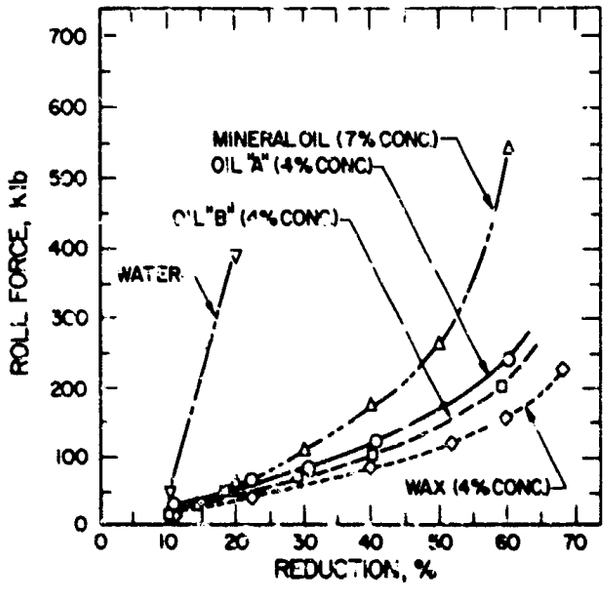

Fig. 6.25. Lubricant efficiency in rolling soft low carbon steel strip (0.010 in. thick, on 8. in. diameter rolls of 16 μ in. RMS roughness, lubricant composition in Table 6.18) [118].

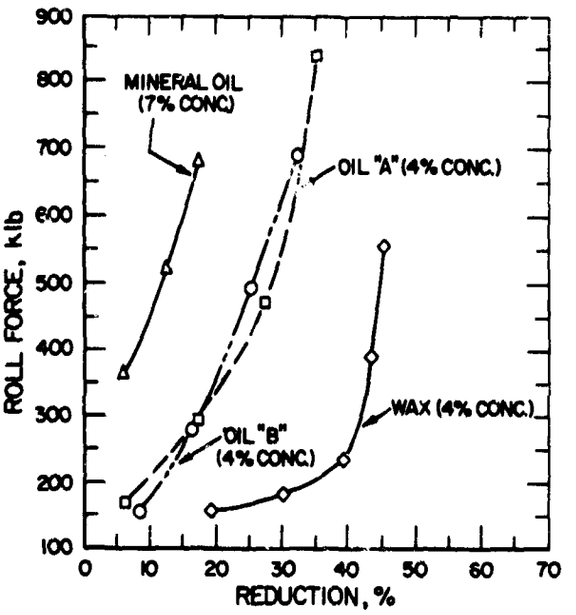

Fig. 6.26. Lubricant efficiency in rolling full-hard low carbon steel strip (conditions the same as in Fig. 6.25) [118].

Tables 6.4 to 6.17; these tables have been compiled to show all the important results of the referenced publications.

Improved Lubricants

Recognition of the need for high viscosity coupled with a high degree of saturation has led to a number of approaches for producing improved rolling lubricants. Proprietary interests usually prevent publication of details (Tables 6.7, 6.9, and 6.10, and Fig. 6.12), but it is clear that modified animal or plant oils of high viscosity give greater reductions. It is often found, though, that these high-viscosity oils tend to trap more dirt, may form more tenacious deposits, and might also lead to skidding of the strip or of the rolls in the roll gap. Roberts [53] reported some improvement over palm oil when 50% methyl ester of tallow fatty acid was added to neutral tallow.

Starting from the premise that the long chain fatty acid portion of the triglyceride molecule is responsible for rolling performance, Shamaiengar [121] found glycerile trioleate with 100% C_{18} chain slightly better than palm oil (Table 6.10). Along the same lines, lard oil (which also contains C_{20} esters) could be expected to and indeed gave better results than tallow. It has also been noted that partial hydrogenation and consequent greater saturation results in better rolling lubricants. Since experiments showed that

triglycerides are always superior to mono- and diglycerides, Shamaiengar suggested that further development could concentrate on modifying the fatty acid radical of the triglyceride. One possibility is to react the hydroxl group of the ricinoleic acid in castor oil with a fatty acid (palmitic, stearic, etc.) to obtain a multiple ester linkage; such lubricants were found to outperform tallow even when used in combination with mineral oil. Shamaiengar also proposed [122] lubricants made by co-polymerization of animal fats with hydrocarbons, which results in a lubricant with controlled amounts of mixed esters, saturated and unsaturated fatty acids and their esters.

A different tack was taken by Funke et al. [123], who considered that the surface activity of fatty acid molecules is exceeded only by that of the phosphonic acid groups, and predicted that the combination of long-chain fatty acids with a phosphonic acid group would give good lubricating properties. Several of the products were solid and had to be dissolved in toluol; the dry coating gave very good performance (Table 6.15). Precoating from a solution would be, of course, impractical, and means of emulsifying the lubricants would have to be found. This was only partially successful.

The condition of long chain length and high saturation is also satisfied by natural waxes, and outstanding results have been obtained with some of them (Figs. 6.25 and 6.26). It would seem, however, that in common with other very high viscosity lubricants, they present problems in application.

In summary is appears that, rather fortuitously, palm oil and the later developed substitutes represent a good balance of properties, and radical improvements are not readily attained. However, even apparently minor improvements can lead to substantial production economies, especially in the rolling of very thin sheet. It should be also borne in mind that most quantitative data available on lubricant performance were generated at relatively low speeds and, even though agreement with plant experience is usually satisfactory, higher rolling speeds, greater heat buildup, and continuous exposure to difficult process conditions could very well accentuate differences between lubricants.

Emulsions

All lubricants discussed above are applied neat, either to the strip surface prior to rolling or as a mechanical dispersion at the rolling mill itself. Instant separation ("plating out") of the lubricant phase assures performance equal to that of a preapplied film. Water is a separate cooling agent which

does not enter the lubricating mechanism, although occasionally improvement has been reported when water was applied in addition to mineral oil. This is probably a cooling effect.

As mentioned in Section 6.34, economy of production as well as the need for reduced pollution prompted the development of closed-loop recirculating systems, in which emulsions of reasonable stability must be used if work stoppages due to a clogged system are to be avoided.

Emulsion development usually aimed at retaining the advantages of directly applied palm oil or its substitutes, yet eliminating its disadvantages. Palm oil applied directly to the strip surface prevents corrosion even on prolonged standing, but must be removed prior to annealing. Emulsions have been sought [111, 116, 124-127] that match the lubricating and corrosion-preventive characteristics of palm oil yet will decompose in annealing without leaving objectionable residues. Quantitative assessment is usually limited to the lubricating ability of the emulsions (Tables 6.7, and 6.11 to 6.17). Comparison between results of various researchers is impossible, because even if the composition of the dispersed phase is similar, the emulsifiers, rust inhibitors, and other additives of undisclosed composition and proportion can drastically change the performance of the lubricant. The mode of application, dilution of the concentrate (Fig. 6.24), and the temperature of the rolled strip and of the emulsion may all have a major effect. Nevertheless, some generalized conclusions may be drawn.

First attempts at replacing palm oil with an emulsion invariably led to deteriorated rolling performance (Table 6.7, Figs. 6.24 and 6.27). It is interesting to note, though, that while emulsions based on mineral oils are relatively poor in performance (lubricants 32, 40, and 43 in Table 6.11; Tables 6.12, 6.13, and 6.17; and Fig. 6.27), they often assure greater reductions than the neat mineral oil itself (lubricant No. 7 in Table 6.11, and Table 6.13). This may be connected with the observation already mentioned that water applied on top of a preapplied mineral oil film improves lubrication (Fig. 6.24 and Table 6.16). Boundary and E. P. additives incorporated in the dispersed phase are variously reported as ineffective (lubricants 36 to 38 in Table 6.11) or moderately effective (Tables 6.14, 6.16, and 6.17), obviously depending on unknown or undisclosed side effects. It is worth noting that the free fatty acid content of "improved emulsions" in Table 6.16 had no bearing on performance, and the lubricant with the highest free fatty acid content was actually one of the poorest in this group.

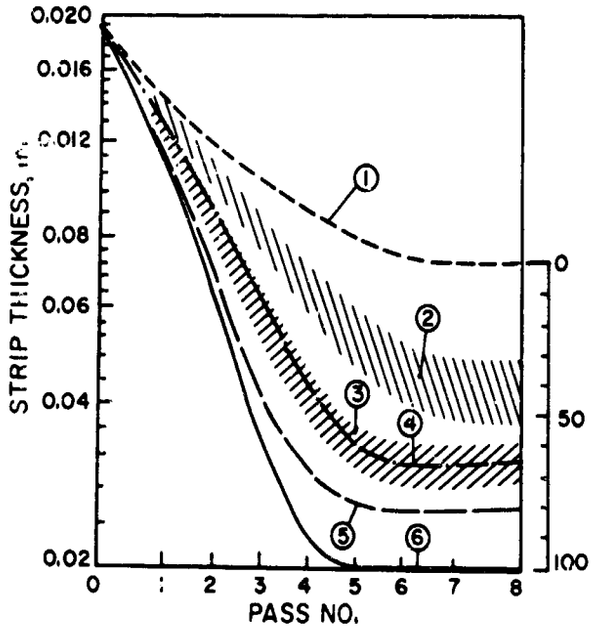

Fig. 6.27. The efficiency of various lubricants in rolling low carbon steel strip (1: water; 2: commercial emulsions; 3: improved emulsions; 4: undiluted concentrate; 5: best emulsion; 6: palm oil) [111].

In contrast to mineral oil, the lubricating ability of fatty oils almost invariably suffers from emulsification (lubricants 29 and 31 in Table 6.11 and palm oil emulsion in Tables 6.12, 6.16, and 6.17), although occasionally equal or slightly improved performance has also been reported (lubricants 44 and 45 in Table 6.11). The development of fatty oil emulsions has taken the same route as that of the neat lubricant itself. Thus, palm oil substitutes derived from animal or vegetable oils, with relatively high contents of longer chain saturated fatty acid components have been used, often with further additives to promote wetting and to protect the emulsion from the effects of freezing (lubricants 56 to 59 in Table 6.11, the synthetic fatty oil emulsion in Table 6.13, tallow emulsion in Table 6.16, tallow and rapeseed oil emulsion and the refined—probably hydrogenated—spermaceti emulsion in Table 6.17). Improved performance over that of neat palm oil has also been reported when high percentages of wax were added to rapeseed oil emulsions (Table 6.12). While it appears entirely feasible to produce emulsions that match the performance of neat palm oil, emulsions offering the same reductions as the improved "synthetic palm oils" in direct application have not been revealed

yet (Table 6.17). There is unanimous agreement that the long chain, highly saturated esters are difficult to emulsify, they tend to trap more dirt, are liable to form invert emulsions, and may be very sensitive to production conditions.

The experimental emulsions in Table 6.7 are effective only at very high concentrations, and were reported to be useful only where cooling is not critical. In this sense, they cannot be regarded as true emulsions, rather as water-soluble solid lubricants or lubricant pastes. The experimental lubricants indicated in Fig. 6.12 are apparently of the same family. Their main advantage would lie in easy removal by water rinsing.

Emulsions have been repeatedly found to give outstanding performance in early passes (Table 6.17, also Ref. 124 and 126), only to fall behind palm oil later on (Table 6.17) when limiting reductions are approached. No rational explanation for this behavior appears to have been proposed, but perhaps the cooling ability of the lubricant predominates in the early passes when heat generation is substantial, and its ability to reduce the coefficient of friction becomes more significant as a roll geometry typical of limiting reduction is approached. It is conceivable that at high speeds the cooling effect would again become of overwhelming importance.

No emulsion evaluation is truly valid unless repeatability, stability, life, and sensitivity to various waters is also investigated. Emulsions containing mineral oil as the dispersed phase are invariably more stable than those based on fatty oils and their derivatives. The relatively low stability of fatty oil emulsions makes them particularly sensitive to the quality of the water. If anionic or cationic emulsifiers are used, calcium present in the water gradually combines with them and the emulsion becomes unstable. Additions of sodium hydroxide or sodium chloride for purposes of adjusting the pH value of the water are also harmful, because they also combine with the emulsifier and break the emulsion. It then becomes necessary either to formulate the emulsion with nonionic emulsifiers or to treat the water with iron-exchange water softeners.

The emulsion should not cause rusting of the rolled sheet. A semi-quantitative assessment by Billigmann and Fichtl [125] indicated that mineral oil emulsions—even when compounded with fatty additives—gave typically moderate to heavy corrosion, as did also emulsions based on tallow. In contrast, emulsions based on palm oil, rapeseed oil, or mixtures of tallow

and rapeseed oil caused only light rusting, even though still somewhat more severe than neat palm oil or even pickler oil (Section 6.43). No relationship between composition and rusting could otherwise be detected. The rusting developed in tests, in which cast iron chips were wetted with the lubricant and placed on a cast iron surface for observation, correlated in no way with actual rusting found on strip rolled with the lubricant and then kept in a production plant, lightly covered with paper to prevent accumulation of dirt. Some rust inhibitors were found effective, but they also impaired the lubricating performance of the emulsion.

The reproducibility of individual batches of emulsion concentrates can be rather poor [111], and the hope has been expressed that synthetic fatty acid emulsions might prove more reproducible [127]. This brings up the question of how the consistency of various batches can be most economically tested. As of this time, only the laboratory-scale rolling test seems to be relevant, although Billigmann and Fichtl [125] have reported that a simple sliding test, somewhat similar to a modified Timken test, gave encouraging correlation between the size of the wear surface and the rolling performance.

The dilution of the emulsion may or may not have an effect on lubricating ability, depending on the composition. No accurate prediction appears to be possible, but as a rule of thumb results indicated [124, 125] that mineral oil emulsions (with suitable additives) improved as concentration increased up to and beyond 5%. Palm oil emulsions gave optimum performance between 2 and 8%, depending on the actual formulation, with performance dropping at higher dilutions. In contrast, tallow and tallow-rapeseed oil emulsions gave better reductions at low (around 1.5%) concentration than at higher ones. The reason for this variable behavior is entirely unknown.

Full-scale tests have been reported only on a few experimental emulsions usually in mills rolling at speeds between 1200 and 3000 fpm—that is, not in the highest available speed range. It was found [111] that performance was initially as predicted from the laboratory rolling experiments; however, a highly variable aging behavior of various lubricants soon became evident. Some of the better emulsions, based on highly viscous fatty oils, collected too much dirt or suffered from insufficient stability, and slipping of the strip has also been reported [126]. It is also clear that results obtained on one industrial mill cannot be transferred to another one without considering production conditions; in general, more rapid deterioration of emulsions is to be expected as rolling speeds increase [125].

Phosphated Strip

Phosphating (Section 4.41) has found widespread application in wire and tube drawing, cold extrusion, and sheet metalworking. The possibility of utilizing such conversion coatings for the rolling of steel has been raised by Lueg and Treptow [128]. They started from the premise that a phosphate coating, in conjunction with a relatively cheap mineral oil lubricant, could provide the same lubricating power as palm oil or its substitutes and at the same time might also minimize the speed effect. A low carbon (0.1% C) and high carbon (1.12 to 1.17% C) steel were phosphated according to three different techniques. With either mineral oil or rapeseed oil as a lubricant, roll forces dropped by 20 to 25% when heavy reductions were taken on the low-carbon steel. In contrast, very little improvement was found on the high carbon steel even with the mineral oil, and rapeseed oil actually gave better results on the untreated surface. It is concluded that phosphating of steel surfaces could become attractive only if savings due to the use of a mineral oil and a possible elimination of some interanneals would more than offset the cost of phosphating. The quality, particularly surface roughness, of the phosphate film seems to be important also, and an optimum treatment would have to be devised.

Optimum Lubricant Quantity

The discussion of the speed effect (Section 6.23) showed evidence that, irrespective of the thickness of the preapplied oil film, there exists a limiting film thickness that will pass through the roll gap [21]. This also means that, if the lubricant application method does not assure an absolute surplus, the relative rating of lubricants may be influenced by the method of application, as already noted by Nekervis and Evans [23].

In a direct application system with the coolant applied separately, the lubricant applied in excess of the optimum is wasted. Bentz and Somers [129] investigated the minimum oil film required in the rolling of 0.010 in. thick annealed and 0.015 in. thick fully hard low-carbon steel strip (blackplate) and 0.011 in. thick annealed, tinned (0.5 lb per base box) strip at 100 fpm. After degreasing, cottonseed oil was applied by an electrostatic process in controlled film weights between 0.20 to 4.5 g per base box (the two sides of sheets in a base box represent 435 sq ft or 40 sq meters total surface area). The backup rolls were cooled with water. Rolling with a

10% aqueous dispersion of cottonseed oil, applied liberally at the roll bite, served as a reference base. Single passes ranging from 10 to 60% reduction were taken, and the oil film thickness necessary to assure minimum roll force was found to increase with increasing pass reduction. Oil films in excess of 1.25 g per base box were wasted on tinplate and on the soft blackplate, but 3 g per base box was needed for the fully hardened material; no explanation for the difference was offered.

In recirculating systems, where lubricant and water are applied simultaneously, the lubricant supply rate will be determined primarily by the cooling requirements.

6.43 Steel Strip Lubrication Practices

Several publications [118, 130-134] deal with the practice of steel strip lubrication; it remains here to summarize practical aspects, in part discussed in previous sections.

The desirable characteristics of rolling lubricants have been touched upon, nevertheless, it will be useful here to recapitulate attributes of special significance for the cold rolling of steel. Reduction of friction is important because of the relatively large ratio of roll diameter to strip thickness, and it becomes a matter of major concern when thin gages are rolled. Freedom from staining on annealing is universally desirable, although the economic sacrifice of degreasing prior to annealing is tolerable, if the required reductions cannot be obtained with an oil of low staining propensity. Corrosion (rusting) is of major significance with emulsions. Cooling capacity gains importance as rolling speeds increase. Freedom from roll pickup and minimization of roll wear is always desirable. Many of the best lubricants are highly viscous and produce a matte surface finish, and sacrifices in lubricating ability must often be made if a bright surface finish is required.

In addition to all the above factors, the contribution of the pickler oil cannot be ignored in the selection of an optimum lubricant.

Pickler Oils

Pickling of the hot-rolled strip is a decisive factor in the success of the cold rolling operation. Insufficient pickling allows scale to be carried over, contaminating the cold rolling lubricant. When present in patches on the strip surface, scale may also become saturated with oil, causing skidding

in the roll gap. Overpickling results in a heavily roughened surface, which serves to trap lubricants and may lead to uncontrollably low friction, as pointed out by Proctor [130]. Careful rinsing after pickling is mandatory because acid residues would change the acidity of emulsions, causing them to break down.

A lubricant film is applied to the strip emerging from the pickling line to prevent rusting, and also to prevent scuffing of the strip surface during handling and uncoiling on the cold mill. This lubricant, referred to as pickler oil, is usually applied at a pair of pinch rolls, and the quantity of oil is controlled through the control of its viscosity. Viscosity, in turn, is governed by the choice of the lubricant and by heating coils submerged in the pickler oil supply tank. Careful control of temperature is imperative when an emulsion concentrate is used as a pickler oil, because overheating would boil off the small quantity of water incorporated in the concentrate and would prevent re-emulsification. Freezing can have a similar effect.

The choice of pickler oil depends on the type of subsequent processing. If the band is to be fed from a reel, danger of scuffing is less and a moderate (200 SUS at 100°F) viscosity oil suffices. However, a heavy duty and viscous (up to 450 SUS) oil with fatty additives is needed if the coil is freely rotating on rollers, with only the edges confined between flanges [131]. Frequently, the pickler oil also provides lubrication on the first stand of the cold rolling mill. In the rolling of heavy gage sheet with light reductions, the pickler oil may suffice with only water applied to all the mill stands.

The pickler oil is not removed entirely during rolling, and it has been recognized as one of the main sources of staining on annealing. Low-cost, contaminated or reclaimed oils are seldom satisfactory, as pointed out by Drake [131]. The pickler oil should be compatible with the rolling lubricant, and if an emulsion or dispersion is used in the mill system, the pickler oil is frequently the emulsion concentrate itself. In order to reduce staining on annealing, the fatty oil and fatty acid contents of the pickler oil are often reduced (to a saponification value of 32-40, and a free fatty acid content of 1-2%) by adding a mineral oil, preferably of a low staining variety.

Sheet Rolling Lubricants

The thicker gages of sheet are rolled with relatively modest (50-60%) total reduction; therefore, lubricant requirements are not unduly severe.

Mineral oils applied at the pickle line are satisfactory for the thickest gages with only water applied on the mill. The mineral oil is blended with fatty oils when heavier duties are imposed, but staining must still be kept to a minimum. Fatty oils dispersed in hot water (at concentrations of 5-15%) become necessary when rolling is taken to thinner gages. Coolant water is applied to the rolls separately. If staining is to be minimized or a "mill clean" sheet produced, a detergent is applied at the last stand of the mill [108].

For high speeds and heavy drafting, palm oil or improved palm oil substitutes are applied in a moderately stable emulsion, which assures adequate lubrication yet allows recirculation and filtration, without taking contaminants into the emulsion. Sheet rolled with such carefully controlled lubricant can be annealed without prior degreasing. Emulsions based on mineral oils and compounded with some fatty additives provide a very economical lubricant for recirculating systems that may be kept clean almost indefinitely, provided that the pickler oil is not emulsified by the rolling lubricant. It will then separate on the surface of the dirty oil tank and in doing so will also trap the residual iron oxides carried over from the pickling line, as well as the iron fines generated in rolling. An emulsion (concentrate) consumption of 3/4 to 1 1/2 lb per ton of steel was reported by Pannek [135], who also remarked that wetting agents improved cooling of the rolls.

Lubricants for Tinplate (Blackplate)

The thin gage blackplate destined for subsequent tinning (also referred to as tinplate) requires reductions ranging from 80-90% on a five- or six-stand tandem mill at design speeds of up to 7000 fpm. It would appear that, for reasons probably associated with lubricant breakdown, maximum speeds of 5000 to 5500 fpm have not been regularly exceeded yet. Because at least the last stands of the tandem mills operate under conditions approaching limiting reduction, the lubricating qualities of the lubricant become of paramount importance. For this reason, only mechanical dispersions have been used in the U. S. A.; substantial efforts are now being made in various countries in the hope of finding emulsions that assure the same reductions as mechanically dispersed palm oil or substitutes do. The mechanically dispersed fatty oil deposits on the strip; this deposition is to be credited with the outstanding lubricating performance, but it is also responsible for

subsequent staining. These lubricants, therefore, must always be removed, whereas emulsions can be harmless in this respect.

As discussed under the heading "Fatty Oils and Derivatives" in Section 6.42, the lubricating ability of fatty oils, expressed in terms of attainable minimum strip thickness, improves with increasing proportions of long chain, saturated fatty constituents. This will be seen from the analyses given by Roberts and Somers [118] for palm oil and two commercially available substitutes (Table 6.18). The lubricating power of these oils may be gaged from Figs. 6.25 and 6.26, and it will be noted that the lower palmitic acid content of the substitutes is more than compensated for by the higher percentage of the stearic acid component present.

Physical and chemical properties most frequently quoted for rolling lubricants are given in Table 6.19. It must be remembered, however, that these values have any meaning only if the lubricant is composed essentially of conventional fatty oils or derivatives.

The melting or pour point is important in that a lubricant that is liquid at room temperature is easier to apply. The melting point (titer) of saturated acids is higher than that of unsaturated ones, and may be lowered by the addition of mineral oils. This, however, leads to a deterioration of rolling performance. Very roughly, therefore, melting point is sometimes regarded as a crude indicator of lubricating ability. For reasons discussed earlier, the viscosity of the lubricant should be as high as possible, without introducing uncontrollable skidding in the roll gap.

TABLE 6.18

Analyses of Palm Oil and Two Substitute Palm Oils [118]

Fatty Acid Component	Fatty Acid Content, %		
	Palm Oil	Substitute Palm Oils A	B
Palmitic	32.3-40.0	27.6	26.1
Linoleic	5.0-11.3	3.9	2.9
Oleic	39.8-52.4	45.9	39.4
Stearic	2.2-6.4	17.1	20.4
Myristic	1.0-5.0	2.9	3.2

TABLE 6.19

Ranges of the Physical and Chemical Properties of Steel Rolling Lubricants [118]

Property	Range
Melting (or pour) point, °C	5-45
Viscosity	50-850 SUS at 100°F (38°C) 45-200 SUS at 210°F (99°C)
Viscosity index	130-160
Saponification value	125-200
Iodine value	40-75
Free fatty acid, %	3-20

The saponification value of fatty oils (glycerides) decreases with increasing molecular weight. If mineral oil (of 0 saponification value) is also present, the saponification value of the fatty oil is lowered; therefore, it can be regarded as a quality indicator only in a very approximate sense. The iodine value is a measure of unsaturation, but should again only be taken as a rough guide because it is also a function of the molecular weight of the compounds. A high iodine value indicative of the presence of unsaturated fatty compounds is, in general, undesirable because polyunsaturated acids readily polymerize into resinous substances and also tend to become rancid as a result of oxidation [118]. The value of free fatty acids has been often debated, but they are present in most lubricants to the extent indicated in Table 6.19. Too low a value is believed to provide insufficient lubrication, while too high concentration is claimed to prevent "plating out" of the lubricant on the strip surface.

The validity of these general indicators diminishes for lubricants that are further removed from natural fatty oils and derivatives—for example, when fatty oil derivatives assume unusual (up to 3500) molecular weights instead of the more normal 280 [132].

When the fatty oil/water dispersion is applied in a total loss system at the mill, three to eight parts of water are added to one part of oil. The consumption is high, approximately 5 to 7 lb/ton of steel [131]. Cooling

water is applied additionally to the work and backup rolls, raising water consumption to several thousand gallons per minute. The lubricant used in recirculating systems is still essentially mechanically dispersed, and separation of contaminants by flotation is not practical. Magnetic separators as well as filters of 60 μ minimum mesh size, operating under a modest vacuum or overpressure (Section 6.34), have been found very efficient. Oil consumption is between 1 and 3 lb/ton of steel [132]. Approximately 1000 gal of water needs to be replaced per hour. The lubricant may be kept in the recirculating system indefinitely if proper filtration is employed. Otherwise, sludge builds up which—even though not harmful in terms of lubricating quality [118]—results in dirty sheet, and the lubricant must be periodically dumped.

The acidity (pH value) of the cooling water is closely controlled by some mill operators who regard an acidic water as the main cause of a lowered lubricant performance. Practices, however, are not uniform, and the matter is still debated. The same applies to the addition of wetting agents which may improve cooling by assuring uniform wetting of the rolls, yet can also cause partial emulsification and thus impair lubricant performance. The cooling ability of a mechanical dispersion is usually between that of water and the neat fatty lubricant [118], as determined by the quench test described in Section 5.9.

Regular tinplate is annealed and then further rolled on a single stand or a two-stand tandem mill at high speeds, with total reductions ranging from 30 to 50% for the production of reduced gage tinplate. A bright finish is desired to assure a reflective finish on subsequent tinning; therefore, the lubricant properties are balanced to give just low enough friction to permit rolling under conditions approaching limiting reduction, while the surface is brightened through boundary contact and the burnishing action of the rolls. Unstable emulsions or relatively stable (tight) mechanical dispersions have been found satisfactory. For example, Drake [131] reports that an oil-in-water dispersion of 8-14% concentration, applied at 66°C (and presumably without extra cooling water delivered to the rolls) gave a better, mottle-free surface than the conventional direct application of a more concentrated dispersion at 45-50°C.

Lubricants for Strip and for Alloy Steels

Lubricating practices for narrow flat strip are similar to sheet rolling, and depending on rolling speed, the lubricant may be a mineral oil, compounded mineral oils, or unstable or stable mineral oil emulsions. Fatty oil emulsions or dispersions give obviously much better reductions, but may be troublesome on annealing, therefore, an appropriate compromise has to be struck.

A special condition exists in Sendzimir mills, where the rolling lubricant also acts as a lubricant for the mill bearings. The lubricant may be a mineral oil (typically of 100 to 150 SUS at 100°F), often compounded with fats, E.P. additives, and oxidation inhibitors. Lower viscosity oils (40-65 SUS at 100°F) are favored for thinner gages and for foil rolling. Highly concentrated emulsions containing 12-20% concentrate in water are sometimes satisfactory for low and medium carbon steels. These allow greater rolling speeds because of their increased cooling capacity, but may lead to more rapid wear of the bearings and must also be changed more frequently. Cleanliness is always of extreme importance; therefore, these mills are used only with properly designed recirculating systems incorporating adequate filtration and removal of iron contaminants. Great care is taken to prevent entry of tramp oil and grease.

Staining on Annealing

Unless the rolled strip is "mill clean" or degreased, the residual oil may cause staining on annealing. The staining propensity of the oil may be measured by some suitable simulating technique (Section 5.8), and correlated with observed staining in production. With any given lubricant, staining is also influenced by the annealing procedure. Continuous annealing, with both strip surfaces exposed to the air or furnace atmosphere, is the most favorable because the lubricant can evaporate freely. In coil annealing, a clean edge is normally found where access to the furnace atmosphere was free, but a dark stain band develops where substantial oil vapor pressure builds up without free ventilation to the outside. In the middle of the coil, white oil residues may be deposited.

A complicating factor in the annealing of steel is staining caused by oxidation and reaction with the protective atmosphere. Lillie and Levinson [136] and Schossberger et al. [137] found that surface stains are composed

of carbon, iron oxides, iron carbides, and oxyhydrates. They are produced during the annealing cycle with some protective atmospheres, and may be eliminated by keeping the CO/CO_2 ratio low (below 2) and by insuring adequate gas flow rate during the heating period. Oil staining can be reduced by venting the furnace covers, and by keeping the stain propensity of the oil low, particularly by eliminating tramp oils from the lubricating system.

Roll Wear

The subject has been discussed in general terms in Section 6.29 and, since the information is based mostly on steel rolling experience, little need by added.

Wear on tandem mills seems to be most rapid in the middle stands, but wear of the finishing roll is of greatest importance from the point of view of strip surface finish. For this reason, work rolls are changed every few hours on the last stand of a continuous hot strip mill. In cold rolling tinplate on a typical five-stand mill [138] the work rolls are changed in the last stand after rolling 150 tons and after 250 tons in the fourth stand, but over 1000 tons may be rolled on the first three stands. Backup rolls need regrinding after 20,000 tons. These figures probably apply to lubrication with a mechanical dispersion of a fatty oil. In the rolling of sheet, quantities are substantially higher; for lubrication with emulsions, quantities ranging from 450-1500 tons were quoted for the work rolls of a single-stand reversing mill [135].

6.44 Lubricants for Stainless Steel

The lubrication of stainless steel presents substantial problems because stainless steel tends to adhere to the roll surfaces and does not allow formation of protective films with boundary lubricants. The high interface pressures also cause severe roll flattening, and conditions of limiting reductions are much sooner approached than on mild steel. Some measure of the difficulty may be gained from comparing reductions shown in Table 6.20 for stainless steel with those in Table 6.7, obtained on mild steel with much lower roll forces.

It appears that viscosity is an overriding factor in determining the lubricating ability of rolling lubricants. Thus, in Table 6.20 reductions increase with the viscosity of the mineral oil and of the animal fats. The

TABLE 6.20

Effect of Lubricant on Reduction Obtained in Rolling Stainless Steel [21]

Lubricant Type	Characteristics	Reduction, %
Mineral oils	70 SUS at 100°F (38°C)	12.5
	600 SUS at 100°F	15.0
	600 SUS + 5% stearic acid	15.0
Fatty oils	Typical animal fat	20.0
	More viscous fat	25.0
	Stearic acid	18.0
"Water soluble"	Experimental, highly viscous fatty oil derivatives	16.0-38.5

0.0052 x 0.250 in. annealed Type 302 strip, conditions as in Table 6.7 but roll force 6000 lb.

experimental water-soluble oils are really viscous pastes that can be rinsed off with water, but are useful because they contain high molecular weight fatty oil derivatives. Whetzel and Wyle [35] indicate that reductions of close to 60% were obtained in a single pass at speeds exceeding 250 fpm when rolling with the most viscous of these experimental lubricants.

The typical steep rise in roll forces with pass reduction may be gaged from the curves given in Fig. 6.28, derived from the rolling of 18% nickel-9% chromium stainless steel sheet of 16 in. width and 0.04 in. initial gage [120]. As expected, a mineral oil emulsion (1) was the poorest, while mechanical dispersions improved with increasing viscosity of the dispersed phase: stearin (2), tallow (3), table fat (4), and castor oil (5); "stearin" is glyceryl tristearate.

Information on industrial practice is very scarce [139]. Emulsions or, more frequently, mechanical dispersions of fatty oils are encountered on four-high mills, where the rolling lubricant is separated from the roll bearing oil and the great cooling power and lubricating efficiency of dispersions

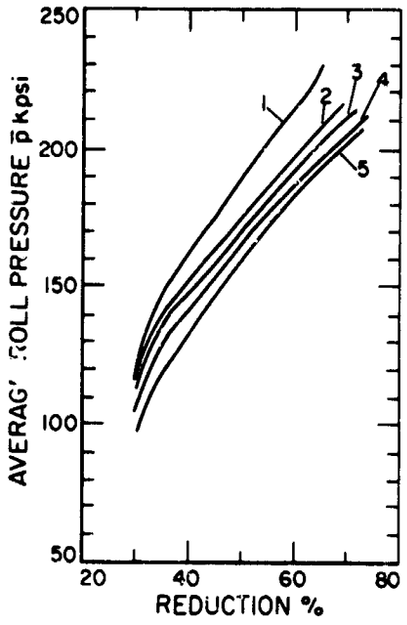

Fig. 6.28. Effect of lubricants in cold rolling stainless steel [120].

can be utilized. Lubricants for Sendzimir mills are usually mineral oil based, applied through a carefully filtered recirculating system, and contain separate additives for bearing protection and for strip lubrication. It would appear reasonable that some of the lubricants used for wire drawing (Section 7.42) should also be suitable for rolling, although surface treatments such as oxalating are unlikely to be economical or practicable. Chlorinated hydrocarbons, chlorinated resins, and, possibly, PTFE coatings could be of some interest, although no evidence of their industrial application could be found. Lubricant removal is always a problem because carbon pickup may occur on annealing.

6.5 ALUMINUM ROLLING LUBRICANTS

The rapidly increasing demand for aluminum and aluminum alloy products has prompted the introduction of mass production rolling techniques not unlike those practiced for the rolling of steel. The production of flat sheet and strip usually begins with the hot breakdown of 8 to 14 in. thick semicontinuously cast slabs (scalped for best surface quality) into a thick blank at temperatures of 350-550°C, depending on the alloy. Rolling is accomplished on two- or four-high reversing mills, two of which are frequently placed in

line for increased productivity. The blank (or occasionally a continuously cast band of similar thickness) is "warm" rolled at temperatures of 200-400°C into a band of 0.080 to 0.150 in. thickness and coiled. The hot band is then cold rolled to thinner gages on single-stand mills (which may be reversing) or on tandem mills comprising 2 to 4 four-high mills. The thinnest conventional strip (can stock) is 0.006 to 0.010 in. thick. Thinner strip is denoted as foil, and is usually rolled on single-stand, non-reversing mills from stock of 0.017 in. thickness to finished gages of 0.00025 to 0.0005 in. (6 to 12 μ).

6.51 Hot Rolling Lubricants

Aluminum is unique among the common industrial metals in that its oxide is hard and brittle but not friable, and thus offers no protection during hot rolling. Virgin surfaces generated during the elongation of the slab adhere to the roll surface readily and, unless a suitable lubricant is used, cumulative pickup (roll coating) is experienced. Ultimately, the slab will stick to and will be wrapped around the roll.

In the early days of rolling with light reductions and low production rates, a smear of mineral oil or animal fat on the roll surface was sufficient to prevent coating buildup. Larger slab weights, increasing outputs and rolling speeds made oil-in-water emulsions the universal lubricants. Almost invariably, the rolling lubricant is a true emulsion of controlled stability, containing 2 to 15% of a concentrate [140]. The concentrate is made up of a mineral oil, one or more emulsifiers, and a number of additives, including boundary additives, wetting agents, deoxidants, foam suppressants, and bactericides.

Roll Coating

The lubricant for the reversing (breakdown) mill is chosen to strike a delicate balance between controlled roll pickup and a sufficiently high coefficient of friction. Heavy reductions (of the order of 1 to 3 in. per pass on readily workable alloys) are desirable for the sake of economy, and the coefficient of friction must not drop below a limiting value; otherwise the rolls refuse to bite.

Pavlov [48] quoted friction coefficients of the order of 0.25 for clean, rough ground rolls, 0.45 for crazed roll surfaces, and 0.55 for rolls coated

with an adhering layer of aluminum. It might appear that these values are too high for lubricated rolling. Considering, however, that with a coefficient of friction of 0.2 and a roll diameter of 40 in. the maximum reduction would be limited to 0.8 in., it is obvious that low friction values cannot be tolerated. In fact, Varley [63] found sticking friction in full-scale rolling experiments with conventional emulsions. On the other hand, poor lubrication would allow the buildup of a heavy and unstable coating, which would impair the quality of the product. Intimately interwoven is a requirement of adequate cooling for the prevention of uncontrolled lubricant breakdown, development of a controlled thermal camber, and protection of the rolls against excessive temperatures. While the composition of hot rolling emulsions is usually a closely guarded secret, some of the desirable properties and their effect on the formation of roll coating has been discussed in some detail [140-144] in particular by Snow [141].

When a freshly ground roll is taken into service (Fig. 6.29a), coating builds up gradually, the rate of buildup depending on the lubricant, the alloy composition (pure aluminum generally giving a heavier coating), and the

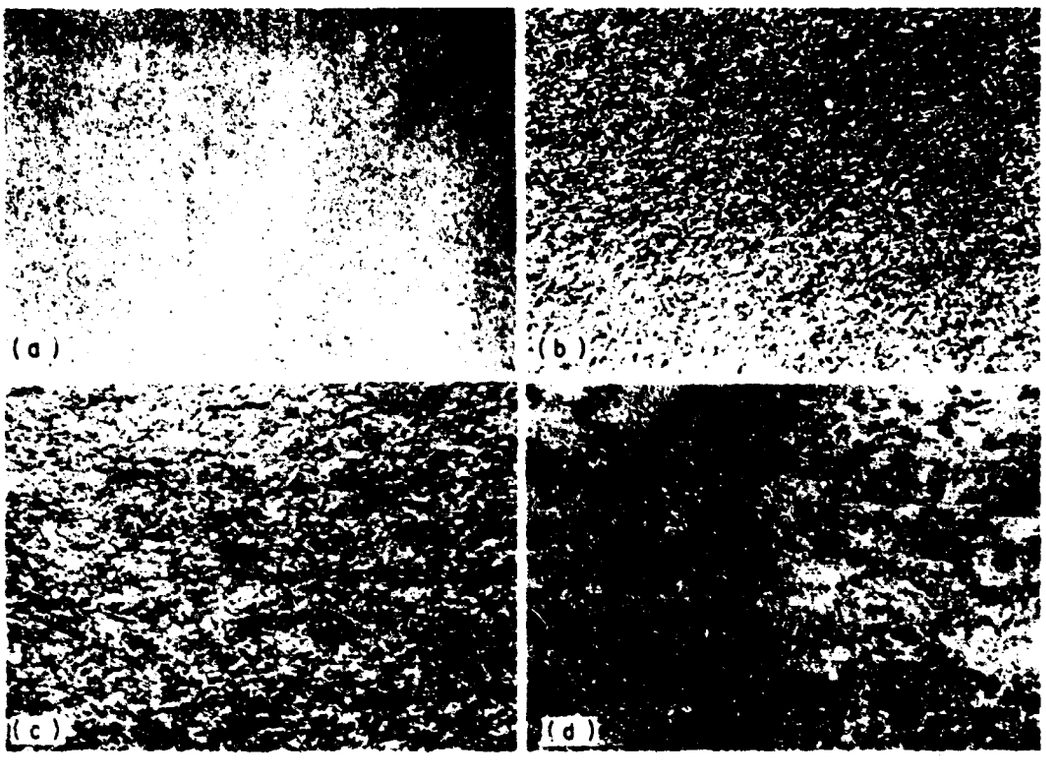

Fig. 6.29. The surface appearance of hot-rolled aluminum blanks [141].

severity of the operation as reflected by pass reductions and rolling temperatures. Problems may be compounded when the emulsion does not work particularly well with cold rolls. The coating is believed to consist mostly of aluminum, although some oxides and probably lubricant residues may be incorporated into it. In the main, however, contact is essentially that of aluminum against aluminum after the initial coating has built up. Ideally, the coating should be just thick enough to permit heavy reductions, and it should be hard and stable (Fig. 6.29b).

If equilibrium is disturbed—for example, by deterioration of the emulsion or by changing to a different alloy or production schedule—the coating may become unstable (Fig. 6.29c) and masses of coating particles, usually of rather small size, are detached. Many will be washed away by the lubricant flow, but some of them become rolled into the slab surface (Fig. 6.29d). These particles become visible at a later stage of rolling, especially if the sheet is anodized [144]. The condition of the roll coating may be checked by taking sheet samples at the hot mill and inspecting them after anodizing. In high-productivity mills control of the coating is often found near impossible by purely chemical mear and mechanical control is resorted to. Wooden wipers made of blocks turned to their end grain are pressed on the surface; in continuous contact with the roll surface, they smooth the coating and control its rate of buildup. More powerful is the effect of power-driven rotary wirebrushes which may be brought in contact with the rolls when deemed necessary, and the roll coating may be partly or fully scoured off. In four-high mills, contact between work and backup rolls exerts some control over coating buildup, at least by evening it out.

The quality of the surface is also influenced by the material of the roll. The view has been expressed that cast rolls craze more rapidly [142] and that the graphitic carbon may wear out [143], thus imprinting a network on the slab surface. In addition, coarser defects originating from the ingot structure may be intermingled. Thus, in alloys prone to segregation localized hot shortness between grains may cause hot tears, which are then filled with lubricant and fail to weld on subsequent rolling. Lubricant trapped in these mechanically sealed defects gives rise to blister formation on subsequent annealing.

In the production of very high quality sheet by earlier batch methods, it was customary to give a caustic etch to the hot-rolled blank so as to

remove the surface with all of its imperfections. This is now judged uneconomical in most instances, and close control of the coating is the primary means of assuring adequate quality of the finished sheet.

Lubricating Mechanism

The mechanism of lubrication by emulsions is by no means understood. It has been postulated that a steam pad helps separate the roll and slab surfaces [142]. More likely, however, a thermal-mechanical breakdown of the emulsion occurs in the contact zone. It has been suggested that surface-active compounds incorporated into emulsions would remain preferentially with the oil phase and, on entering the roll gap, would displace the water film with an oil film on the roll surface [142]. This concept is somewhat similar to "plating out" of lubricants in the cold rolling of steel. Some calculations by Butler [140] have shown that even a thin film would present a substantial thermal barrier, and it is conceivable that the deposited oil and oil residues act as a parting agent and also keep temperatures low enough to prevent total decomposition. Contact would be essentially boundary, and this view is confirmed from the appearance of the surface of hot-rolled blank of acceptable quality (Fig. 6.29b). The blank surface is uniformly covered with minute smeared-over protrusions, similar in appearance to fish-scale, but contiguous with the substrate. Only when coating troubles begin to develop will actual folding over, shown by Herenguel [143], be observed.

Hot Rolling Emulsions

There appears to be no universal agreement on the desirable properties of an emulsion. The majority view regards very stable, translucent emulsions as poor lubricants. Less stable emulsions or even mechanical dispersions are good lubricants but cause problems in recirculating systems, are more difficult to filter, and could also make pasty coatings that tend to become unstable. The stability of an emulsion is, of course, greatly influenced by the nature of the emulsifier and its reaction to water hardness. In this respect, ionic emulsifiers are likely to suffer more because the calcium of hard water will combine with them and render the emulsion unstable. Nonionic emulsifiers adapt better to differing water qualities but are more expensive. Recently, there has been a noticeable trend towards the use of deionized water. It is also considered that low ash contents are desirable,

and this aim may be achieved by using ammonia rather than sodium soaps as ionic emulsifiers [140].

The dispersed phase is usually a mineral oil; although the highly viscous, heavily compounded oils are considered better lubricants, they are apt to stain when the strip is coiled up. Therefore, lower viscosity oils with relatively nonstaining additives are more popular. In this respect, it is interesting to note that the coefficient of friction as measured by the angle of acceptance on clean abraded steel rolls was reported [145] to increase from 0.35 to 0.55, as the base oil viscosity of experimental 5% oil-in-water emulsions decreased from 8500 to 200 Redwood 1 sec in the rolling of 2.5 in. thick commercial aluminum blocks at 550°C. After the coating had built up, roll force and torque were also found to be higher with the lower viscosity oil. Emulsions for breakdown mills, where a large angle of acceptance is needed, tend to be based on lighter viscosity oils, while more heavily compounded and higher viscosity oils are permissible on tandem mills where the absolute reductions are smaller but high percentage reductions are desired. Sometimes these requirements are met by using the same lubricant at a lower concentration on the reversing mill and at a higher concentration on the finishing mills. A further factor enters into the choice of the emulsion when the reversing mill comprises resin-impregnated fabric roll neck bearings, which are lubricated by the emulsion. Emulsion temperature is then usually controlled between 30 and 50°C.

Variable importance is attached to the wetting properties of the emulsion. Some emulsions contain wetting agents which are replenished simply through the periodic addition of emulsion concentrate; others employ separate wetting agents. Snow [141] pointed out that not all wetting agents are necessarily effective, and not all of those that are effective can be used because troublesome foaming may develop.

The emulsion is always recirculated. Great care is taken to assure uniform distribution of the emulsion over the roll surface, and individually adjustable spray nozzles are mandatory to compensate for changes in thermal camber. Metallic fines, accumulated soaps from hard water, and tramp oil and greases have to be removed. The lubricant system usually includes a filter bed with a woven or fibrous filtering medium that is advanced automatically. Centrifuging is efficient on stable emulsions, but activated (fuller's earth) filters would remove surfactants. Tramp oils

are difficult to separate and are often found responsible for emulsion breakdown and for staining; they are best dealt with by eliminating the source of contamination.

An emulsion will age even in the best lubricant system. An extensive check is routinely kept on the quality of the emulsion by carrying out tests for oil concentration, alkalinity (regarded by some as an indicator of lubricant breakdown), concentration of metallic fines and of ash, saponification value, as well as for wetting (Section 5.9) and staining (Section 5.8).

Development of hot rolling lubricants has been hampered by inexplicable differences in lubricant performance on different mills, even when they work ostensibly under almost identical production conditions. Obviously, much remains to be learned yet about the mechanism of lubrication by aqueous emulsions and dispersions, about the exact mode of lubrication in the contact zone between the hot metal and the roll, and about the dynamics of coating development and breakdown. An ideal lubricant would prevent coating buildup altogether, yet without dropping the coefficient of friction to values where rolling becomes impossible. This objective may be unattainable, but it is conceivable that by control of roll surface finishes and by allowing a minimum of pickup, a very stable, durable and thin coating could be developed, without resorting to mechanical means of preventing excessive coating buildup.

6.52 Cold Rolling Lubricants

Until very recently, all lubricants for the cold rolling of aluminum were composed of a mineral oil base and suitable additives. Past efforts at replacing them with emulsions failed because of water staining and corrosion occurring on storing the coils prior to annealing or shipment. Claims have been made regarding the development of satisfactory cold rolling emulsions [54], but no data could be found in the literature yet. Therefore, the following discussion will be restricted to lubricants with a mineral oil base.

Experimental evidence quoted in Section 6.21 has established beyond doubt that lubrication in the rolling of aluminum is of the thin-film type, in which boundary or hydrodynamic lubrication prevails depending on process conditions. Coefficients of friction measured in the rolling of aluminum (Tables 6.21 and 6.22) are also typical of thin-film or mixed lubrication.

TABLE 6.21

Coefficient of Friction Measured in Rolling Aluminum Strip [11]

Lubricant	Pass No.	Reduction %	Coef. of Friction (μ)
Dry	1	23.5	0.092
	2	23.0	0.101
	3	22.0	0.100
Paraffin (kerosene)	1	24.5	0.081
	2	21.3	0.087
	3	29.0	0.070
Paraffin + 1% oleic acid	1	24.8	0.059
Paraffin + 5% lead oleate	3	27.5	0.056
Paraffin + 5% sodium oleate	3	27.9	0.059
Graphite in SAE 30 oil	1	33.5	0.055
Palm oil	1	24.0	0.066
	3	33.4	0.066
	4	47.7	0.069
Castor oil	3	21.6	0.057
Lanolin	4	25.4	0.025

Conditions as in Table 6.4, but 0.067 x 1.5 in. annealed, commercial purity Al strip.

TABLE 6.22

Coefficient of Friction in Rolling Aluminum Strip [112]

Lubricant	Pass No.	Reduction, %	Coef. of Friction (μ)
None	1	29.2	0.12
	2	20.5	0.13
Paraffin (kerosene)	1	25.7	0.066
+ 5% stearic acid	2	37.4	0.064
Dynamo oil	1	22.0	0.063
	2	20.0	0.062
Graphite in oil	1	31.0	0.045
	2	28.0	0.048
Coconut oil	1	42.3	0.048

Conditions as in Table 6.5, but 0.040 x 1.35 in. cold rolled 99.5% Al strip, TS = 22 kpsi.

Consequently, both lubricant viscosity and the presence of additives are of great importance.

Effect of Lubricant Viscosity

With an uncompounded mineral oil containing no boundary additives, the friction coefficient should decrease with increasing viscosity, by increasing the average thickness of the lubricant film for any given pass reduction and rolling speed. This is most clearly reflected in the experiments of Iwao et al. [39] (Table 6.23). Assuming that the kerosene fraction was predominantly paraffinic, the total elongation obtained in 6 passes increased with increasing viscosity in the series composed of kerosene, lubricant C-40, and C-100. In contrast to the poorer performance of naphthenic oils found in the rolling of steel (Table 6.6), friction on aluminum was invariably controlled by viscosity, irrespective of whether the lubricant was predominantly paraffinic or naphthenic, or a mixture of the two (Table 6.23). The relatively high elongation given by the nonrefined light oil must be attributed to the presence of polar impurities. Even polybutenes which performed poorly on steel gave reductions similar to those obtained with mineral oils of comparable viscosity on aluminum.

TABLE 6.23

Lubricant Performance in Rolling Aluminum Strip [39]

Lubricant	Viscosity, cs 37.8°C	98.9°C	Total Elongation, $(\ell_1 - \ell_0)/\ell_0$
A Kerosene fraction	1.8	0.9	2.3
B Nonrefined light oil	3.2	1.3	2.7
C40 Paraffinic Al-rolling base oil	4.0	1.5	2.4
D60 Naphthenic mineral oil	9.8	2.4	2.9
C100 Paraffinic mineral oil	21.8	4.2	3.1
D100 Naphthenic mineral oil	21.0	3.8	3.1
50% C100 + 50% D100	21.6	--	3.1
LV5 polybutene	13.8	—	2.9
LV10 polybutene	16.9	3.5	2.95
Polybutene	21.7	4.0	3.15

0.040 x 1.8 in. mill hard Al strip, rolled at 85 fpm in 6 passes.

Additives

Virgin aluminum adheres to the roll surface; fortunately, it is also highly reactive and is readily protected by polar boundary additives. A comparison of curves for mineral oil and compounded oil in Fig. 6.3 reveals that the boundary additive affected roll force, forward slip, and coefficient of friction only slightly in the predominantly hydrodynamic regime of lubrication but caused a very marked drop in all these values in the predominantly boundary regime.

Fatty acids are the most efficient, and the presence of even 0.2% oleic acid assures greater reductions. As shown by Chertavkish (quoted by Pavlov [48]), the effect tapers off and little improvement is gained above 1% addition. Saturated fatty acids are generally more effective, as has been shown by Gumins'd and Willis [146] in plane-strain compression experiments, and this observation should apply also to rolling. Saturated acids, however, tend to be less soluble in mineral oils and have not been investigated in detail. For similar chain lengths, fatty alcohols are somewhat less effective than acids, but have been proposed [146] as additives for their low staining tendency.

Fatty oils were once used extensively in the neat form. Their high viscosity assures extremely low friction (lanolin in Table 6.21 and coconut oil in Table 6.22), but their efficiency as additives to mineral oils depends greatly on their free fatty acid content. Improvement is rather modest when the fatty oils are almost neutral. For example, Schey [16] has found that 5% lanolin was needed to drop roll forces as much as 1% oleic acid would, and rapeseed oil could not match this performance even at 10% concentration (Table 6.24). Kleinjohann [147] also found that μ (calculated from forward slip) decreased only gradually from 0.09 to 0.055 as the "plant oil" content of a lubricant was increased from 5 to 35%. It is likely that much of the improvement could be ascribed to increasing viscosity with the addition of lanolin and other fats. If the viscosity of the base oil increases, the greater average thickness of the oil film allows less boundary contact; therefore, the effect of boundary additives diminishes (Fig. 6.30) and becomes unnoticeable when almost full-fluid lubrication is attained.

E. P. additives are regarded as ineffective and have apparently not been investigated in detail. Some limited data available suggest that graphite added to oil reduced friction (Tables 6.21 and 6.22) although the magnitude

TABLE 6.24

Lubricant Performance in Rolling Aluminum Strip [16]

Lubricant Base	Additive Type	%	Viscosity Redwood 1 sec 70°F	20°C	Roll Force, klb/in. width
Paraffin (kerosene)			—	1.9	60.5
Mineral oil			45	7.3	53.5
Mineral oil	Rapeseed oil	1	45	—	54.5
Mineral oil	Rapeseed oil	5	46	—	54.0
Mineral oil	Rapeseed oil	10	50	—	52.0
Mineral oil	Lanolin	1	45	—	53.0
Mineral oil	Lanolin	5	49	—	50.5
Mineral oil	Lanolin	10	57	—	47.0
Mineral oil	Oleic acid	1	45	—	50.0

Roll force obtained with constant roll setting on 14.3 in. diameter rolls of 3 μin. AA roughness at 43 fpm, 0.080 x 3.0 in. mill hard Al-1.25% Mn alloy strip.

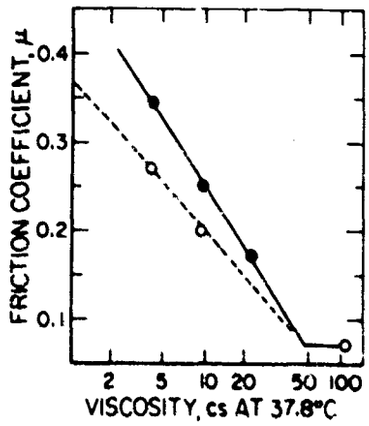

Fig. 6.30. The effect of mineral oil viscosity in cold rolling aluminum (solid line: mineral oils; broken line: with oleic acid [39].

of the effect is difficult to determine in the absence of comparative data for a base oil of the same viscosity. However, graphite tends to cause pitting corrosion and is usually avoided.

Staining Propensity

Staining is a particularly severe problem with aluminum rolling oils, because the high reflectivity of the metal makes all stains immediately visible, and also because annealing temperatures are low enough to prevent distillation of all but the lowest boiling point lubricants.

The staining propensity of mineral oil fractions increases with the chain length of the molecule; therefore, it also increases with the boiling range, viscosity, and flash point of the lubricant (Table 6.25). Lubrication with very light oils may be improved with suitable boundary additives, but the very low flash point still presents exceptional fire hazards. Therefore, very narrow cut (boiling range typically 60°C) mineral fractions are usually desirable which contain a minimum of light fractions that create the fire hazard and a minimum of the heavier fractions that would cause staining. It has been stated [146] that paraffinic oils stain less for the same viscosity than do aromatic or naphthenic ones. For the same boiling range, mineral oils containing unsaturated compounds (as indicated by the bromine number) or sulfur stain much more heavily (Table 6.26).

TABLE 6.25

Staining of Light Petroleum-Base Fractions [140]

Fraction	Boiling Range, °C	Viscosity at 25°C, cs	Flash Point, °F (°C)	Staining at 350°C
1	140-180	—	—	None
2	180-200	—	—	Very slight
3	200-225	1.64	158 (70)	Slight
4	225-250	2.38	183 (84)	Slight
5	250-275	3.13	246 (119)	Slight
6	275-300	5.61	240 (116)	Slight
7	300-324	8.70	283 (139)	Slight to moderate

TABLE 6.26

The Effect of Unsaturation, Sulfur Content, and Percentage of Carbon Atoms in Ring Structure on Brown-Staining Characteristics of Base Oils [146]

Boiling Range, °C	Bromine Number	Total Sulfur Content, %	Percentage of Carbon Atoms in Ring Structure	Brown Staining in Can Test	
				At 300°C	At 350°
200-225	5	0.125	39	Heavy	Slight
200-250	5.2	0.13	39	Heavy	Considerable
200-250	0.4	0.14	30	Slight	None
200-250	0.6	0.006	39	Moderate	Traces
200-250	0.4	0.007	32	None	None
213-242	4.7	0.04	29	Heavy	Considerable
240-318	0.2	0.003	22	Slight	None
260-330	0.8	0.07	32	Considerable	Traces

The staining propensity of additives is a function of composition and of chain length. Guminski and Willis [146] found that within any one homologous series, staining increased with chain length, and that staining of paraffins, alcohols, aldehydes and acids was proportional to the polarity of the molecule. Thus, the highest nonstaining member of paraffins contained 14 carbon atoms, that of alcohols 10, of aldehydes 8, and of acids only 6. If the lubricating efficiency of these additives is judged from the reductions obtained in the plane-strain compression test, the alcohols show the best combination of lubricating ability and low staining (Table 6.27). The same authors also indicate that white staining is a direct function of acidity and, for this reason, they suggest that acids should be avoided; it would appear, however, that their criteria must have been too strict, because lubricants compounded with fatty acids have been used industrially with considerable success.

6.53 Cold Rolling Lubrication Practices

The base oil of the aluminum rolling lubricant is usually chosen at the highest viscosity compatible with low staining tendencies. Since staining is less critical in the early stages of cold rolling, somewhat heavier oils

TABLE 6.27

Comparison of Reduction Indices of the Highest Nonstaining and Lowest Staining Members of Various Homologous Series of Organic Compounds [146]

Homologous Series	Highest Nonstaining Member of Series	Reduction Index of 2% Solution of Highest Nonstaining Member of Series (% Reduction in Plane-Strain Test)	Member of Series Forming Only Traces of Stain in Can Test at 300°C	Reduction Index of 2% Solution in Petroleum Fraction of Boiling Range 275-300°C of Member of Series which Forms Only Traces of Stain
Paraffins	n-Tetradecane $CH_3(CH_2)_{12}CH_3$	16	n-Hexadecane $CH_3(CH_2)_{14}CH_3$	16
Alcohols	1 Nonanol $CH_3(CH_2)_7CH_2OH$	33.4	1 Decanol $CH_3(CH_2)_8CH_2OH$	37.4
Aldehydes	Caprylaldehyde $CH_3(CH_2)_6CHO$	22.1	Not known*	—
Acids	n-Caproic $CH_3(CH_2)_4COOH$	32	n-Enanthic $CH_3(CH_2)_5COOH$	33.5

*Capraldehyde $CH_3(CH_2)_8CHO$ already produced considerable staining.

(typically 100 SUS at 100°F) have been used for heavier gages, and a lighter fraction of typically 35 SUS at 100°F (or 45 Redwood 1 sec at 70°F) for intermediate and finishing passes [54, 148-150]. The high rolling speeds of up to 2000 fpm aid in building up an efficient lubricant film and permit reductions of 50-60% per pass. Finishing passes call for a very low viscosity lubricant if a bright finish is to be obtained, and kerosene has been used.

A relatively low viscosity is desirable because circulation of the large oil quantities required for cooling of the rolls and of the strip is facilitated and because too high a viscosity could cause slipping of the strip in the roll gap. A very low viscosity would, however, create excessive fire hazard because of the too low flash point; when the recirculating system is operated at pressures in excess of 100 psi, fires and even explosions could occur if the oil mist ignited by a diesel effect [150]. A flash point below 120°C calls for special caution, and 140°C is preferable.

For minimum staining a highly refined paraffinic (less than one third by weight aromatic and naphthenic hydrocarbons) oil with a narrow (60-90°C) boiling range has been recommended [146], with a bromine number below 1, sulfur content below 0.08%, and with inherent resistance to oxidation. Guminski and Willis [146] developed an accelerated aging test in which approximately 1% of aluminum drillings is added to the lubricant, which is then kept for 24 hr in an open bottle in an oven heated to 110°C. Acidity and staining are then determined, and the criterion is given that acidity should not increase over 0.025 mg KOH/g after 24 hr.

All lubricants contain additives, which are chosen for low cost and good boundary lubricity. Oleic acid in concentrations up to 2.5% has been used. Lanolin, palm oil, and other fatty oils have also been employed, but the poor reproducibility of their properties makes them less desirable additives. They become really effective only if free fatty acids are present, either intentionally or as a result of gradual decomposition. Fatty alcohols and "synthetic additives" of undisclosed composition have been recommended too. Some lubricants also contain antioxidants and, rather rarely, wetting agents. The rolling qualities of a lubricant are judged in practice either from roll forces, if means for their measurement are available, or from the maximum reduction that can be taken without the appearance of the herringbone defect (Section 6.28). Guminski and Willis [146] found that plane-strain compression results correlated well with the rolling performance judged from the

onset of herringbone on a tandem mill delivering strip at 1300 fpm, and that laboratory staining tests gave a good indication of brown and white staining experienced in a production trial, with staining observed on the slitting and coiling line.

The choice of the rolling oil will also be influenced by the annealing practice. When the strip surfaces are exposed to the furnace atmosphere in continuous anneal, the oil evaporates without leaving residues even at temperatures that would cause severe brown staining in a coil form. Oil trapped between layers of a coil is subjected to a gradual distillation; the temperature gradient existing between the surface and the center of the coil and the limited access of air to spaces removed from the coil edges combine to cause a band of brown staining close to the strip edge. The strip edge itself is usually clean because sufficient oxygen is present to assure complete oxidation of the carbonaceous material. The center of the coil shows brown stains only in extreme instances, probably because the lubricant is gradually driven off in the absence of oxygen. Staining becomes a severe problem when a low-temperature (typically 180-260°C) recovery anneal is given. Interleaving the strip with tissue paper may then help to absorb the lubricant. In any case, staining may be considerably reduced by limiting the amount of residual oil on the strip surface, at least by applying well-constructed air jets at the exit side of the strip, and sometimes also by felt wipers or edge rollers that soak up excess oil. Tramp oils, especially oil leakage from roll neck bearings, are often the most troublesome source of staining, and various efforts have been made to improve the oil seals, change the lubricants to a nonstaining synthetic variety, or construct bearings that can operate satisfactorily with the very low viscosity rolling lubricant.

Older, slow-speed rolling mills needed little cooling, therefore, the lubricant could be applied by dripping on the rolls or to wipers applied to the strip surface on the entry side. Felt wipers on the rolls help to distribute the oil and also accumulate debris but may develop superficial, uneven roll wear that imprints as a streaky surface on the rolled product. At speeds above 200-300 fpm, flood lubrication is essential. Large recirculating systems with advanced methods of filtration were first developed for aluminum rolling lubricants. Usually, the total flow is passed through wire mesh filters, and a bypass flow of 10-20% is treated with active earth filters. Oils containing lanolin had to be heated to 50°C; other additives may be

filtered at ambient temperatures but some loss of surface-active compounds is unavoidable. Systematic checks on viscosity, staining propensity, and additive content are run and appropriate additions are made. The purpose of filtration is to keep the ash content low (typically below 0.05%). Ash consists mostly of aluminum fines which do not seem to impair the lubricating qualities of the oil but cause a dirty strip finish and may also contribute to staining.

Sendzimir mills again present a special case because the lubricant must be suitable for lubrication of the bearings, too [151]. For protection of the bearings, 30-60% of the total flow is passed through earth filters. The rolling mills are usually fitted with exhaust hoods that remove oil vapors. Particularly when highly flammable kerosene is used as a coolant, sufficient air is entrained to ensure a noncombustible mixture [152]. After extracting the oil, the exhaust air is released to the atmosphere. Fire extinguishers capable of quenching a full fire with CO_2 gas flow are incorporated and may be operated manually or automatically.

The rate of lubricant supply has increased over the years, and is now typically of the order of 10-20 gpm per inch width of rolled strip at pressures of 20-150 psi.

6.54 Foil Rolling Lubricants

A substantial proportion of rolled aluminum strip is finish rolled into foil, in gages between 60 and 12 μ. With the usual 8 to 16 in. work roll diameters, rolling takes place under conditions of limiting reduction and, apart from the effect of tension, the most significant variable is that of lubrication.

Lubricants are very similar to those used in rolling aluminum strip [153, 154]. In order to assure reductions of 50% per pass, heavier lubricants are selected for the initial stages of rolling. Finishing passes, however, must be made with the lighter lubricant (typically of 42-45 Redwood 1 sec at 70°F), partly to assure the desired bright finish and partly to avoid damage to the foil in the last pass. Even with adequate control of tensions and of lubrication, it would be difficult to attain the desired reductions on a single strip of 12-20 μ thickness; therefore, it is customary to roll two strips together (pair rolling).

Pair rolling can lead to undesirable unevenness of the contacting strip surfaces, reviewed in some detail by Brzobahaty [155]. Since orientation differences in recrystallized, coarser size grains are the primary cause of overall waviness, process annealing is usually limited to low temperatures where only recovery occurs. While slight roughening and consequent loss of luster are still to be expected on the mating surface, heavier localized defects may be introduced by excessive lubricant entrapment. Damage becomes more severe with increasing lubricant viscosity, and can lead to perforation of the foil. Such perforation sometimes extends in a line in the rolling direction, following the breakup of an individual oil drop into smaller droplets. A very thin lubricant film is desirable because it prevents sticking (welding) of the paired foil during rolling and annealing.

The sensitivity of aluminum to the speed effect (Section 6.23) is put to practical use for the control of overall gage, in combination with back tension and roll preload setting.

Even though the size of aluminum particles suspended in the lubricant is small, the danger of perforating the foil by rolled-in particles is great; filtration is conducted with great care and active earth filters usually handle 50-60% of the total flow. Cooling and flameproof heating systems are incorporated for accurate control of lubricant temperature.

6.6 COPPER AND BRASS ROLLING LUBRICANTS

Slabs of copper and its alloys are either semicontinuously cast or cast into permanent or water-cooled molds. Initial breakdown is usually, but not always, by hot rolling; surface imperfections are removed either by scalping the cast slab, or by milling the whole surface of the hot-rolled slab of approximately 0.5 in. thickness. Further rolling is carried out cold, on single-stand or tandem mills.

6.61 Hot Rolling Lubricants

The oxides of copper are reasonably good lubricants and parting agents, and the oxides of brass also serve well enough to separate the roll and workpiece surfaces during rolling (Section 4.28). Therefore, hot rolling of copper and copper-base alloys is usually carried out without a lubricant in the laboratory, but in high production mills there is a need for a roll

coolant, usually mineral oil emulsions [156]. A light smear of the roll surface with a fat has sometimes been used but is of doubtful value [157].

6.62 Cold Rolling Lubricants

We have seen that copper and some of its alloys adhere rather readily to the roll surface and cause a "copper cast." For some obscure reasons, this does not necessarily raise the coefficient of friction, as shown by the relatively low friction values in Tables 6.28 to 6.30, even for dry rolling.

Mineral oils will lower friction in proportion to their viscosity (Table 6.31). Boundary additives are rather ineffective, as far as can be judged from the meager information available (Tables 6.28 to 6.31). Even less is known about the lubricating value of extreme pressure additives; sulfur causes severe staining and is usually limited to below 0.5%. Johnson [158] rolled cartridge brass at 600 fpm and calculated friction from measured roll force. He found extreme pressure agents ineffective, "oiliness additives" (probably boundary additives) only moderately effective, and a mineral oil of 300 SUS viscosity at 100°F gave friction values similar to that of neat lard oil. Calculated friction coefficients were of the order of 0.06 to 0.08, generally somewhat higher than those reported in Tables 6.28 to 6.30.

At speeds in excess of 500 fpm, roll pickup, side skidding, and inadequate cooling were reported by Belfit and Shirk [159] even with low viscosity (50 SUS at 100°F) oils. Separately applied oil and cooling water are still found on slower mills but are rather undesirable because residual oil could cause staining on annealing. Emulsions applied in a recirculating system are now widely used [156]. Emulsions are made of mineral oil (sometimes with fatty additives) and appropriate emulsifiers (such as sulfonates) to give a stable or slightly unstable emulsion. Sulfur-containing compounds are avoided, both as additives and as emulsifiers, because of the staining they cause on copper-base alloys. The viscosity of the base oil is generally higher (around 200 SUS at 100°F) for initial breakdown passes, and lower on the finishing mills. Emulsion concentrations also tend to be higher in initial heavier passes than in finishing ones. The recirculating system is kept in condition by regular checks of concentration, ash, and pH. Screen-type filters remove larger particles, while copper and brass fines are trapped by free oil and are removed from the surface of the tank. Increasing sophistication of the emulsions will undoubtedly lead to stricter controls and to filtration through beds used for aluminum rolling lubricants.

TABLE 6.28

Coefficient of Friction Measured in Rolling Copper Strip [11]

Lubricant	Pass No.	Reduction %	Coef. of Friction (μ)
Dry	1	29.0	0.093
	3	31.0	0.069
	4	12.4	0.071
Water	1	26.0	0.075
Paraffin (kerosene)	1	23.9	0.067
	3	31.5	0.068
Graphite in SAE 30 oil	2	32.4	0.061
Palm oil	1	26.9	0.075
	2	28.4	0.066
Olive oil	2	30.2	0.058
Castor oil	3	34.1	0.046

Conditions as in Table 6.4, but 0.062 x 2 in. OFHC copper strip.

TABLE 6.29

Coefficient of Friction Measured in Rolling Brass Strip [11]

Lubrication	Pass No.	Reduction %	Coef. of Friction (μ)
Dry	1	15.1	0.093
Water	1	29.2	0.061
Paraffin (kerosene)	1	15.0	0.067
Graphite in SAE 30 oil	2	27.8	0.049
Olive oil	1	33.8	0.057
	5	28.0	0.055
Lanolin	6	28.0	0.043

Conditions as in Table 6.4, but 0.062 x 1.5 in. 63/37 brass strip.

TABLE 6.30

Coefficient of Friction in Rolling Brass Strip [112]

Lubricant	Pass No.	Reduction %	Coef. of Friction (μ)
None	1	28.1	0.104
	2	25.4	0.108
	3	22.4	0.082
Paraffin (kerosene) + 5% stearic acid	1	16.3	0.082
Dynamo oil	1	27.6	0.043
	2	24.7	0.053
	3	19.7	0.062
Graphite in SAE 30 oil	1	19.0	0.057
	2	18.5	0.057
	3	21.6	0.062
Coconut oil	1	3.6	0.055
	2	3.6	0.048
	3	11.3	0.064
Lanolin	1	16.0	0.029
	2	9.8	0.044
	3	22.3	0.041
Castor oil	1	9.3	0.030
	2	27.4	0.039
	3	18.2	0.037
	4	15.0	0.038

Conditions as in Table 6.5, but 0.040 x 1.35 in. 60/40 brass strip with 60 kpsi TS.

TABLE 6.31

Effect of Lubricant on Reduction Obtained in Rolling Copper [21]

Lubricant Type	Characteristics	Reduction, %
Mineral oils	70 SUS at 100°F (38°C)	19.0
	600 SUS at 100°F	22.5
	600 SUS + 5% stearic acid	23.5
Fatty oils	Typical animal fat	31.0
	More viscous fat	34.5
	Stearic acid	27.5
"Water soluble"	Experimental	24.5-59.0

0.0055 x 0.250 in. annealed strip; conditions as in Table 6.7, but roll force 1600 lb.

Special alloys of copper are produced in smaller quantities, narrower widths, and at slower rolling speeds; cooling is therefore less important. Bastian [157] suggests medium-viscosity (130-150 SUS at 100°F) mineral oils compounded with 20-30% of fatty oils and fatty acids.

6.7 TITANIUM ROLLING LUBRICANTS

Titanium and its alloys present one of the most formidable rolling tasks for two principal reasons. First, titanium adheres readily to the roll surface, yet does not react readily with common lubricants. Secondly, the yield strength of the material is high at room temperature, and texture hardening resulting from preferential orientation in α-titanium and titanium alloys increases its resistance to transverse compression; therefore, rolling forces are extremely high and conditions of limiting reduction are very soon reached. For these reasons, it is preferable to conduct as much rolling as possible at elevated temperatures—where the oxide affords some protection against roll pickup, the yield stress is substantially lower, and lubrication is mostly a matter of cooling—and to limit cold work to thin gages only.

Rolling to thicknesses of approximately 0.1 in. presents no particular problem. Below this gage, strip is usually processed on cold mills, with

frequent process anneals (typically after 20-40% reduction). Mills with small work-roll diameters, such as the Sendzimir and Schloemann mill are favored because roll forces are reduced and the effect of roll flattening minimized. Alternatively, sheet may be hot finished by pack rolling in hand sheet mills between steel sheets [160]. A parting agent such as lime and alumina powder is put between the sheets to prevent sticking. This technique, however, is likely to fade out. Obviously, the technology of titanium rolling is not yet established and development of powerful lubricants will be a key in future efforts.

6.71 Hot Rolling Lubricants

No specific publications dealing with hot rolling lubrication could be located; it can be surmised, however, that at the low production rates typical of today, the oxide (discussed in Section 6.21) is adequate as a parting agent and separate cooling is not necessary. After initial breakdown in the β range (typically about 1800°F), finish rolling is usually conducted in the $\alpha+\beta$ range (typically around 1600°-1700°F), where the yield stress is substantially higher. The reasons for this practice are not entirely clear, and finishing in the β range would probably solve some of the problems, provided the properties of the finished product are acceptable.

6.72 Cold Rolling Lubricants

Very few investigations have been published on the efficiency of lubricants for the cold rolling of titanium. Wilcox and Whitton [161] rolled 0.037 in. thick commercially pure titanium strip at 80 fpm on 8 in. diameter rolls having a surface finish of 2 to 3 μin. AA. Taking three passes of 4-5% reduction each, first-pass reduction curves were constructed and the efficiency of lubricants and surface treatments was judged from rolling force calculated for a 10% reduction (Fig. 6.31). It will be noted that, irrespective of surface treatment, the straight mineral oil A (viscosity 750 Redwood 1 sec at 70°C) was slightly better than the same oil compounded with sulfur and chlorine E.P. additives (lubricant B). A soap consisting of potassium palmitate and stearate, applied in a 25% aqueous solution to the strip (and presumably allowed to dry), was considerably better on all but the oxidized surface (lubricant C). Lanolin (lubricant D) was the best conventional lubricant, undoubtedly because of its high viscosity. Roll forces dropped to

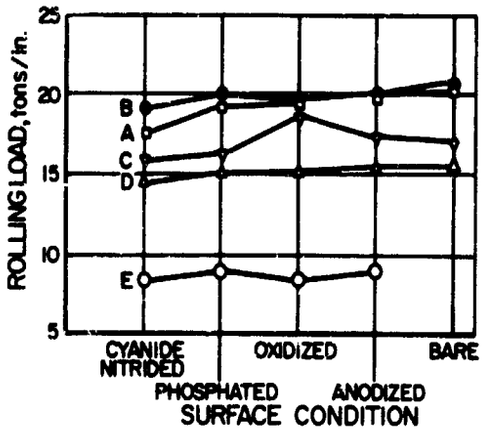

Fig. 6.31. The efficiency of lubricants in cold rolling titanium with a 10% reduction [161].

half when a fluorolube grease (lubricant E, a chlorofluorinated hydrocarbon containing graphite) was used. It is remarked that particular care is required in handling it and that it would be unsuitable for industrial application, but it does show the potential improvement that could be gained with an outstanding lubricant. The bare titanium surface (produced by pickling in a 5% hydrofluoric acid, 20% nitric acid bath) gave generally highest friction. Strip surface oxidized by annealing in air for 40 min at 700°C was slightly better than an anodized film and only slightly worse than a fluoride-phosphate coating. A cyanide-nitrided surface (produced in an aged cyanide bath by immersing for 2 hrs at 560°C) was undoubtedly the best with all lubricants, but the gains from surface treatment are small compared to improvements due to lubrication with higher viscosity substances. It is not clear at all whether chemical reactions had any part in improved lubrication.

Rather similar results were registered by Pavlov et al. [162] in rolling various titanium alloys from 0.060 in. thickness on 7 in. diameter rolls. A synthetic compound consisting of esters with amino groups allowed reduction to 0.030 in. in 5 passes, but edge cracking occurred at thinner gages. Castor oil was the next best and was most suitable for thinner gages. Fatty esters, with free oleic acid added, proved ineffective.

6.8 REFRACTORY METAL ALLOY LUBRICANTS

Refractory metals such as tungsten, molybdenum, columbium, tantalum, and their alloys present a number of rolling difficulties [163], but few of them are associated with friction. Many of them show limited ductility in the as-cast condition, or are more conveniently cast to a round ingot. A sheet bar is then extruded or forged which is further hot rolled into sheet. True hot working temperatures are very high, between 1600° and 1900°C, but many alloys can be effectively "warm worked" between 900° and 1200°C. Periodic recrystallization anneals are then needed. The basic concern is that gas pickup from the atmosphere impairs the properties of the material and that rapid oxidation and volatilization of the oxide occur. Four approaches have been used:

1. The billet is heated in an inert atmosphere and then rolled on conventional equipment, with transfer times kept to a minimum. The oxide formed on exposure to air serves as a lubricant.

2. The billets are heated and rolled under a protective atmosphere or in high vacuum, thus eliminating oxidation at all stages of processing. This calls for special equipment, and lubrication with a suitable substance (usually molybdenum disulfide or tungsten disulfide) is necessary. Possible contamination by contact with the lubricant has to be considered.

3. The billet is encapsulated into a steel, stainless steel, or nickel-base superalloy can which protects it during heating and rolling. The surface of the strip is likely to be somewhat rumpled, but the surface needs conditioning after removal of the can anyway. Rolling temperatures must not, of course, exceed the hot rolling temperature of the can material, and lubrication is usually unnecessary because the oxides part the roll and workpiece surfaces effectively.

4. A glass coating applied to the billet protects against oxidation during heating and rolling. Friction may, however, be too low to permit heavy reductions. In this respect, coating with an aluminum-12% silicon alloy applied to the surface of the workpiece by hot dipping was found useful in rolling a tantalum alloy [164].

Generally, the working temperature of refractory metals may be gradually lowered as the cast structure is eliminated. The same applies to tungsten in which the ductile-brittle transition temperature drops with the

amount of prior work. Warm rolling around 400°C is favorable because neither gas pickup nor oxidation occur and conventional lubricants may be used. Organic polymers such as PTFE were found very effective in reducing roll forces in the rolling of tungsten at 400°C and at room temperature. Mineral oils with suitable boundary and E.P. additives proved useful in rolling at room temperature [165].

Vanadium and its alloys are readily rolled both hot and cold, and the same applies to zirconium. The latter is used extensively in foil gages, for which it is rolled on Sendzimir mills or other mills with small work-roll diameters, with conventional compounded mineral oil lubricants.

6.9 OTHER METALS

Nickel and cobalt-base superalloys are usually hot rolled, and no lubricant appears to be necessary. Some of them possess an extremely narrow hot-working range, and canning in mild steel or stainless steel may be of benefit for reduced cooling. Cold rolling, when required, is no more difficult than that of high-strength steels. Small-diameter work rolls are preferable because of the high yield stress of the materials, and lubricants based on mineral oils and containing boundary and extreme pressure additives appear to be used. The same applies to nickel and to the lower strength nickel alloys.

Beryllium presents a special case because its oxides are toxic. It is canned in steel when hot rolled at about 750°C. Below this temperature, the bare metal may be rolled with appropriate precautions. It does not appear to adhere to the roll surfaces sufficiently to cause special lubrication problems, although detailed information on lubrication techniques could not be located.

Magnesium and its alloys are rolled with techniques similar to aluminum, except that the rolled quantities are usually small. After initial hot rolling at temperatures around 400°C, the sheet or strip is further rolled at slightly elevated temperatures, typically 250-300°C. Most alloys have only very limited ductility below this temperature, and cold rolling is restricted to small reductions per pass, followed by process anneals after 20-30% cold work. Magnesium adheres to the roll surface just as aluminum does, and lubrication practices are somewhat similar. A smear of a mineral oil or fatty oil was found sufficient in hot rolling small quantities;

heavily compounded emulsions are more successful for larger scale production. Cold sheet rolling may be conducted dry; strip rolling calls for a lubricant, but no information could be located on present practices. It could be assumed that oil-base lubricants used for aluminum rolling (Section 6.52) would work well enough.

Zinc is rolled at 150° to 250°C with an occasional smear of a mineral or fatty oil lubricant, or even on dry rolls.

The soft metals tin and lead were the first materials to be rolled and require no lubrication in small quantities. When rolled to foil, a light mineral oil serves adequately as a coolant.

6.10 SUMMARY

The extensive information presented in this chapter bears evidence of the interest that lubrication in rolling has evoked from about 1930 on. It also makes it clear that increasing production rates, the introduction of new materials, and the demand for more controlled and reproducible quality and dimensional tolerances have quickened the pace of research and of practical development since World War II.

The first step of rolling operations, namely, hot rolling, requires little more than a coolant for most materials because the oxides perform the requisite parting function efficiently enough. Aluminum and its alloys are not protected by the oxides and the need for controlling roll coating resulting from pickup has led to the formulation of some rather sophisticated emulsions. The maintenance of these emulsions is essential if uniform surface quality is to be assured, and this has prompted the development of effective recirculating and filtering systems. While coating control by purely chemical means would be desirable, this aim has not been achieved yet and periodic removal of excess coating by mechanical means is still generally practiced in high production mills. The problems are somewhat similar in the rolling of magnesium, except production rates are usually lower and thus difficulties are not so acute.

The cold rolling lubricant is of vital importance for all materials. Invariably friction must be reduced in order to lower roll forces and permit the rolling of thinner strip in fewer passes and fewer intermediate anneals. In most modern mills, the lubricant also has to be an effective coolant.

This dual function is satisfied by various means, somewhat dependent also on the material of the strip.

Steel strip is lubricated with palm oil or improved substitutes; the total loss system of application, with the lubricant preapplied to the strip and water supplied at the mill, or a mechanical dispersion of lubricant in water applied at the mill, has proven highly effective but presents serious pollution problems and will no doubt be replaced with closed recirculating systems. These demand lubricants of greater stability, and the problem is that of formulating stable or only moderately unstable emulsions with a lubricating performance similar to that of neat palm oil. While palm oil itself lubricates through a thin film mechanism, in which the hydrodynamic component plays a significant role, the lubrication mechanism operative with emulsions is not understood, and it is likely that a better understanding of controlling factors will be necessary before fully satisfactory or even superior emulsions can be found.

Water staining and corrosion has led to the development of oil-base rolling lubricants for the cold rolling of aluminum and its alloys. The mechanism is rather well understood, and lubricants are usually tailored to individual duties by choosing the lowest possible hydrocarbon chain length (in order to minimize staining on annealing) compatible with the requisite hydrodynamic lubrication. Boundary additives are incorporated and systematically replenished for controlled friction and reduced adhesion. Future development is likely to turn to emulsion systems with their greater cooling power. The problem appears to be not so much in adequate lubricating power but in avoidance of staining.

The steel and aluminum lubrication techniques are applicable to most other materials. Since production rates are usually lower, cooling is often a less important consideration. The chemically inert materials such as stainless steel and titanium do not respond to boundary additives and only to a limited extent to extreme pressure lubricants. Higher viscosities provide a partial solution, but better lubricants are still desirable if roll loads are to be kept reasonably low and, at the same time, an acceptable surface finish produced.

The rolling of strip is and will remain the highest volume metalworking process, and efforts at improving lubricants will no doubt continue. A better understanding of the operative lubricating mechanisms will no doubt be

needed if substantial advances are to be made, particularly in lubrication with emulsions and for the rolling of some of the more difficult materials. It is hoped that the survey presented in this chapter will contribute toward a more systematic approach to empirical studies and also inspire some more fundamental work.

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Chapter 7

WIRE DRAWING LUBRICATION

John A. Newnham

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7.1 INTRODUCTION

Although the major duty of a wire-drawing lubricant is often considered to be to prevent or minimize wear [1], the very possibility of drawing some compositions had to await the development of suitable lubricants. High carbon steel, for example, could not be drawn before the soll coat was introduced [2]. Thus, the wire-drawing lubricant performs many additional functions, among which are: reducing the friction in order to save power, obtaining greater reductions per pass and greater total reduction between anneals, and preventing pickup and adhesion of the wire material to the die which cause tensile failure of the wire in extreme cases. Once these initial tasks have been performed, industry turns to the lubricant to minimize die wear, which can severely limit the productivity of a wire mill.

There are several ways in which these objectives can be achieved; not only is a whole range of lubricants available, but there are also a number of recently introduced special techniques. These include methods for creating a thick lubricant film, and vibration of die elements for a reduction of boundary friction in difficult operations.

First of all, however, it is the aim of this chapter to introduce the conventional wire, bar, and tube drawing operations with respect to friction and lubrication, and to describe the effects of several process variables on lubrication. Then the most recent process modifications will be discussed, and the special requirements for the various tube drawing methods outlined. Subsequently, typical wire drawing lubricants and their properties will be listed, and finally, recommendations made for specific materials and operations.

7.2 FRICTION AND LUBRICATION EFFECTS

7.21 Lubrication Mechanisms

It is of immediate interest to examine the means of lubricant action which predominate in the more established techniques of wire drawing. An initial distinction can be made between "wet" and "dry" drawing practices, since in

each of these operations a different prime function is required of the lubricant.

As the names suggest, the basic difference is in the physical nature of the lubricant: dry drawing is accomplished with an initially solid lubricant, while wet drawing involves a liquid. Various factors may govern the selection of one method over the other. Dry drawing has as its aim the greatest possible reduction in area of the wire with minimum die wear; surface roughness resulting from deformation of the wire surface through the thick lubricant film is often of minor importance. It may become necessary also in very low-speed drawing, e.g. of bars, where liquid lubricants would be inadequate. Wet drawing is frequently practiced in the nonferrous industry and is also used on steel following dry drawing, because a bright surface finish can more easily be imparted to the wire with a thinner layer of lubricant at the die-wire interface. Liquids, especially water-based liquids, are more effective coolants than solids and, as a result, are employed to prevent excessive temperature rise in high-speed drawing—for example, in submerged drawing machines. In addition, many multi-die drawing machines are splash lubricated, and cannot utilize solid lubricants.

There are instances when these requirements overlap; liquid lubricants might cause too much pickup in a slow-speed operation, and so a grease of intermediate consistency may be employed to impart good surface finish. Furthermore, the mode of lubrication at the die-wire interface and the resultant surface properties of the drawn product are related to the drawing speed, the lubricant viscosity, and the strength of the wire, as will be seen in more detail in Section 7.24. Therefore, by suitable manipulation of lubricant and drawing speed, either wet or dry wire drawing can often be made satisfactory for a given wire material. The geometry of the wire drawing process is such that two distinct regimes of lubrication can be obtained within the practical range of process conditions. When drawing speeds and lubricant viscosities are low, boundary lubrication is predominant [3], and there is intimate contact of die and wire surfaces, separated in places by only a few molecular layers of lubricant. Under these conditions reductions are somewhat limited, but the product surface is bright. Increasing speed and viscosity will increase the thickness of the separating lubricant film, and while a relatively dull surface finish can be expected, much larger reductions can be taken without lubricant breakdown.

Lubricant film thickness, then, is one of the major differences in lubricating mechanism between wet and dry drawing. These two processes will now be examined in greater detail with respect to their requirements and functions.

7.22 Wet Drawing

One of the most important functions of a lubricant in the drawing of fine wire—generally by wet drawing techniques—is the reduction of frictional heat [5, 6]. As a direct result, many wet wire-drawing lubricants are designed to extract heat from the die and wire at the fastest possible rate. Since lubrication is primarily of the boundary type, it is important to keep the interface temperature low enough to avoid chemical breakdown of the lubricant. When drawing steel wire, low temperatures are often required also to prevent metallurgical changes. The most efficient cooling method is either to submerge the dies, the wire, and the machines in lubricant, or to recirculate large quantities of lubricant to and from the die.

These lubricants are frequently in the form of solutions or emulsions having water, the most efficient common heat exchange medium, as the main constituent [7]. Generally, such lubricants are easy to apply to the die and wire and to store. However, many drawing machines operate with mineral oil-based fluids, particularly if water staining or corrosion of the wire could cause problems.

Wet drawing is frequently practiced on thinner gages of steel (particularly in diameters below 0.050 in.)[5] and on all gages of stainless steel, copper, brass, and aluminum. Copper is drawn mostly into electrical wire, so the need for a smooth surface finish is self-evident. Wet drawing is chosen for other materials either because the wire is too fine to draw dry, or because other properties such as weldability [8] or aesthetic appearance for increased sales are desired. Better weldability is obtained in wet drawing because the wire surface is relatively clean, and will not normally need special treatment prior to welding.

The improved surface finish is obtained because of the mode of lubrication, which is deliberately restricted to the predominantly boundary regime. Intimate contact of die and wire is allowed since only a thin layer of lubricant need be interposed under boundary conditions. Therefore, considerable smoothing and polishing of surface irregularities is possible [9, 10], provided

good boundary lubrication can be maintained. Hot rolled surface, after either pickling or mechanical descaling, has an average peak-to-valley height of at least 40 μ in. [11]. After drawing through polished dies, such wire is progressively smoothed until the roughness lies between 20 μ in. [11] and 1 μ in. [12], depending upon the number of passes, the total reduction, and the state of lubrication. The predominantly circumferential surface scoring evident on rolled bars changes to longitudinal on the drawn product after a single pass.

The effects were summarized in terms of lubricant selection by Ford and Wistreich [13], who noted that a smoother wire finish requires closing of the small pits and wrinkles on the wire surface by burnishing. This is best achieved by using a lubricant which would normally be considered poor (compared, for example, with a solid soap), since it gives higher friction. Thus lubricant selection is based on the correct balance between higher friction to give good finish and good lubrication to reduce die wear. Excessive die wear is prevented only if the lubricating fluid possesses good cooling and boundary lubrication properties; in consequence, highly developed oil-based compounded fluids and water-based emulsions find wide application [5, 7, 14-17].

Wistreich [3] considers that the main problems in wet drawing are deterioration of lubricant and scuffing of the dies. The lubricant deteriorates through chemical instability of some constituents and through sludging with insoluble metal soaps and fine metallic dust [18]. These effects probably cannot be eliminated, but closer chemical control and more efficient filtering are methods of extending the life of the lubricant; some of the techniques described in Section 6.34 could be employed to advantage. Scuffing can be eliminated by use of improved lubricant coating, as is provided—usually for steel—by phosphating, or by improvement in coverage and adhesion of the boundary lubricant to the wire. Phosphating, however, is successful only with a soap or other solid lubricant, and is not normally used in wet drawing. In order to improve coverage, the British Iron and Steel Research Association followed an idea accredited to Williams [19] and drew freshly pickled and neutralized mild steel wire on a commercial nine-hole machine. The lubricant was a soft soap in water, applied to the wire by an electrophoretic technique, with electrodes in front of each die. A considerable improvement in surface properties of the drawn product resulted; the wire had a higher luster and was free from tarnishing for longer than normal. This was due to more efficient coverage with the lubricant; however, the method was not sufficiently reliable for industrial purposes.

The two functions of preventing metal-to-metal contact and ensuring good finish can be satisfied simultaneously with a two-component system: the first acts as a separator, and the second assures reasonably low friction [6]. In wet drawing, metal deposits such as copper and tin are frequently employed as separators, whereas lime, borax, or phosphate coats are more typical of dry drawing. A lubricant applied to the draw die fulfills the second function.

In wet drawing, the lubricant is rarely preapplied, and recirculating systems are more common. Soap solutions are avoided in these systems because of their tendency to foam. A lubricant of high stability is desired to minimize the frequency of lubricant changes with its consequences in lost time and high cost.

Although the fundamentals of drawing for surface finish are well enough understood, the lack of stability of some emulsion-type lubricants creates practical problems which may be difficult to overcome, and which may make dry drawing more attractive. At low speeds, however, wet drawing does not give an adequate film thickness to ensure separation of die and workpiece, making solid lubricants often mandatory for bar and tube drawing.

7.23 Dry Drawing

Dry drawing operations have as their aim the greatest possible reduction in area of the wire. The general implication of this is that the resultant surface of the wire is not important, so that solid lubricants such as soaps may be used. The mechanism by which such lubricants operate has been clarified through a number of experiments.

As will be seen in Section 7.24, the decrease of drawing load observed with increasing speed and lubricant viscosity in dry drawing is contrary to the behavior expected in pure boundary (and also in fully hydrodynamic) lubrication. Much greater lubricant throughput than is characteristic of boundary conditions has been measured [20, 21], and Ranger and Wistreich [22] have calculated a film thickness of between 1000 and 30,000 Å from electrical resistance measurements between die and wire, using wax as a lubricant. This is far in excess of the thickness of a monomolecular layer (possibly of the order of 100 Å for some soaps). These investigators also noticed a rapid variation of electrical resistance under all experimental conditions, which corresponded to Lueg and Treptow's [23] observations of a rapidly

fluctuating drawing force and temperature. Furthermore, both Ranger and Wistreich [22] and Baron and Thompson [21] found that lubricant throughput increased sharply as the die angle was reduced to low values (about 2°).

On the basis of these observations, a theory of the lubrication mechanisms involved in dry drawing has been proposed by Wistreich [3, 9, 24]. Even though the lubricant, such as soap, is normally solid, it becomes a non-Newtonian fluid under the high temperatures and shear rates prevailing in the die. The high pressures increase its viscosity and thus prevent dangerous overthinning. The geometry of wire drawing is one of the most favorable ones for hydrodynamic conditions to develop. In Fig. 7.1, the arrow points to the entry zone where lubricant is carried by a solid surface (the wire) converging upon another surface (the die). Under these circumstances the lubricant becomes trapped in the converging channel and, as long as the viscosity of the lubricant and the velocity of the wire are adequate, a hydrodynamic wedge can form which forces the die and wire apart. If the die angle is reduced, the lubricant is sheared over a much greater distance and hydrodynamic action is further encouraged.

However, the observed speed effects suggest that neither fully hydrodynamic lubrication nor purely boundary lubrication occur. The prevailing intermediate mechanism operative in dry drawing is often described as "quasi-hydrodynamic lubrication," and may be regarded as being similar to the mixed or thin film lubrication discussed for rolling (Section 6.21). Wistreich [3, 9, 24] considers that a fluid film continually seeks to establish itself locally, but high pressures keep the film so thin that changes in surface configuration are sufficient to cause its collapse, with reversion to boundary contact. Whether one or the other mechanism predominates depends upon surface roughness, wedge angle (die angle), bearing area, interfacial temperatures and pressures, and the rheological properties of the lubricant.

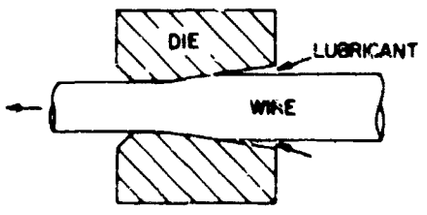

Fig. 7.1. Sketch of wire drawing process showing regions where the geometry may induce hydrodynamic effects.

This theory of lubrication accounts for the dependence of friction and drawing load on drawing speed, the viscosity-temperature-pressure relationship of the lubricant, and the die angle.

An integral part of this theory is that rupture of locally formed fluid films is caused by surface irregularities or asperities, and extension of this argument might be that with a smooth wire surface, the fluid film will not break down. However, very favorable process conditions—in terms of speed, lubricant viscosity, etc.—would be required in order to form a hydrodynamic film, and normally one relies upon the surface pockets and asperities on the wire to trap the lubricant. Thus, with suitably roughened surfaces, partial fluid film lubrication can be achieved with much lower speeds, lower viscosities, and higher die angles than with smooth wire. Lancaster and Rowe [25-30] have developed this theme and propose that surface pockets can be formed by grit-blasting the wire, and much better lubrication will result upon subsequent drawing, whether soaps or liquid lubricants are employed.

In industry a variety of lubricants are found to fulfill the requirements of dry drawing. The most common lubricants are soaps, of course, but whereas polar compounds having good boundary properties were once considered to be essential for dry drawing [15, 31], this property now takes a secondary position. For optimum boundary lubrication, materials of a high melting point are preferable, so that pure soaps would be more suitable [32]. Under quasi-hydrodynamic conditions, Wistreich considers it more important to have a gradual transition from the solid to the fluid state [3] so that blended soaps derived from natural fat bases would be superior to pure soaps, although no direct experimental evidence appears to be available. Alternative lubricants for dry drawing include petroleum greases and undiluted soap-fat compounds in instances where the finish obtained from drawing with soaps is not acceptable [17].

Lubricant carriers are invariably used for the dry drawing of steel wire. As their name implies, their purpose is to pick up and retain the solid lubricant on the wire and, additionally, to prevent metal-to-metal contact. These carriers include the sull coat, which is essentially a soft layer of hydrated oxide on the steel; it is used in conjunction with lime or borax. More expensive and, in specific instances, more efficient is the system comprising a phosphate coating with superimposed reactive soap or some other solid lubricant film (the phosphate coating alone can act as an abrasive). Other

materials which are difficult to draw may benefit from similar coatings—for example, an oxalate coating for stainless steel, or a fluoride-phosphate coating for titanium and its alloys. These lubricants and carriers will be described in more detail in Section 7.3.

7.24 Speed and Viscosity Effects

Both speed and viscosity can have large effects on lubricant action in wire drawing, so that the selection of both parameters is one of major industrial significance. To a great extent, speed and viscosity are interrelated, since increased speed causes a temperature increase at the die-wire interface which can markedly reduce the viscosity of the lubricant. Counterbalancing this effect is thickening of the hydrodynamic film with increasing speed. The competing phenomena can, to some degree, be observed separately, and in this section it will be convenient to discuss, first, the variation of lubricant viscosity and then consider the effect of speed.

Viscosity Effects

Tourret [4] drew aluminum wire at a constant speed with four straight mineral oils of increasing viscosity. The results (Fig. 7.2) show that the drawing force decreases steadily as lubricant viscosity increases. As discussed in Section 7.21, this behavior indicates that partial fluid film conditions exist in wire drawing and that an increase in viscosity improves the separation of die and wire.

Further evidence of this was provided by Bramley [18], who observed the surface of aluminum wire drawn with a mineral oil. The surface could be progressively brightened by diluting the mineral oil with a light paraffin,

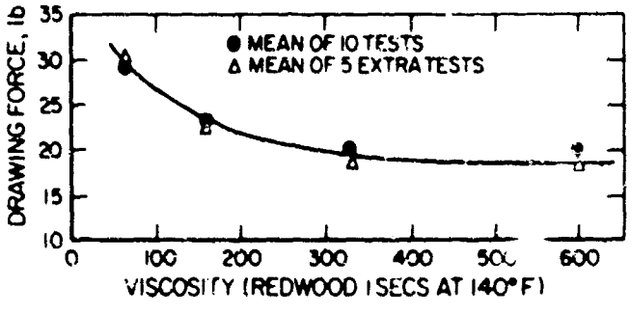

Fig. 7.2. Effect of lubricant viscosity on force required to draw aluminum wire using straight mineral oil [4].

and eventually scoring of the wire resulted. This observation confirmed that a decrease in die-wire separation occurred as the lubricant viscosity dropped. This was manifested by the change from a dull finish, representative of good separation when hydrodynamic pockets of lubricant are formed on the surface, to a bright finish, typical of boundary lubrication.

Tourret [4] conducted similar experiments for copper in which a soap was progressively diluted with water and, as a result, the drawing force steadily rose. Although viscosity was not the only property affected by dilution (the concentration of boundary additive also varied), there is no doubt that the contribution of viscosity was a major factor. Treptow [33] confirmed these results by a similar technique for steel.

It must be remembered, however, that the magnitude of the viscosity effect will be determined also by the strength of the wire being drawn [4, 18, 34]. Since aluminum is very soft, it shows changes of large magnitude with comparatively small change in lubricant viscosity. Greater changes in viscosity are necessary for copper to respond, and the still higher strength of steel discourages fluid film conditions even with relatively high viscosities, particularly at low speeds.

The viscosity of a lubricant is affected by process variables such as temperature and pressure. Thus, the measured viscosity at normal temperature and pressure is no indication of the condition of the lubricant in the drawing die. It was seen in Section 4.2 that viscosity increases with pressure much more rapidly for mineral oils than for fatty oils, but the earlier solidification of fatty oils could still make them more effective lubricants. There are also temperature variations in the die gap, with fairly high local temperatures at contacting asperities. In general, lubricants become less viscous at higher temperatures; Papsdorf [31], Ranger and Wistreich [22], and Hoggart [35] have all presented evidence of this under wire drawing conditions.

If lubrication were fully hydrodynamic, increasing temperatures would lower the friction coefficient, which is dependent upon the shear strength of the liquid. With partial fluid film conditions, however, higher temperatures reduce the die-wire separation, and hence increase friction. This has been demonstrated experimentally by Ranger and Wistreich [22], who measured the electrical resistance between die and wire in the drawing of bright mild steel wire of 0.1 in. diameter using a coating of synthetic wax as a lubricant. When the tungsten carbide die was heated externally, without change in the

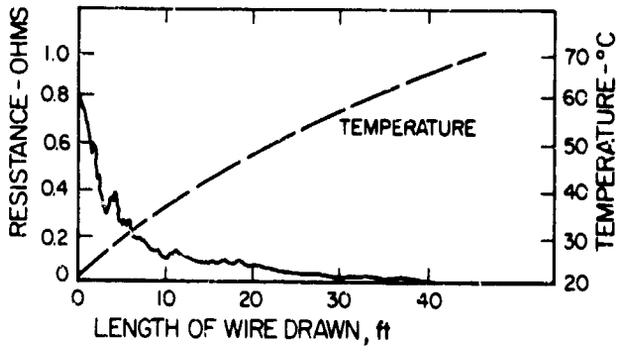

Fig. 7.3. Effect of length of wire drawn on temperature and electrical resistance between die and wire [22].

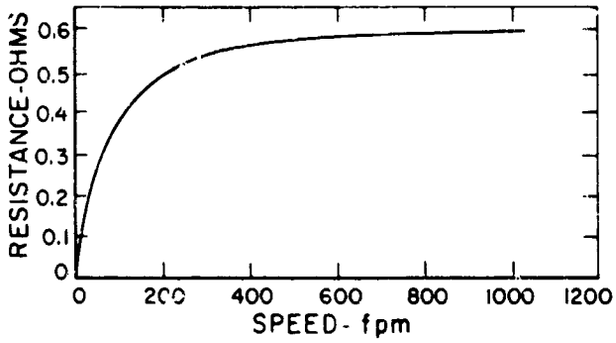

Fig. 7.4. Effect of drawing speed on electrical resistance between die and wire [22].

drawing speed, the resistance measured between die and wire dropped (Fig. 7.3). This was attributed to a decrease in lubricant film thickness owing to the rapid change of viscosity rather than to a variation of electrical resistivity of the wax with temperature.

Speed Effects

Speed changes cause simultaneous temperature and pressure variations in the die gap but, under favorable conditions, the overall effect is that higher speed increases the fluid film thickness and hence causes a drop in drawing load. The thicker film resulted in increased electrical resistance in the experiments of Ranger and Wistreich [22] (Fig. 7.4). This, in turn, led to a decrease in drawing load.

Lower drawing loads were registered with increasing speed by Pomp and Becker [36] for steel wire at speeds up to 1509 fpm, by Ranger [37] also for

steel wire at speeds between 0 and 2000 fpm, and by Wistreich [38] who plotted data taken from Christopherson and Naylor's work [39] on drawing copper at speeds up to 600 fpm and who also recorded the results of the British Iron and Steel Research Association on the drawing of steel wire at speeds up to 5000 fpm. In this latter work, however, it was seen that while the drawing force was reduced as speed increased up to 4000 fpm, even higher speeds caused an increase in force, presumably because of an excessive rise in wire temperature and the allied deleterious effects on the calcium stearate lubricant.

The lubricant behavior observed in these experiments corresponds to a quasi-hydrodynamic mechanism, since lubricant throughput and, hence, die-wire separation are enhanced by an increase in speed. This has been confirmed by Tourret [4] who also pointed out that these effects are more readily observed when drawing soft materials—for example, aluminum or annealed brass [21] —than with work-hardened or high strength materials (this again points to the similarity of viscosity and speed effects).

The quasi-hydrodynamic nature of lubrication has been confirmed by means of a radiotracer technique employing radioactive sodium stearate [40]. As the severity of the draw increased, the thickness of the fluid film was reduced. Under such conditions, the boundary component becomes more prevalent in the quasi-hydrodynamic mechanism and the coefficient of friction can be expected to rise. Lueg and Treptow [41] indeed found an increase in friction with increasing pressure in drawing patented steel wire over a pressure range of 150 to 400 kpsi. Below this range of pressures, Pawelski [42] calculated a similar rise in friction in a low-speed strip drawing test on mild steel with mineral oil and fatty oils as lubricants.

Even though increased speed causes increased die-wire separation, and thus a reduction of frictional heat, deformation heat is produced at an increased rate. Since there is little die-wire contact, little heat will be abstracted directly through the die, and the lubricant will tend to overheat in the inlet of the die as well as in the contact zone. Thus, the lubricant could break down and even greater wire and die temperatures would be produced by the additional friction heat. On multiple-die drawing equipment the temperature of the wire entering the die is usually also controlled, either by internal cooling of capstans or by submerged drawing.

Ordinarily, too high a temperature rise is offset in practice by selecting a more efficient lubricant and coolant. Many lubricants are versatile and can be used over a wide range of speeds, but it is conceivable that a lubricant that is satisfactory at a speed of 1200 fpm might fail at much higher speeds [43]. Therefore, operating speeds are chosen very carefully in industry, and are dependent upon such factors as labor cost, die life, equipment cost, and lubricant cost [6]. Generally, however, if die wear can be kept to a minimum and suitable lubricants can be found, higher speeds always give increased productivity. Under such conditions the lowest viscosity lubricant is selected that gives adequate performance [18]. However, care must be taken to ensure that such a lubricant will also perform adequately during stopping and acceleration for such operations as butt welding of wire, and that the acceleration required for good performance of a given lubricant does not exceed the strength capabilities of finer wires. These factors form the ground rules for the selection of speed and viscosity in a given operation.

7.25 Friction in Drawing

The coefficient of friction in wire drawing has frequently been measured by various techniques described in Section 5.23.

Linicus and Sachs [44] obtained $\mu = 0.04$ in their rotating die experiments on steel wire. Split die experiments by Wistreich [38] gave friction values of the same order of magnitude. In a review of previous work, Tourret [4] found that the friction coefficient for low-carbon steel drawn with soap is between 0.02 and 0.10. The experiments considered covered a broad range of conditions such as speed, die angle, and soap composition, and friction was usually calculated from the draw force.

Lewis [45, 46] quoted friction values between 0.16 and 0.18 in drawing copper at between 1000 and 2000 fpm with steel dies and a commercial drawing lubricant. These values indicate boundary lubrication and seem excessively high. MacLellan [47] found $\mu = 0.06$ for drawing copper through tungsten carbide dies at very low speed (1 1/2 fpm) using a commercial lubricant, and 0.08 through diamond dies with ethyl palmitate or with ethyl stearate. Castor oil, a less efficient boundary lubricant, gave much higher friction coefficients (0.10 to 0.21).

The values observed are obviously dependent upon the method of calculation. For example, Baron and Thompson [21] drew 65:35 brass wire in

tungsten carbide dies at speeds up to 3 1/2 fpm, and obtained values of friction between 0.03 and 0.06 with soap as a lubricant. With three other lubricants—an aqueous emulsion, castor oil, and a suspension of graphite in oil—friction was between 0.06 and 0.09, while with an extreme pressure oil it was around 0.10. At the low speeds employed, these values were lower than normally expected, but Baron and Thompson were testing various wire drawing theories and selected that due to Davis and Dokos [48], whereas consistently higher values of friction were given by Sachs' theory [49].

Wistreich [9] has given a more general statement of the behavior of various lubricants, saying that soaps and other solid lubricants will give a coefficient of friction between 0.02 and 0.05 in wire drawing, irrespective of the material of the wire or die (no doubt because of thick film conditions). When liquid lubricants are used, the value increases to between 0.08 and 0.15, since the lubricant has a lower viscosity and there is a greater tendency for boundary conditions to predominate. As an approximate guide, Wistreich [9] gave figures of $\mu = 10^{-2}$ in dry drawing, and 10^{-1} in wet drawing.

Wistreich also indicated that, on the basis of evidence presented by Baron and Thompson [21], the friction coefficient increases with die angle and yield stress of the wire, but decreases with application of back-pull. Thus, μ seems to be pressure dependent, though in this example the change occurs rather because the lubricant is able to form a more coherent separating film as the pressure is reduced than because the friction of a boundary layer is affected. Under high pressures, lubricant films have a tendency to be thinned unless they are trapped either by small surface pockets or by tool and workpiece geometry.

Further evidence on the effect of pressure on friction coefficient was provided in the well-documented strip drawing experiments of Pawelski [50], in which strip was prehardened to various degrees by cold working, thus maintaining a constant process geometry. Earlier wire drawing tests of Lueg and Treptow [51], conducted as a sequence of draws on the same wire, also seem to confirm (Fig. 7.5) that local contact dominates the pressure effect; higher pressure causes thinning of the lubricant and greater susceptibility to boundary conditions. The effect of pressure remains, nevertheless, controversial because in most experiments other conditions (reduction in area, surface extension, surface finish) change concurrently with pressure.

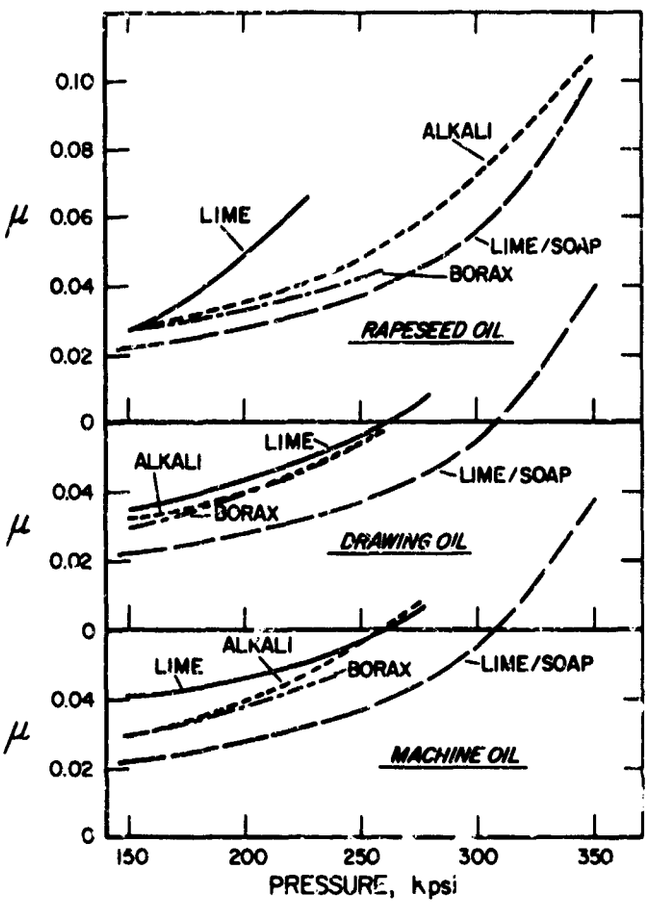

Fig. 7.5. Effect of friction coefficient on die pressure using several wire coatings and lubricants in the drawing of 0.53 carbon steel wire [51].

Pawelski and co-workers [50, 52] found rather unexpectedly that the friction coefficient in drawing decreased as the percentage reduction increased, whereas the work of Majors [53] on the drawing of steel and aluminum showed that there was little effect of reduction on friction. This phenomenon is very sensitive to the type of lubricant employed.

Johnson and Rowe [54] have demonstrated by both experimental and theoretical means that friction has negligible effect on redundant work in wire drawing. Conversely, Hundy and Singer [55] have found that the inhomogeneity of deformation, as measured by the hardness variation across drawn copper wire, increases as the friction increases for a 20° die angle but does not change with a 30° die. It should be noted, however, that 20° and 30° dies are of little practical significance.

It is customary in all experiments leading to determinations and comparison of friction to assume a constant value of μ in the die gap. This may be the only realistic way of dealing with this quantity for comparative purposes, but indirect evidence indicates that there is considerable variation of friction along the contact surface of the die. This evidence comes from the experiments of Cook and Wistreich [56] in which lead alloy strip was drawn through a wedge-shaped die made of plastic that was optically sensitive to stress, and the pressure variation at the die-metal interface measured by a photoelastic method. Calculated friction varied between 0.05 at the die entry and 0.01 at the die exit. This variation has more recently been confirmed (Fig. 7.6) by a similar photoelastic method by Ohashi and Nishitani [57].

Thus the values of μ used in or obtained from wire drawing theories must necessarily be averages, but this in general does not detract from their value in predicting drawing loads. As far as lubricant comparison is concerned, die life, surface finish, metal pickup, and cooling are often more important than the coefficient of friction.

7.26 Die Wear

Two of the major industrial requirements of wire drawing lubricants are the maintenance of a good surface finish on the drawn product and the

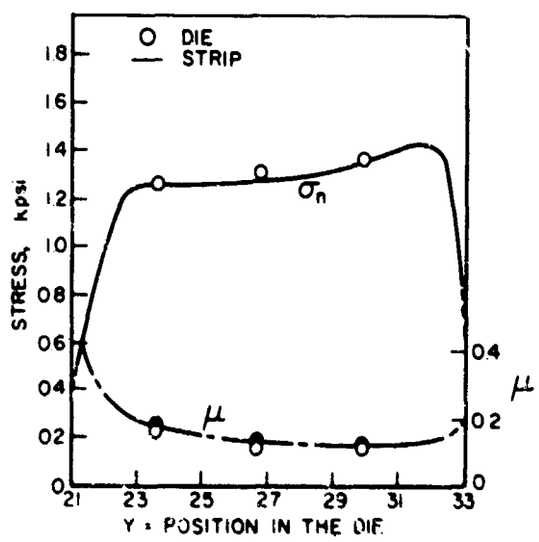

Fig. 7.6. Variation of pressure and friction coefficient with position on the die face (Y) in simulated wire drawing [57].

reduction of die wear. The overall costs of die wear could be very high, for not only is replacement or rework involved but also the loss of production due to die changes could represent a permanent operating inefficiency.

There is also a substantial problem with the wear of capstans (cones) in slip-type drawing machines. These capstans are employed to transmit the pull force to the wire in a drawing machine that is both compact and capable of high-speed production. In slip machines, a 2% velocity differential is allowed to develop between capstan and wire, so that adequate pull is ensured. The capstans tend to wear and cause scoring, and must be replaced. The cost of replacement is fairly high and, since the same lubricant is used both on the capstan and in the drawing die, some attention is usually paid to selecting a lubricant which will prevent excessive wear of both items. However, die wear cannot be overcome entirely by boundary lubrication since wear debris contaminates the lubricant and may cause scoring even in the presence of the best boundary lubricants. In most slip-type drawing equipment, the lubricant is recirculated and filtration of debris from the fluid becomes extremely important.

The lubricant itself can contribute to the die wear produced by means of cavitation erosion at the entry plane. Thus, even if a hard, relatively wear-resistant die material is used with the most efficient lubricants, die wear will continue, although the rate may be substantially reduced.

Wear at Die Entry

The intensity of wear in a given die varies along the die-wire interface. The highest rate of wear occurs at the die entry where "ringing" takes place (Fig. 7.7). Wistreich [9] notes that ringing is usually more severe than

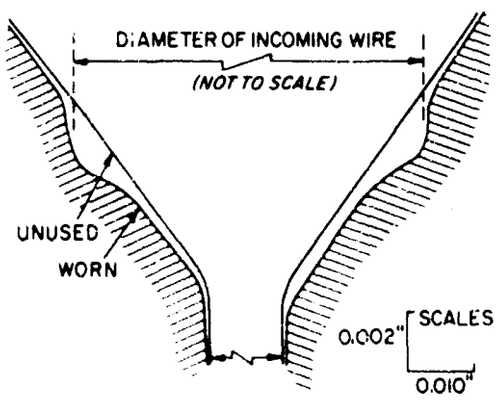

Fig. 7.7. Section of a worn wire drawing die [9].

wear at the exit plane. Therefore, substantial wear might take place before the wire gets seriously oversize, yet as soon as a ring has formed, lubrication conditions become potentially more difficult. Thus, the life of a die in continuous industrial use will be determined by both the point at which lubrication is impaired with a resulting poor surface finish and the maximum acceptable size or deviation from circularity of the drawn product as set by engineering tolerances.

Papsdorf [31] noted that if the size of the drawn product is measured at regular intervals after a new drawing die is installed and this size is subsequently plotted against the tonnage of wires drawn, then a curve of the type shown in Fig. 7.8 is obtained. The die undergoes rapid wear during its early life. Then follows a stage of uniform wear rate until the die becomes so badly worn that further drawing is impossible. Papsdorf [31] considers the first part of this curve to correspond to the wearing down of surface peaks to give more flattened asperities, while the last state is connected with ringing of the die surface at the entry plane.

From experiments in which process conditions such as back-pull, die angle, and the angle of wire entry into the die were varied, Wistreich [58] has deduced that ringing wear is caused by size irregularities or vibration of the incoming wire. This results in the rapid oscillation of the line of contact between the die and wire surface and, in consequence, a narrow region of the die surface is subjected to a cyclic compressive stress, varying between zero and full die pressure. It is Wistreich's hypothesis that subsequent wear is the result of fatigue failure of the surface layers of the die. Cleaver and Miller's observation [59] that in drawing copper wire the intensity of ringing increases with lateral vibration of the wire, adds weight to this theory. Ringing of dies is obviously aggravated by wear debris present in lubricants.

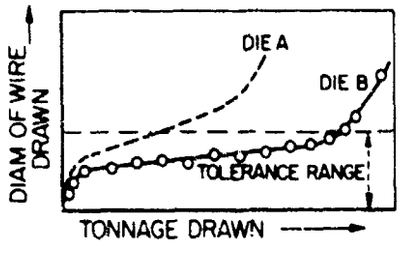

Fig. 7.8. Typical wear behavior of wire drawing dies, represented by the change in diameter of the drawn wire with the total quantity drawn [31].

Even with clean lubricants, sudden pressure drops in an oil film can cause cavitation erosion of the die, while a liquid lubricant may also penetrate under the influence of pressure discontinuities into the surface structure of the die, causing microcracks [31].

Wear at Draw Cone

Although it can be seen that conditions are highly favorable to rapid wear at the entry plane of the die, it is also true that wear occurs elsewhere in the draw cone of the die, and a fatigue mechanism, followed by loosening and separation of die surface particles, cannot be the cause. According to Wistreich [24], the theories of Bowden and Tabor [32] relating to the welding of asperities are more relevant in these regions. This idea has been confirmed by Button et al. [60] and Dahl and Lueg [61], who made radiotracer studies of the distribution of wear debris from radioactive cobalt-bonded tungsten carbide dies on the surface of the drawn wire, and by Wistreich [62], who made a metallographic examination of the profiles of worn dies. The mechanism proposed for die wear is that, initially, the cobalt welds on a microscopic scale to the metal of the wire, until the tungsten carbide grains are isolated and are pulled out from the matrix of the die. These carbide grains were said to be seen as intense spots of radiation on autoradiographs of the drawn wire [60, 61], where they had become embedded. Wistreich [9] notes that a similar mechanism also holds true for diamond dies.

However, there is evidence to show that this mechanism operates only under certain circumstances. Golden and Rowe [63] used a die in which both tungsten and cobalt were radioactive. Tungsten has only a short half-life so that the distribution of strong tungsten radiation could be measured immediately after sliding the die over copper. After 400 days, only the relatively weak cobalt radiation was present. From the two autoradiographs it appeared that both tungsten carbide and cobalt were evenly distributed over the copper surface, and the composition of the wear debris was nearly identical to that of the original die. Therefore, steady wear of both materials must have occurred simultaneously. Golden and Rowe [63] attributed the difference in observed wear mechanisms to differences in the surface preparation of the copper workpiece specimen. They had noted [64] that defects or chemical inhomogeneities in copper surfaces led to sudden increases in wear, and autoradiographs then showed a steady background with discrete spots of high

intensity superimposed on it. This is equivalent to the type of wear seen by Button, Davies, and Tourret [60] and later by Dahl and Lueg [61] and is therefore strongly dependent upon the surface preparation of the workpiece specimen. Holzhey et al. [65] have similarly investigated die wear in the drawing of a chromium steel using radioactive dies.

Wear of Land

In the die land, an additional wear mechanism is operative, leading to a rapid increase in the size of the drawn product. The rate of wear here lies between that observed at the entry plane where ringing occurs and that in the central conical portion of the die where the wear rate is the lowest. According to Wistreich [62], wear in the land results primarily from abrasion by the particles that are freed from the surfaces nearer the entry plane.

However, it should be noted that abrasion by oxide or other fine particles is important not only in the die land but everywhere else in the die, including the draw cone, when a recirculating or submerged system of lubrication is used. The particles are then generated in the draw cone but are also brought in by the lubricant. The only adequate method of preventing this is careful filtration of the lubricant.

Reduction of Wear

For the many ways in which wire-drawing dies are worn, there are a corresponding number of methods by which die wear may be minimized. The most obvious of these is to use hard, abrasion-resistant materials for dies. Wistreich [9] has given some comparative figures to illustrate the relative efficiency of various die materials. For an increase in die bore of 0.001 in., a (rather impractical) mild steel die would draw 1/4 to 1 mile, a high carbon steel die 15 to 40 miles, tungsten carbide 50 to 200 miles, and diamond 1 million to 8 million miles of steel wire. Although diamond is far superior to any other die material, the cost factor must also be considered. It is normal to find diamond dies in use only for drawing very fine gage wire, not merely because of initial cost considerations but also because of the limited size of available diamonds.

By far the most common die material is cobalt-bonded tungsten carbide (usually in a steel bolster); but high carbon steel, which might be hard-chrome plated for steel tube drawing, still finds wide use as a die material, particularly for large-diameter rounds and for sections.

Riley-Gledhill [20, 66] has found that substantial wear is caused through misalignment of the wire as it is fed into the die. This is equivalent to increasing the die angle on one side of the wire while decreasing it on the other. Since one-half of the die suffers much greater ringing than the other half, dies must be discarded earlier than if ringing wear had been evenly distributed. Riley-Gledhill suggests that the use of two guide pulleys enables more accurate alignment of the ingoing wire on most wire drawing machines and also reduces vibrations in the wire. This, together with efficient cleaning and lubrication of the rods, has proved to be a most efficient remedy for excessive die wear.

Even distribution of die wear may also be obtained by rotating the die. This method has been used for separating the frictional force from the deformation force [44], since the friction vector is no longer in the axial direction. For the same reason the pull force in the axial direction is reduced [67], which would allow larger reductions. These dies have been used in the aluminum industry, and have proved advantageous in equalizing die wear and in the production of perfectly round wire [68].

It was seen in Section 7.24 that higher speed causes increased separation of die and workpiece surfaces. With metal-to-metal contact thus minimized, die wear will be reduced. Under conditions of predominantly boundary lubrication, corrosive wear of dies, especially steel dies, can occur when highly reactive E.P. additives (for example, chlorinated oils) are employed. If lubricant film thickness does not increase when speed increases (for example, with solid lubricants), then increased temperature is a great problem since die wear also increases. Hedman [69] has observed that a four-fold increase in drawing speed can lead to a reduction in die life by a factor of six. Holtzberger [70] considers that, for a given wire diameter, die performance—expressed in length of wire drawn—varies inversely as the root of the drawing speed. This supports the theoretical work of Siebel and Kobitzsch [71] and Korst [72] who calculated that the die temperature rise due to friction is proportional to the square root of the drawing speed and wire size. From this it can be inferred that die life is inversely proportional to the temperature generated at the interface. With hard wires this temperature may be several hundred degrees Celsius [24]. Thus, it is most important that when speed is increased, the heat generated by friction is minimized and the heat of deformation is not passed onto the die. Ranger [37] has suggested that water

cooling of the die can assist in reducing the die temperature, but particular attention should be paid to cooling the die inlet and the entering wire so that the lubricant will not overheat prior to entering the die.

Wistreich [9] has noted that the promotion of a thick lubricant film between die and workpiece by the method proposed by Christopherson [73] (described in Section 7.27) is successful in eliminating ringing wear of dies. This adds weight to the hypothesis that ringing is caused by pressure fluctuations at the entry plane, since under conditions of hydrodynamic lubrication the fluid exerts full pressure on the die walls throughout the operation. Therefore, in the absence of a cyclic stress system, the fatigue failure cannot develop.

This method also minimizes abrasive wear since small hard particles are washed through the die by the thick fluid film. In fact, under ideal conditions, the only way in which wear can occur in hydrodynamic drawing is during starting and stopping, when the speed is inadequate to support a fluid film, and by erosion of the die by the liquid. Obviously, fluid erosion and chemical attack of dies can be very important when full fluid lubrication occurs, but the rate of fluid erosion is relatively small; suitable noncorrosive lubricants may be substituted for E. P. oils when a thick film can be generated.

7.27 Hydrodynamic Lubrication

With the current industrial demands for increased productivity, it has been inevitable that ever higher finishing speeds are needed in wire drawing. Such a trend has posed a number of problems to the lubrication engineer and the die designer, whose responsibility it is to ensure satisfactory performance in the operation.

Essentially, the problems involved may be attributed to two causes. First, increased speed of operation results in an increased rate of heat generation, which ultimately affects the performance of the lubricant [74]. Thus, both surface finish of the drawn product and die life may be adversely affected. Second, if drawing speed increases and the die life per unit length of drawn product decreases or remains constant, the time lost in changing the dies and rethreading the wire becomes a large factor in determining the productivity of the wire mill. Wistreich [62, 75] quoted statistics of a wire mill which indicated that time lost in die replacement was equivalent to one machine in twenty standing permanently idle. Wistreich [76] has also

observed that the solution to these problems does not lie wholly in improving drawing lubricants, since only marginal gains can be foreseen here. The only practical method of ensuring satisfactory performance is to separate completely the die and workpiece surfaces by a film of lubricant so that die wear and frictional heat are minimized.

This was first envisaged by MacLellan and Cameron [77] in 1943, who constructed an apparatus in which oil was supplied under pressure from an oil pump to a wire drawing die, in order that fluid film conditions could be obtained. This mechanism was hydrostatic rather than hydrodynamic, and the main object was removal of debris (swarf) from the die, and not minimization of die wear. However, according to Cameron [78] the idea was abondoned because the oil supply tube became choked with swarf, and no simple way of removing it could be found. Some years later, the idea was revived and subsequently developed in two different directions. Milliken [79] presented a design for pumping high-pressure oil to the die-wire interface in 1955, while Christopherson and co-workers proposed in 1954 [73] and 1955 [39] a method of obtaining full fluid lubrication by a novel die design. The two methods of obtaining the same result are quite different: the former is equivalent to forced hydrodynamic wire drawing, while the latter may be called pure hydrodynamic wire drawing, since it is the motion of the wire which causes the buildup of oil pressure and, hence, the hydrodynamic lift. Besides these two methods for improving lubrication, a pure hydrostatic method has also been discussed, but this has as its main objective the drawing of low-ductility materials. The pure hydrodynamic method will first be considered here.

Lubrication with Oils

Christopherson's method involved the use of a tube of up to 30 in. (but generally around 9 in.) length through which the wire passed before entering the die (Fig. 7.9). The clearance between the wire and the tube was very small (about 0.002 in.), and a mineral oil was used as a lubricant. By this means, oil pressures of the order of the yield stress of the wire were developed purely by viscous action. At the start of the drawing operation lubricant throughput was small, and the die pressure and friction were high. With increasing drawing velocity, the flow of lubricant through the die increased and the drawing force dropped sharply. However, the pressure at the die inlet remained approximately constant, since this was largely determined by

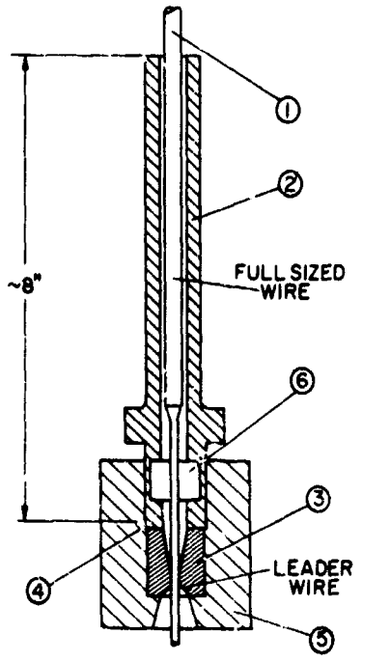

Fig. 7.9. The Christopherson tube for promotion of hydrodynamic lubrication in wire drawing with oils [73].

the yield strength of the wire. On reaching this condition, further increases in speed could be made with little effect on drawing force. A theory enabling predictions of the dimensions required to obtain a specified pressure with a given lubricant was also derived by Christopherson [39], and this will be discussed later.

There are, however, some obvious disadvantages in using oil as the lubricant in this process. Inconveniently long tubes with small wire-tube clearances must be used to develop adequate oil pressures because of the relatively low viscosity of oil. Also, oils will not adequately lubricate the wire on starting and stopping the operation. Under rapid acceleration, the speeds attained prior to reaching full fluid conditions may cause breakdown of fatty oils, while E. P. additives are corrosive and attack the inlet tube. The tube is also prone to considerable wear by cavitation erosion and other means.

Lubrication with Soaps

It was apparent that if these disadvantages could be overcome, the process had great industrial potential. For this reason, investigators at the British Iron and Steel Research Association concentrated their efforts on adapting the process so that dry soap could be used. The modified design of

the die and the performance achieved thereby have been reported by Sturgeon and Tattersall [80] and Wistreich [1, 3, 76]. A drawing of the die configuration finally adopted is shown in Fig. 7.10 Wistreich [76] notes that this die has similarities to "pressure-dies" used industrially, one of which (Fig. 7.11) was discussed by Hedman [81]. The "pressure-dies" have excess soap return passages which prevent a high soap pressure from being reached. The development of these apparently reaches back to 1933; although the original purpose was a design that would assure better cooling, it was

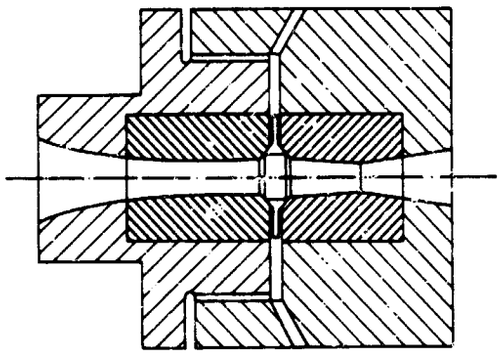

Fig. 7.10. The BISRA nozzle-die unit for promotion of hydrodynamic lubrication in wire drawing with soaps [76].

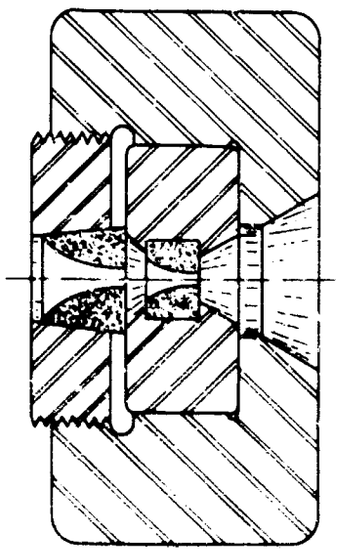

Fig. 7.11. A typical industrial pressure die for promotion of low pressure forced lubrication in wire drawing [81].

inevitable that the die arrangement—effectively a tandem die—should also improve lubrication, even though fluid pressures of only about 1000 psi are achieved.

The BISRA die unit (Fig. 7.10) overcomes most of the problems and objections associated with the Christopherson tube, and is capable of developing 60,000 psi or more pressure. Because of the high viscosity of soap, the unit is only about 2 in. long. Since soap is also an excellent boundary lubricant, problems in starting and stopping are eliminated. Perhaps the greatest asset is that it may be incorporated in a production mill with little or no trouble since soap is a standard industrial lubricant. In extensive industrial trials under the supervision of the BISRA team, die life was improved by 2 to 20 times; the lower figures derived from multi-hole drawing of low and medium carbon steels in which the nozzle die was used in the first draw only, while the greatest improvement in die life was in single-hole drawing of uncoated stainless steel rod.

The trials also showed that the soap throughput was dependent upon the quality and feeding of the soap. Vibration of the soap box gave a significant increase in throughput, but agitation of the soap in the bell of the nozzle with a piece of wire gave even better results. The most important requirement of the soap appeared to be a low rate of viscosity decrease with increasing speed (and hence temperature). Optimum throughput resulted when the initial size of the soap powder particles was between 20 and 40 mesh.

The technique has great potential in industrial dry drawing lines, and is gaining in importance in this direction. Similarly designed dies were also used successfully by Kolmogorov and co-workers [82-84] for the drawing of nickel and nickel-alloy wires and also for the drawing of tubes without a mandrel. Obviously, lubricant throughput is an important factor in this process: if too little lubricant flows through the die, conditions may revert to boundary lubrication with its higher rate of wear; and if the throughput is too great, control over the size of the drawn bar is lost and a "bamboo" surface may be produced with oscillatory fluid film conditions [76].

As noted in Section 7.24, speed generally has the same effect on die-wire separation as viscosity, and a very high speed can be expected to cause full fluid conditions even with conventionally designed dies. Such behavior has been indicated in the work of Parsons et al. [85], who built a draw bench driven by compressed air, which was able to draw bar at impact speeds up to

150 fps. Examination of the surface of aluminum and copper bar drawn on this machine using a fluid lubricant showed numerous pockets, indicating hydrodynamic lubrication conditions.

Theories of Hydrodynamic Lubrication

Optimum throughput of lubricant is dependent upon a combination of drawing speed, lubricant viscosity, tube length, and wire-tube clearance, so that in order to obtain optimum conditions in the operation without undue experimentation, it is necessary to use a theory. In this way, the most suitable values of the interdependent variables can be determined. There are currently three theories available, the first of which was proposed by Christopherson and Naylor [39]. For hydrodynamic lubrication, the lubricant pressure at the die entry must be of the order of the yield strength of the material being drawn. Using this assumption, Christopherson and Naylor's theory allows calculation of suitable tube lengths for given flow rates, or vice versa. The wire is assumed to take up an eccentric position in the tube, according to a minimum drag hypothesis, which generally leads to a solution with eccentricity varying along the length of the tube.

The solution involves numerical integration, but the authors have drawn families of curves [39], which are presented in terms of two parameters, K_p and K_d, defined by:

$$p = \frac{K_p}{\gamma} \qquad \text{and} \quad S = K_d \cdot 2\pi a \cdot \frac{\eta v \ell}{h_0} \tag{7.1}$$

where p = oil pressure;

γ = pressure coefficient of viscosity;

S = total drag per unit length;

a = radius of wire;

η = viscosity of lubricant;

v = velocity of wire;

ℓ = tube length;

h_0 = oil film thickness.

The curves are given for different values of $\bar{q}$, lubricant flow ratio, and are plotted against $\lambda = 6\eta v \ell \gamma / h_0$. Thus the need for elaborate calculations is eliminated. Good agreement was obtained between theoretical and experimental values of pressure buildup in the inlet tube.

The analysis and the method of application of the solution are relatively simple, but the theory is by no means an exact one. For instance, there is little basis for the minimum drag hypothesis which is an essential part of the derivation. Further, the theory assumes isothermal conditions and does not consider deformation in the die, so that all calculated predictions must be considered as only approximate.

The second theory, proposed by Osterle and Dixon [86], deals with the inlet tube and the conical portion of the die separately. Strain hardening of the wire is allowed for, viscosity is assumed to be both temperature and pressure dependent, and both isothermal and adiabatic conditions are considered. The momentum, energy, and continuity equations are solved numerically to find the pressure variation along the length of the tube and the velocity and temperature variation across the lubricant film.

The lubricant is assumed to take on the temperature of the wire, determined by the work of plastic deformation, and the pressure variation in the die is found from plasticity equations by assuming spherical symmetry in the metal deformation zone. Then the Reynolds equation and the condition that the lubricant flow rate is the same at each section lead to a formula predicting the film thickness variation in the die.

While this theory accounts for a number of variables, no supporting evidence was put forward. When applied to Christopherson and Naylor's [39] experiments, discrepancies assume large proportions, and the theory must, therefore, be regarded as unproven.

Tattersall [87-89] has put forward a third theory, in which three separate zones are considered. The first zone is the inlet tube, the second is that portion of the die in which the wire is undeformed, and the third is the region in the die in which the wire deforms plastically. Isothermal conditions are assumed, and viscosity is treated as a function of pressure in the case of oil, and as a function of drawing speed in the case of soap. The Reynolds equation is integrated for the first two zones, then at the section separating zones 2 and 3 the axial pressure gradient is taken as zero and the lubricant pressure as equal to the yield stress of the material. These assumptions lead to an equation for lubricant flow rate in terms of known independent parameters:

$$\sigma_0 = \eta\left[6q\left(-\frac{2\ell}{h^3}+\frac{1}{ah^2}\right)+6v\left(\frac{\ell}{h^2}-\frac{1}{ah}\right)+\frac{3}{2a}\cdot\frac{v^2}{q}\right] \qquad (7.2)$$

where σ_0 = the yield stress of the wire;

η = viscosity of the lubricant;

q = lubricant throughput;

ℓ = length of parallel portion of inlet tube;

h = clearance between wire and tube;

α = die half-angle;

v = velocity of wire.

The results obtained with this theory were compared with Christopherson and Naylor's experimental data, and good agreement in pressure at the die entrance was obtained, but the lubricant flow rate was usually 2 to 3 times greater than that observed. The inaccuracy was attributed to possible eccentricity of the wire in the tube and/or the high shear strain rate which may reduce the lubricant viscosity. Better correspondence between theory and experiment was observed with soap lubricants.

The theory does not consider the actual deformation of the metal or the variation of lubricant film thickness in the die. However, this is the only theory which predicts lubricant flow rate in terms of known independent parameters, and which also gives generally good agreement with experiment. It would be desirable if the theory could include thermal effects and film thickness variations in the die. This appears, at present, the best of the three available theories.

This theory can also be applied to soap as a drawing lubricant. In experiments conducted by Tattersall, the pressure of soap lubricant in the inlet tube was measured while drawing mild steel wire at various speeds up to 80 fpm using several inlet tube lengths and clearances. The soap pressure increased with speed to a maximum before decreasing. Soap throughput varied similarly, but surface finish was generally poorer at high soap pressures, when greater quantities of soap separated the die and the wire.

The apparent viscosity of one of the soaps was calculated by substituting experimental values for pressure and lubricant throughput into the theoretical equations derived for the parallel portion of the inlet tube; a relationship $\eta = \eta_0 \exp(-Bv)$ resulted (Fig. 7.12), where η is viscosity, v is speed, and η_0 and B are constants, η_0 being the apparent viscosity at zero speed. The results from six different nozzles or inlet tube geometries fell on the same curve as shown in Fig. 7.12. Different soaps exhibited widely different behavior (Fig. 7.13). When this viscosity relationship was

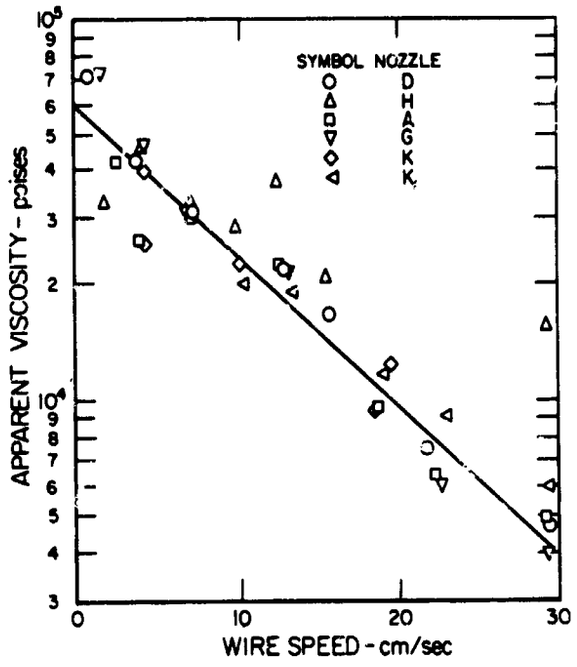

Fig. 7.12. Calculated variation of apparent viscosity with drawing speed [87].

substituted into equations relating to the whole nozzle-die unit, curves agreeing with experimental pressure and throughput data were obtained. Tattersall considered this to be adequate explanation for the existence of maxima and their dependence on nozzle dimensions and soap properties.

Tattersall concluded that the wire speed at which lubricant flow was a maximum was unrelated to nozzle dimensions and depended only on the properties of the soap. In contrast, if oils are used, geometry will be the dominant factor.

This theory has since been employed by Chu [90] to produce design graphs in which the geometrical factors of the nozzle design were correlated with lubricant properties, speed, die angle, and film thickness.

Forced Hydrodynamic Lubrication

The second method of achieving complete separation of die and workpiece by means of a thick lubricant film involves the application of an externally pressurized lubricant to the die-wire interface.

Milliken [79] is credited with first suggesting the basic technique. He envisaged a porous die material through which pressurized lubricant would flow to the working surface. The idea was purely hypothetical, and limited

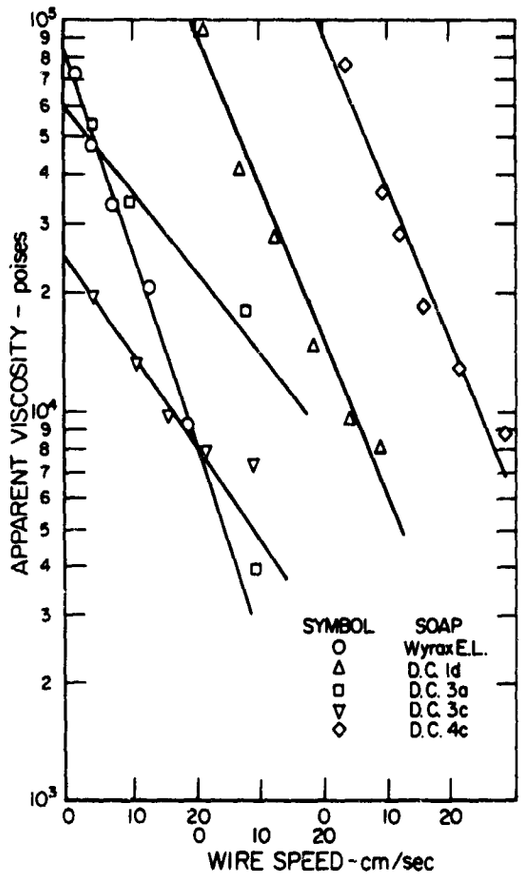

Fig. 7.13. Variation of apparent viscosity with drawing speed for five soaps [87].

by the need to furnish a die material with sufficient porosity to allow passage of lubricant fluid yet with adequate strength to support the pressures involved. A similar idea was proposed by Tourret [91], who suggested pumping lubricant under pressure to the die-wire interface.

Subsequent workers were successful in producing working models of equipment based upon Milliken's ideas, but with the pressurized fluid supplied to the wire ahead of the die. In the technique presented by Butler [92], lubricant is fed to a pressure chamber which has tappings for a pressure gage and for bleed holes (Fig. 7.14). There is a die at each end of the chamber; the first is an ironing die which takes only a very light pass, while the second is the main reduction die. These two dies, which are mounted by means of sealing rings, provide adequate sealing against lubricant loss. Because lubricant is applied under pressure, it is not lubricant viscosity and die design

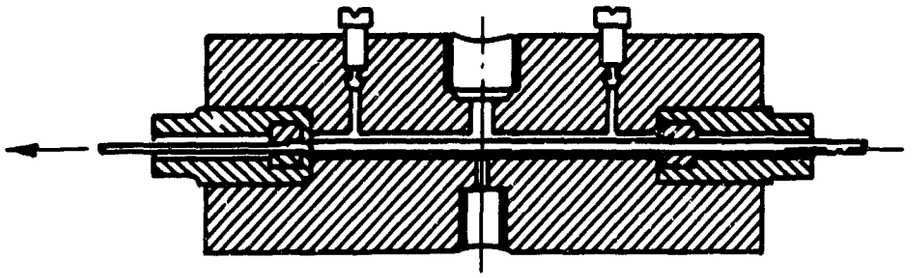

Fig. 7.14. Section of pressure chamber for promotion of thick film lubrication in wire drawing [92].

that primarily determine the pressure of the lubricant at the die-wire interface. In fact, the pressure can be varied to suit the particular conditions required, which is not true of the Christopherson-tube type of arrangement. The other main advantage of this technique is that some degree of ovality of the incoming wire can be eliminated by the ironing die. In pure hydrodynamic drawing, ovality of the incoming wire would cause a substantial variation in lubricant film thickness which might be deleterious to the drawn product.

Butler found some promise in the technique during preliminary experiments on aluminum wire at low speeds, even at pressures as low as 20,000 psi. However, he pointed out several potential disadvantages, too. One of these was also the main criticism of Christopherson's technique—that is, the difficulty of ensuring adequate lubrication in the initial stage of drawing prior to pressurization. This does not, of course, apply to BISRA's nozzle-die unit because soap is used. There is also the possibility of lubricant contamination, resulting in buildup of sludge in the pressure chamber, and it is necessary to provide a high pressure cut-off to act just before the end of the wire enters the ironing die. The cost of installing such units in an industrial drawing mill may be high, and the entire operation would need to be reoriented so that oils and not soaps could be accommodated.

Butler [92] performed some confirmatory shop-floor tests at speeds up to 900 fpm. Using a light oil containing 5% oleic acid as a boundary additive, a reduction of 45% in drawing load was achieved for annealed aluminum with a pressure of 10,000 psi. Since the frictional contribution in most drawing operations is less than 30% of the draw force, some of the observed reduction in force must have been due to deformation of the wire in the pressure chamber, and it is also likely that the lubricant was not of optimum viscosity for the draw.

Other workers have used a similar technique to Butler's, with the aim of eliminating some of the experimental problems and accumulating process data. Moseev and Korostelin [93] and Vasilev [94] developed, apparently independently, a similar apparatus. In their experiments, steel and aluminum were drawn at speeds up to 16 fps with reductions up to 35%. The optimum lubricant pressure for steel was between 57,000 and 64,000 psi; higher pressures caused the wire to break in tension near the entry to the second die. At the optimum pressure levels, the drawing force fell by 18-20% for steel wire and by about 25% for aluminum. The greater drop in force with aluminum was considered to be the effect of reducing a much higher initial friction coefficient. The force would, no doubt, drop less if a better lubricant were used.

Thomson, Hoggart, and Suiter [95] drew copper in a similar die and pressure chamber arrangement, capable of pressures up to 45,000 psi and speeds up to 3000 fpm. They found that there was a substantial initial reduction in pull-force with increasing fluid pressure (Fig. 7.15) corresponding to a pronounced increase in lubricant film thickness. The second drop in pull force, associated with pressures around 25,000 psi, was attributed to deformation of the wire ahead of the second die under the combined action of back-pull (due to the first die) and hydrostatic pressure. Ribbing was sometimes observed when annealed wire was used, giving a bamboo-shaped product. This was assumed to be due to local yielding ahead of the second die, which gave rise to stable necks in the annealed material because of its high initial

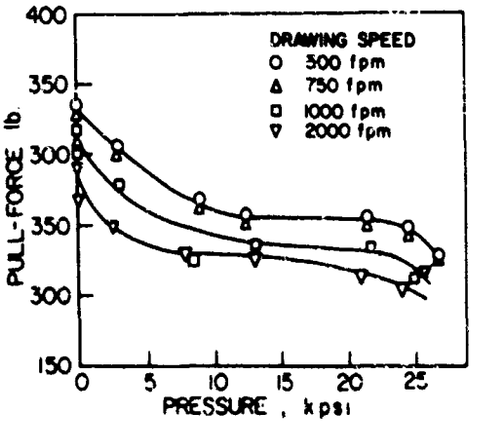

Fig. 7.15. Effect of lubricant pressure on drawing force for hard copper wire [95].

work-hardening rate. With hard wire, however, this condition caused tensile failure under the hydrostatic load.

Thomson et al. [95] found drawing force to be independent of the initial viscosity of the lubricant, in contradiction to Butler's results [92]. This was explained by the low drawing speeds used in Butler's experiments, in which case more nearly isothermal conditions would prevail and initial lubricant viscosity would be of great significance. At high speeds, adiabatic conditions would be approached, and the viscosity of the lubricant at the interface temperatures would be more important. Thomson et al. showed that with increasing temperatures the lubricant viscosities became more similar, which explains the relative insensitivity to viscosities measured at room temperatures. They also noted that the pressure coefficient of viscosity for the oils used in their own and in Butler's work had not been established, and must have had an effect of unknown magnitude.

Thomson et al. [95] did not encounter any buildup of sludge or swarf in the pressure chamber, but only 450 lb of wire was drawn. Neither did some of the other potential draw backs predicted by Butler occur in these experiments. Accordingly, the technique may have potential value as a method for improving lubrication in wire drawing but, unless soap lubrication is objectionable for some reason, it is difficult to foresee exactly where it could compete against the BISRA nozzle-die unit as an industrial tool, since this has on its side simplicity in design, ease of operation, and low installation costs. Currently, the choice of method would be fairly straightforward, since the BISRA unit has been shown to perform efficiently under industrial conditions, whereas the forced lubrication technique is still an experimental process. In a recent review of the suitability of the two processes for use in industry, Juretzek [96] reached a similar conclusion.

In at least one instance, a modified version has found direct application in industry. This particular unit, built for the removal of scale and surface defects from steel bars, incorporates a scalping (shaving) tool ahead of the draw die (Fig. 7.16) rather than an ironing die. As described by Gottschlich and Breyer [97, 98], the bar first passes through the scalping tool which removes the surface material, then into a chamber containing a fluid lubricant under high pressure, and subsequently through a drawing die. In this technique, both scalping and drawing dies are supplied with lubricant, resulting in a significant improvement in surface finish over that observed without

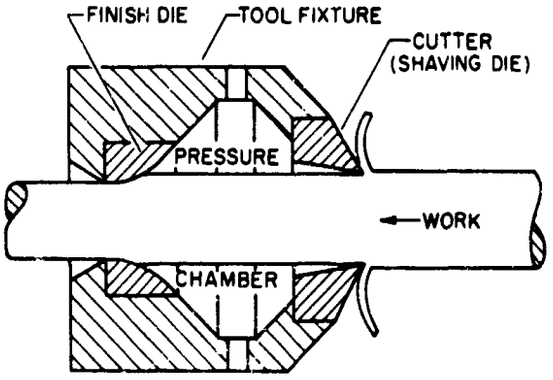

Fig. 7.16. Section of shaving tool using lubricant under pressure [98].

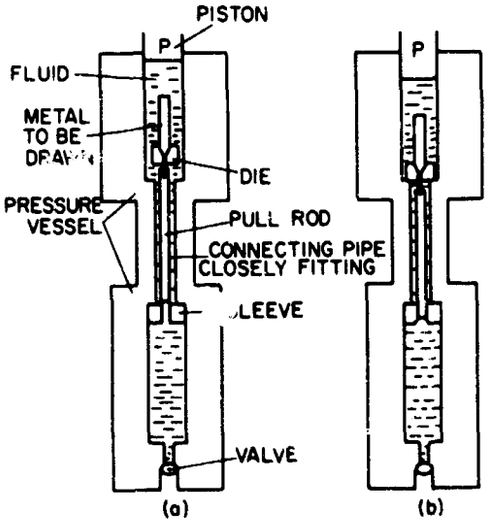

Fig. 7.17. Sketch of apparatus for hydrostatic wire drawing [99].

pressure lubrication. The method is similar to that used in the nonferrous industry, except that forced lubrication is not required there.

Hydrostatic Drawing

The third method of obtaining substantially increased lubricant throughput is by pure hydrostatic drawing. In this process, the increase of lubricant film thickness is a secondary product of an operation primarily designed to allow brittle materials to be drawn by imposing a high enough hydrostatic stress to delay fracture. Bridgman [99] first investigated this process with the apparatus sketched in Fig. 7.17. Holes provided in the die equalize the pressure above and below the die. When the pull rod is in the position shown in Fig. 7.17b, the valve at the bottom of the vessel is opened. The resultant

pressure drop in the fluid below the pull rod causes the wire to be drawn through the die. A similar apparatus was used by Beresnev et al. [100] for the drawing of aluminum wire.

Pugh [101] considers in detail the advantages inherent in deformation processes carried out under hydrostatic pressure: greater reductions may be taken, the residual ductility is increased, and less damage is done to a material by a given deformation since the generation and growth of cracks and voids is inhibited. Greater separation of tool and workpiece should also result because of the high pressure of the fluid surrounding the workpiece. It should be understood, however, that this is not the primary aim of such techniques and, as a result, fluids are frequently suggested which have good high-pressure stability but poor lubricating properties.

The drawback of this type of apparatus is that only short lengths of wire may be drawn. The only difference between the wire drawing apparatus and that of hydrostatic extrusion is that an intermediate chamber has been inserted to ensure that the drawn wire is under the same hydrostatic pressure as the original wire, the benefit being the advantage of drawing into a slightly more pressurized fluid than is otherwise possible, which better prevents surface cracking. In fact, a much more practicable technique for reducing the diameter of ductile wire has been proposed by Pugh [101], using the apparatus shown in Fig. 7.18, in which wire is extruded rather than drawn. A long

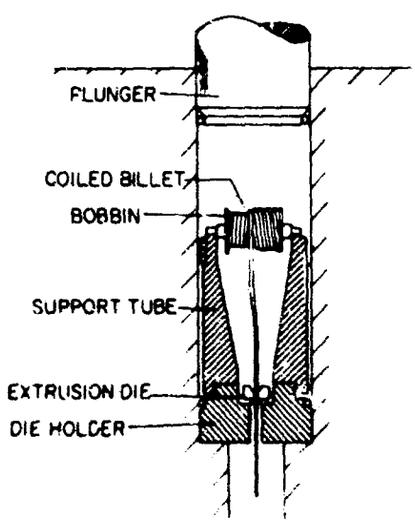

Fig. 7.18. Sketch of apparatus for hydrostatic extrusion of wire [101].

coil can now be processed, since size is not limited by the length of push rod chosen. This method appears to be of much greater industrial interest than the hydrostatic drawing technique, and could find application in the forming of wire from brittle materials, such as α/β brass and magnesium. More recently, various solutions to extruding or drawing with hydrostatic pressure have been proposed that eliminate the need for spooling the rod yet allow semicontinuous operation [102].

In summary, it is apparent that increased lubricant throughput can greatly reduce die wear as well as drawing forces in wire drawing. Of the methods of obtaining this increased throughput it seems that the BISRA nozzle-die unit is practically more advanced than any of the other techniques, with the possible exception of the rather low pressure "pressure-die." Pure hydrostatic drawing is not chiefly concerned with improving lubricating conditions and does not achieve very high drawing speeds, but separation of tool and workpiece is increased. The forced hydrodynamic methods, in which lubricant is supplied under pressure to the die-wire interface, appear to be in the experimental stage.

Thus the nozzle-die unit, based upon Christopherson's original conception, is seemingly the most promising technique. This would be used only for incorporation into a dry-drawing line, where large reductions are sought rather than good surface finish. It is conceivable, however, that the pressure-die could find application in wet drawing where a high quality surface finish is required. With the lower pressures developed, slight increases in fluid throughput could assist considerably in removing swarf or wear debris from the die-wire interface. Thus not only die wear but also surface finish could be improved.

7.28 Ultrasonic Drawing

Ultrasonic vibration applied to the tool in metalworking operations is a fairly new concept. Blaha and Langenecker [103] demonstrated in 1955 in the tensile testing of zinc single crystals that the static load required to cause yielding was reduced when the specimen was vibrated at ultrasonic frequencies (20 kHz or more [104]). Langenecker and co-workers [105, 106] noted that the effect of increasing the energy of the vibrations was equivalent to increasing the temperature of the deforming metal specimen.

Several theories have been advanced to account for the sometimes large load reductions observed, often on the basis of an interaction of dislocations and dislocation-locking mechanisms with the ultrasonic wave [107-109]. However, the most satisfactory explanations of the effect have been proposed by Kristoffy and co-workers [110], Nevill and Brotzen [111], and Winsper and Sansome [112]. These authors observed in their experiments that the reduction in deformation load due to the application of ultrasonic vibrations was equal to or less than the amplitude of the applied oscillatory stress. This is demonstrated in Fig. 7.19, which shows the load-displacement behavior of an aluminum tensile specimen that was subjected to ultrasonic vibration for a short time. Pohlman and Lehfeldt [113] arrived at a similar conclusion in tensile testing of polycrystalline copper. Other work by Rowe [114] with very high frequency and high energy input in the dry drawing of copper at low strain levels showed that any real reduction in yield stress was due to a temperature rise in the workpiece, and that the same reduction could be obtained by means of an induction heater placed ahead of the die. When viewed in this way, the yield stress is not reduced, but one source of energy is replaced by another usually more expensive one. It can be surmised that such techniques would not be used in industry for purposes of load reduction since (a) there is no load reduction due to decrease in yield stress, (b) the cost of equipment might be prohibitive, and (c) there may be a tendency to produce excess debris in the process, which would damage dies very quickly.

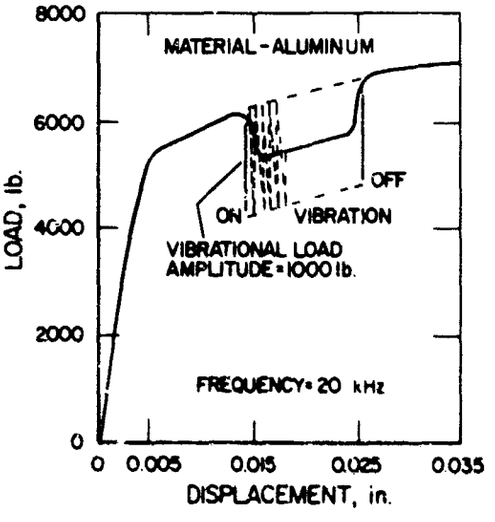

Fig. 7.19. Effect of load amplitude of imposed ultrasonic vibration on the apparent reduction of static load in tensile testing aluminum [110].

The second aspect of ultrasonic deformation is much more important, and real gains in production technology can be foreseen. This concerns a reduction in interface friction between tool and workpiece when the tool is vibrated. Frictional reduction has been observed by a number of investigators not only in simple sliding [115] but also under conditions of plastic deformation. Fridman and Levesque [115] considered that the vibration facilitated the shearing of welded asperities so that friction was reduced, while Balamuth [116] speculated that friction dropped because the real time of tool-workpiece contact was reduced by the vibrations, though the significance of reducing contact time in the presence of a lubricant was not explained.

Winsper and Sansome [112], however, found no significant reduction in friction in their work, because a good commercial wire drawing lubricant was used. Therefore, ultrasonic energy applied to the tools will probably only assist in reducing friction and improving surface finish over the levels now obtained commercially in those instances where good lubrication techniques are not available. Otherwise, the only benefit that can be envisaged will occur when the vibrations aid in generating and maintaining squeeze- or hydrodynamic films. Most evidence of frictional effects, other than that of Winsper and Sansome [112], seems to have been derived from experiments in which very poor, if any, lubricants were used, as will be seen below.

Vibration of Die

Ultrasonic energy applied to wire, rod, and tube drawing has been reviewed by Jones [104] and by Winsper and Sansome [117]. Its aim is the reduction of friction and the improvement in surface finish. When the lubricant film is thick, metal-to-metal contact is eliminated and friction is already very low in dry drawing with soaps so that ultrasonic vibration will have very little application here. Partial boundary contact in wet drawing develops higher friction, and vibration could be of particular value in the drawing of materials that are difficult to form and lubricate, such as the titanium alloys. Nevertheless, most of the work to date has neglected these potentially valuable areas of research since the main concern has been the demonstration of force reduction.

Severdenko and Klubovich [118] drew 0.06 in. diameter copper wire at a speed of only 1.67 fpm with a 36.5% reduction. With longitudinal oscillation of the die at 20 kHz the drawing load was reduced by 50% of that required without oscillation.

Robinson and co-workers [119-121] drew a variety of wire materials of 0.04-0.05 in. diameter including copper, iron, aluminum, and stainless steel to give reductions up to 41%. A similar longitudinal oscillating stress produced reductions of drawing force of up to 50%, though this decreased with increased speed.

Oelschlägel and Weiss [122, 123] drew aluminum, iron, copper, and lead wires, but with the die vibrated in a direction normal to the wire axis. Wires and die were cooled with flowing water. Up to 62% reduction in drawing force was obtained for lead, and 48% or less for other wires.

Boyd and Maropis [124] reported the multipass drawing of tin wire down to 0.025 in. diameter with axially vibrated dies. Their most significant observation was that at a given power input the reduction in drawing force decreased with drawing speed (Fig. 7.20). This is consistent with the explanation that heating is the main effect of the vibrations, since at higher speeds the heat of deformation increases and eventually overshadows the vibrational heating.

Pohlman and Lehfeldt [113] drew copper, aluminum, and steel wires with axial vibration and a vegetable oil lubricant and concluded that ultrasonics

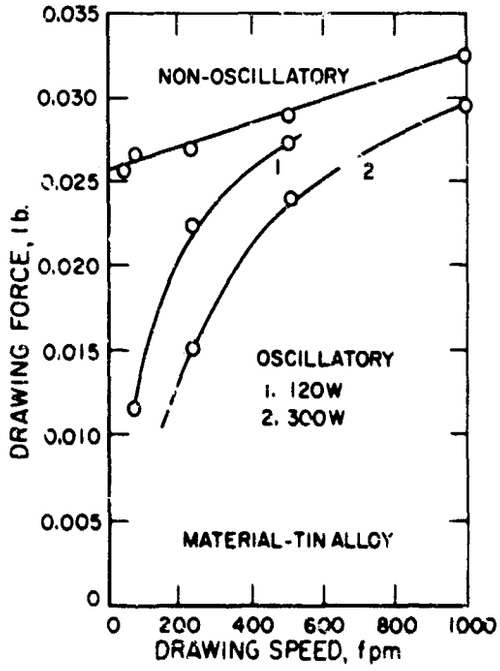

Fig. 7.20. Variation of static pull-force with drawing speed in ultrasonic wire drawing, compared to the force in drawing without ultrasonics [124].

affected the draw force more than it did friction. This was explained by superposition of the alternating acoustic stress, and did not involve a real reduction in yield stress.

In wire drawing, therefore, little seems to have been achieved by vibrating the die. There is scant reference to the drawing of difficult materials like the titanium alloys, and it is doubtful that the claimed reduction in friction with more conventional alloys is meaningful in industrial terms. The lubricant is rarely specified, and in those cases where lubricant composition is given, it is frequently not an industrially recommended material. Moreover, the speeds employed are always less than 400 fpm and are therefore of little practical interest, except for bar drawing. At slow speeds many of these experimental lubricants have poor boundary lubrication properties, so that the lubrication conditions will be greatly inferior to those achieved in industry, and ultrasonics is capable of improving upon such unfavorable conditions. At higher speeds the difference will be less marked because partial fluid film conditions will develop, and the heat of deformation will overshadow vibrational heating effects. Therefore, it is hardly surprising that the effect of ultrasonic vibration is reduced. It is unlikely that similar improvement would result if ultrasonic vibration were employed for drawing wire of commercial materials for which good lubrication practices exist. It is also possible that significant advances will yet be made in the wire drawing of difficult-to-form metals and alloys [125], where galling is a problem in conventional drawing. To date, however, little has been reported in this direction. Another fruitful field may be vibration of dies in bar drawing, because the low speeds discourage thick film lubrication, but here again the cost of large ultrasonic installations must be set against the cost of more complex but successful lubricating systems. Tube drawing may become the most practical area of application, as discussed in Section 7.29.

Agitation of Lubricant

An alternative application of ultrasonic energy was found in the agitation of liquid lubricants. This was successful in the submerged drawing of copper, aluminum, and Nichrome fine wires [126, 127]. In drawing copper wire at 1000 fpm through nine dies, 30% reduction per die was attained compared to 20% conventionally, and the machine was said to be capable of drawing hard Nichrome and pure copper to 0.0007 in. diameter. The chief advantage here is not, of course, any drawing force reduction. The ultrasonic vibration

apparently prevents entry of foreign particles into the die with the wire. Thus, since these particles no longer score the wire as it is drawn, a much better surface finish results. Moreover, since these particles can often cause pickup of wire on the die surface and eventual tensile failure in drawing, much greater ultimate reductions can be taken. Such application of ultrasonic energy in wire drawing may well prove far more significant industrially than vibration of the die.

7.29 Tube Drawing

Seamless tubes are manufactured by several techniques, and the overall economy of the selected manufacturing method is determined by such factors as sizes, tolerances, and strength levels specified, material to be deformed, and quantities required. Rotary piercing and rolling are cheaper than extrusion provided that the volume of tubing produced is high enough; otherwise the capital cost of equipment may be prohibitive. Extrusion is flexible enough to accommodate a wide range of sizes, alloys, and deformations, because die changes are relatively cheap and simple. Therefore, it is usual to find nonferrous materials and special (highly alloyed) steel compositions extruded into tube, since the volume produced is relatively low, while carbon and low alloy steel tube production often involves rotary piercing, rolling, and stretching techniques.

Typical sequences of tube production from billets start with hot rotary piercing between skewed rolls, cones, or disks, with a stationary or rotating plug assuring a sound inner surface. Prevention of wear on these plugs presents one of the most difficult hot-working lubrication problems and is still not solved to full satisfaction. The rough pierced material is sized and elongated in a second mill with skewed rolls or by rolling over a mandrel (plug) between grooved rolls, over a bar in a Pilger mill, or in stretch-reducing mills. Hot-worked tubes are also produced by the Ehrhardt process, which involves pushing the tube on a mandrel through a series of draw rings or roller dies [128, 129]. Tubes from this process are removed from the bar by reeling, which involves lightly cross-rolling the external surface of the tube, causing slight expansion of its diameter.

If the size is less than about 1 1/4 in. diameter and if good surfaces, accurate shape, and close tolerances are required, then cold drawing (or possibly cold reducing on a mandrel) is necessary.

The three basic methods of tube drawing have been discussed in Section 2.31, and are illustrated schematically in Fig. 2.6. Sinking is a process having great similarities to wire drawing in that only the outside diameter is in contact with a metalworking tool; hence similar lubricants and lubrication modes would apply. Obviously, sinking cannot be used where close-tolerance internal surfaces are needed. Mandrel or plug drawing operations involve the use of a fixed mandrel (Fig. 2.6a) or a floating plug (Fig. 2.6e) designed to enable reduction of tube wall thickness. Heavier reductions are possible in drawing on a bar (Fig. 2.6f), which moves at the same exit velocity as the tube, and which is removed in a subsequent reeling operation.

The best quality tubes are produced by drawing on a stationary plug or mandrel, but the most difficult problems of lubrication also occur in these processes. Tubes that cannot be coiled are drawn in straight lengths on draw benches, which use speeds typically around 40 to 400 fpm. Therefore, the tendency to form a partially hydrodynamic film is greatly reduced, even at the outside surface of the tube. Conditions are even more severe at the internal surface; good coverage cannot be guaranteed with drawing pastes or solid soaps, even when applied by dipping, and lubricant breakdown will frequently lead to galling at dry spots.

Liquid lubricants can be applied to the inner surface more easily, but few liquids are efficient enough boundary lubricants to prevent some metal-to-metal contact, and those that are frequently promote corrosive wear of the plug or mandrel (for example, the chlorinated oils). Wear problems are doubled in any event, since ringing wear is evident on the plugs as well as on dies. These difficulties are greatly magnified when less reactive materials, such as stainless steels or titanium alloys, are to be drawn.

In attempts to overcome such problems, special techniques have been employed with varying degrees of success.

Increasing Lubricant Film Thickness

For tube drawing on a bar, a tandem die arrangement, similar to the pressure die shown in Fig. 7.11, has been used industrially since about 1955, according to Rowe [114]. Two dies are used, the first die taking a small sizing reduction and the second taking around 40%, while the region between the dies is enclosed so that the lubricant can build up a high pressure, thus promoting thick film lubrication at the second die. This technique works well at 100 fpm, with the tubes having a dipped coating of sodium soap.

Matsuura [130] has tested an essentially similar method for tube sinking, except that the lubricant is supplied to the region between the two dies under pressure. He also proposed a method for tube drawing with two plugs and a mandrel, and with lubricant supplied under pressure to both the internal surface, through the mandrel, and the external surface (Fig. 7.21). However, no apparatus was built in any work reported to date to prove the value of the technique for plug drawing. Since no lubricant is supplied to the internal surface of the tube at the first plug, the benefits from such a technique are rather doubtful, because the area of lubricant starvation and possible seizure has only been moved back from the secondary plug to the primary plug.

Similar tandem plug arrangements, which allow a natural pressure build-up in the region between the plugs rather than pumping lubricant under pressure, have apparently been tested [114]. Little success was obtained here also, presumably for similar reasons.

It should also be noted that hollow plug bars are sometimes used in practice, with chlorinated oil pumped to the working interface. This does not necessarily promote thick film conditions, but ensures an adequate supply of lubricant.

Application of Ultrasonics to Tube Drawing

Tube drawing has also attracted attention as a process which might benefit by application of ultrasonics.

Boyd and Kartluke [131] experimented in the tube drawing of copper with vibrated die only, and obtained apparent reductions in draw force of up

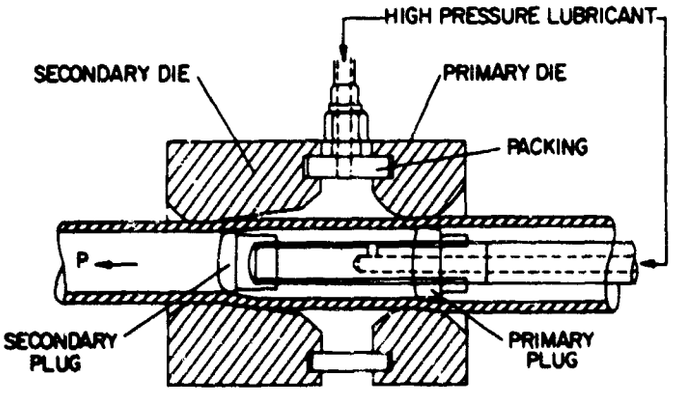

Fig. 7.21. Proposed method for supplying lubricant under pressure to both internal and external tube surfaces in tube drawing [130].

to 68%. Copper is, of course, relatively simple to work plastically, since it rarely presents lubrication problems. Nosal and Rymsha [132] reported 20 to 40% reduction in force when sinking steel tubes with superimposed axial oscillations. This operation is essentially no different from bar drawing, from the mechanical point of view, and is less critical; in tube drawing with a plug or mandrel, the greatest benefits of ultrasonics are likely to be in the reduction of friction at the inner surface of the tube, which is extremely difficult to lubricate adequately.

Mainwaring [133] reported experiments in which the mandrel was vibrated in the drawing of aluminum and stainless steel tubes. As a result, load was reduced up to 58% with aluminum, and—more important—galling was minimized and the inside surface of the tube was of better finish. It should be noted that the claimed force reductions in all the above-mentioned work were based on observations of static load and neglected the stress amplitude of the vibrations, and so do not represent real force reductions.

Tube drawing represents the only process where ultrasonic vibration is used as a production technique mostly for stainless steel and various aluminum and copper alloys [134-136]. This is an area of production where lubrication problems are common, purely because complete coverage of the inner surface cannot be guaranteed by conventional techniques. Ultrasonic vibration of the mandrel has great potential as a method for solving these problems especially for difficult-to-form materials.

However, it is probable that surface finish will suffer if a vibration amplitude is chosen which gives a near-zero interface velocity, thus allowing conditions similar to stick-slip to develop. It seems more likely that a better surface will result when the interface velocity is always positive. Therefore, consideration must be given to the ratio of interface velocity variation to mean interface velocity.

Industrial tube drawing practice does not generally rely upon either of these special techniques to ensure a satisfactory product. Coatings are very important in tube drawing, and the phosphate (for steels), the oxalate (for stainless steels and nickel alloys), and fluoride-phosphate (for titanium and zirconium alloys) chemical conversion coatings used in conjunction with a lubricant or the various plastic coatings represent standard industrial practice for prevention of metal pickup. These will be discussed more fully below.

7.3 LUBRICANT TYPES

Although there is a wide variety of lubricant compositions available, both industrial and experimental, to perform different functions, they can conveniently be divided into four categories. Firstly, the lubricant carriers will be considered. These prevent contact of the die with the material of the drawn bar; they are always solids and frequently porous. Secondly, the soaps will be discussed as one form of solid lubricant; thirdly, graphite and molybdenum disulfide as another. Finally, the drawing pastes and greases, the oils, and the emulsions will be considered together.

7.31 Lubricant Carriers and Wire Coatings

Because of surface extension and the high pressures occuring in the drawing of ferrous alloys, conventional lubricants cannot always be relied upon to prevent metal-to-metal contact; therefore, a solid surface layer is almost invariably employed on steel wire. This layer is known as the lubricant carrier, and its function is not only to prevent metal adhesion to the die, but also to pick up and carry lubricant through the die. This latter requirement is far more important in dry drawing than in wet drawing, since soaps do not readily adhere to the surface of ferrous metals.

A typical dry drawing sequence for heat-treated steel rod involves pickling or mechanical descaling to remove surface oxide due to heating (Section 4.5) followed by washing. Often, it is next sprayed with acidified water to produce a soft, hydrated oxide film known as the sull coat. Subsequently it is immersed in a hot slaked lime suspension and then baked to give a dry lime coat. This coating adequately picks up dry soap powder from the box or tray immediately in front of the die. The soap itself may contain a certain amount of lime added as a pigment or solid filler.

Thus, a distinction must be made between the sull coat—which is a protective coating, having greater importance under more severe conditions where metal-to-metal contact is more likely—and the lime coating—which is a lubricant carrier. While the sull coat is restricted to ferrous materials, other coatings and carriers such as lime, metallic materials (copper, tin, lead), polymer coatings, as well as conversion coatings (e.g., phosphates) may be used on a variety of metals.

In certain instances, it is unnecessary to employ both a protective coating and a carrier. Frequently, lime, borax, or phosphate used with soap

will perform the dual function adequately although, of these, perhaps only the phosphate coating will withstand very high reductions or drawing speeds. When a protective coating is used, it should be evenly distributed and ductile enough to remain continuous throughout the drawing operations. Thus, metal coatings are ideal, but are also expensive and usually more important in wet drawing where they ensure an attractive finish of the drawn product. The newer polymer coatings are also excellent but again expensive, so that their use is limited to the very difficult-to-draw materials such as stainless steel, nickel alloys, and titanium alloys.

Lime Coatings

Lime is probably the most widely used of the lubricant carriers mainly because of its relatively low cost. Part of its duty is in neutralization of any sulfuric acid carried over from the pickling bath, in order to prevent corrosion. However, as Lueg and Treptow [137] point out, the physical as well as the chemical properties are important in determining the effectiveness of the lubricant carrier. Miller [138, 139] notes, for example, that the best suspensions of calcium hydroxide are prepared from quicklime rather than commercial hydrated lime and, in particular, from rotary kiln pebble lime of size between 1/8 to 3/8 in., as opposed to shaft kiln quicklime or lump and pulverized limes. Furthermore, lime with a high calcium content is preferable to lime having high magnesium oxide content, even though magnesium oxide reacts with more acid than calcium oxide and magnesium sulfate is far more soluble than calcium sulfate [137]. The advantage of high-calcium lime is in its physical characteristics.

Both cold and hot baths are used for lime coating, but there are contradicting reports concerning the resulting differences. Cold liming is said [140] to give a quicker and more durable coating, but hot limed wire is also believed [137] to rust more readily because of too rapid drying. Bastian [141] has suggested 60°C as the best operating temperature of a lime bath. In any case, care must be taken to ensure uniform distribution of the lime coat on the wire surface.

Certain guidelines to the liming process can be stated with certainty. For instance, lime adheres better to a rougher wire surface, and the thickness of the lime coating, which is increased in proportion to the number of immersions, should increase with the number of passes planned in subsequent drawing operations. Stalson [142] further states that the coating thickness should increase with the wire diameter.

Whether the wire is sull-coated or not prior to liming is determined by a number of factors. Sulling is recommended [137] if many passes are to be taken or steel dies used. The sull coat can, however, lead to excessive die wear if the coating is uneven.

After sulling and liming, the wire is baked; a sull coat is not necessary [137] if the lime coat is baked for 10 minutes at 180 to 200°C. The combination of sull and lime coat was recognized as a standard treatment for wire drawn for subsequent cold heading [143]. After baking, the wire is drawn using a soap. Bastian [141] considered that low fat, high soap compounds may be used to avoid precipitation of insoluble soaps due to reaction between the lime and the free fat in the soap. The possible reactions between lime and soaps will be discussed further in Section 7.32.

Apparently, there has been some dissatisfaction with the performance of lime [137, 143-146] because of its insolubility, its relatively poor neutralizing action, and its relatively low ability to pick up soap at high speeds. It is said [25, 44] to produce a dust which saturates the atmosphere around the drawbench, creating unpleasant operating conditions, and it also tends to clog filters, pumps, and pipes in subsequent pickling baths. Several alternatives have been proposed, and borax has now found some application in dry drawing mills.

Borax Coatings

Among the advantages of borax over lime are its solubility and its cleanliness [147]. It also requires only one immersion of wire to obtain an adequate coating of borax [137], and the resultant coating is baked more quickly and neutralizes acid carried over from the pickling bath more effectively [143]. Furthermore, borax need not be removed prior to welding since it acts as a flux, whereas limed wire must be cleaned first [137]. Borax-coated wire also gives better results in subsequent galvanizing [146, 147].

The borax coating is obtained by dipping a wire (which may be sulled) into a borax bath, which is composed of various types of borax in water. Borax has the composition $Na_2B_4O_7 \cdot X\,H_2O$, where X can be 5 or, more frequently, 10 [147]. The borax content of the bath is between 5 and 30%, increasing with the coating thickness required [34, 144]. In general, a higher carbon steel requires a thicker coating than mild steel, as does a heavier drawing pass. The bath temperature may be anywhere in the range 80 to 95°C, but the higher the temperature, the better the neutralization of acid on the

wire [144]. The pH of the solution is kept around 9 [144, 147], the usual limits being 8.4 and 10. After dipping coarse bars, air drying is all that is necessary, but wire may retain water and will need to be lightly baked at 105° C. It should be noted that lime always requires baking.

The borax coating is used in conjunction with a lubricant of powdered or dipped soap, paste, or grease [144, 147]. At high speeds hard insoluble soaps based upon calcium stearate are found to give longer die life than the sodium soaps [144], although small quantities of sodium soap are invariably blended in [35, 144, 146]. Calcium soaps are more difficult to remove when the wire is to be galvanized or tinned, and for such applications, dipping in sodium soap may be preferred. Pomp [148] observed that zinc and aluminum stearates are used more frequently with borax coating.

The cost of the borax coating is claimed [137] to be lower than the lime coat, especially if finer sizes of wire are considered, but the opposite point of view has also been put forward [138, 144]. However, lime still finds considerable use in the less rigorous operations, such as relatively low speed drawing of low carbon steels [144], or in small wet drawing machines [35], after an initial dry draft.

Conversion Coatings

The phosphate coating is of a distinctly different type, being acid rather than basic. It thus cannot neutralize the acid carried over from pickling, but will counteract the formation of rust [137]. The application of a phosphate coating and its properties have been described in great detail elsewhere [12, 145, 149-156] and have been discussed also in Section 4.4. Phosphating will therefore be only briefly considered here.

The phosphate coating on steel is obtained by immersing wire that has been properly cleaned in a solution of zinc dihydrogen phosphate and phosphoric acid combined with accelerators which are usually nitrates and chlorates, as described in Section 4.41. The phosphated wire is then neutralized in a dilute borax or lime solution, and soap is applied immediately prior to drawing.

In general, powdered sodium soap, sometimes mixed with about 2% of molybdenum disulfide (in drawing spring wire) is adequate as a dry lubricant for phosphated wire, while a neutral emulsion of drawing grease [12, 152] is found to be a good liquid lubricant.

Continuous phosphating lines [153, 156] do not differ radically, except that immersion times are much reduced, for example, to about 15 sec [153].

The dry soap used in one continuous drawing line [156] contained an undisclosed proportion of lime and was of controlled particle size. This compound allowed lubricant retention for subsequent heading operations, provided that drawing dies had half-angles between 7 1/2° and 9°.

Phosphating finds wide application in the lubrication of steel bar, wire, and particularly tube [157-159]. Similar conversion coatings are important in drawing other materials, for example, a fluoride-phosphate coating is employed in the cold extrusion and drawing of titanium and its alloys [160, 161]. For stainless steel and nickel alloys, the oxalate coating, which again involves chemical conversion of the metal surface (Section 4.42) has found wide application in drawing [11, 153, 162-166]. The major advantages of conversion coatings are improved surface finish of the drawn product caused by reduction of pickup [150, 151] and improved corrosion resistance in storage both before and after drawing [150]. In addition, Machu [167] states that such coatings will withstand up to 25 drafts in either wet or dry wire drawing. For steel, zinc phosphate coating weights of 280 to 650 mg/ft^2 (3 to 7 g/m^2) were said to be sufficient for drawing speeds up to about 3000 fpm and cumulative area reductions up to 95%. This, however, is acknowledged to be an expensive process and can only be justified if carried out as a continuous operation [151, 153, 156].

Waterglass

Silicates have been used experimentally as lime substitutes [41, 145]. Waterglass has been shown to neutralize excess acid, and to give a low-friction protective coating on wire. This coating has been prepared for plant trials [145] by mixing 1 part waterglass with 7 parts water at 70°C and adjusting the SiO_2/Na_2O ratio by addition of caustic soda until the ratio is about 2:1 to ensure sufficient reserve of alkali. This is most important [41] to prevent precipitation of silica, which causes severe damage to the wire surface.

Coating with waterglass can either follow or take the place of coppering. In the shop tests of Goncharov et al. [145] both methods were used, but it was concluded that coppering was not necessary. Waterglass also improved the working conditions in the wire mill by reducing dust contamination of the atmosphere.

Leug and Treptow [41] found that waterglass crystallized in a much more favorable manner than either lime or borax and that it improved lubrication

conditions. Die life and production rates increased slightly. The major disadvantages were that the coating responded poorly to hot dip galvanizing and was unsatisfactory for wet drawing, since the lubricant caused softening of the coating, leading to a buildup of waterglass in the die. There is also a danger of decomposition of the waterglass, generating silica particles, which cause abrasion. This material could, however, be valuable for high-temperature drawing and for refractory metals.

Metal Coatings

Metal coatings are gradually being replaced in many areas of drawing. Most common is the copper coat deposited on steel wire in wet drawing practices. This is applied after pickling when the wire is passed through a bath of copper sulfate, possibly containing 1 to 3% of iron sulfate, and a thin layer of copper is immersion-plated on the wire surface. The coating has excellent resistance to penetration in subsequent drawing with a liquid lubricant. The drawn wire has a bright surface finish which is very attractive. Its color can vary between a copper pink and white, depending upon the bath composition. A yellow shade is obtained on the coppered surface if tin or zinc salts are added, and a bright white surface results if nickel sulfate replaces the copper salt in the pickling bath. Coppering has been discussed by Bonzel [168] and Pomp [148].

Use of the lead coating was once necessary to prevent galling in the drawing of stainless steel, particularly in tube drawing. The residual coating is always undesirable, and must be removed as much as possible. Prior to the development of oxalate coatings and the various resins and varnishes currently employed, lead was the only satisfactory lubricant for stainless tube drawing. It was not unduly expensive since it was relatively easily recovered from the drawn product by acid pickling, and it lasted for several passes. However, it is difficult to remove all traces from the surface of the stainless steel. This presented a serious problem of toxicity in the food industry, which is a major market, and a problem of high neutron absorption in the atomic energy industry. This method of lubrication is now used rarely, if at all.

Plastic Coatings

The coatings which have replaced lead on stainless steel are the oxalate coating used with a more conventional soap or oil-base lubricant, as

described earlier, and various plastic coatings. These plastic coatings and their application procedures are expensive compared to the cost of drawing materials like carbon steel, but constitute a very small part of the cost of the more expensive stainless steel, nickel alloy, or titanium alloy tubes. Moreover, pickup must be avoided in these materials; otherwise they are merely converted into scrap. The tendency for adhesion and pickup increases when the tube is drawn many times—for example, in the production of hypodermic needles in stainless steel—and these plastics, along with the oxalate coating, are very effective in preventing pickup.

In the U. K., methacrylic resins [169, 170] are very widespread for difficult tube-drawing operations. They are usually applied by spraying, or by dipping the tubes into a room-temperature bath containing the resin in an organic solvent, and removed by boiling liquid solvent. In the U. S., the formulations tend to include chlorine; for example, a chlorinated rubber is one of the more frequently used coatings. Application and removal is similar to the methacrylic resin.

Obviously, such plastic coatings must be removed before and reapplied after process anneals; otherwise the plastic would decompose, and carbon would diffuse into the surface of the tube, forming chromium carbides in stainless steel and titanium carbides in titanium alloys. However, a great advantage of the plastics is that pitting, which is evident on removing the oxalate coating from stainless steel (especially from fine tubes), is not a problem in the solvent removal practices.

7.32 Soaps

Boundary layers of soap can be formed in situ by applying fatty acids to reactive metals. However, in wire drawing boundary films are of secondary importance since conditions of mixed boundary and fluid lubrication prevail. Consequently, the viscosity-pressure and viscosity-temperature relationships are more important than melting point and adsorption in determining lubricant effectiveness [171], and in this respect blended soaps are superior to pure stearates [1, 171]. Melting characteristics are important [172] in setting the upper temperature of operation. The upper limit of soap melting temperatures is around 300°C [172, 173], but addition of solid fillers can extend the melting range at least to 350°C [170] while additionally increasing the viscosity. Lime is the most frequently used filler [9, 174].

Most soaps used as wire drawing lubricants are based upon stearates [17, 171, 175-177], and there is evidence that they give better performance than other soaps [41, 174]. Certainly there has been a steady move away from sodium soaps made from vegetable oils and animal fats [9], such as the sodium-tallow soaps. The most commonly used stearates in dry wire drawing are sodium, calcium, and aluminum based [171, 176, 177] while potassium stearates are almost exclusively found in wet drawing [17].

Soap is applied to wire, bar, and tube either by dipping in a bath of soap solution, or by passing the workpiece through a soap box, located immediately in front of the die, which contains solid soap powder. Calcium and aluminum stearates are always used for soap box application, while the water-soluble sodium soap is hygroscopic and rapidly picks up water from the atmosphere, to form large agglomerations unsuitable for dry soaping. Sodium soaps are employed for dipping, which is a convenient sequence to other batch operations such as borax coating of phosphate- and oxalate-dipping. Dipping is the only practicable method when drawing speeds are very low, as for large diameters and for nickel alloys.

However, when dipping is considered for limed wire, attention must be paid to the relationship between the lime and the sodium soap. Papsdorf [31] notes that during drawing with a lime coating, the sodium soap lubricant forced between the die and the lime coating is exposed to high pressures (up to 300,000 psi) and temperatures (150 to 250°C) and is converted to calcium soap, with some iron soap also being formed. Lime is frequently added to the soap to increase its viscosity and melting temperature [17]. Generalized, qualitative criteria for determining the limiting lime: soap ratio and lime coating thickness for various wire and rod sizes have been put forward by Stalson [142]. A lime-soap lubricant combination which may be suitable for drawing coarse wire and rod may be unsatisfactory for fine wire sizes (Fig. 7.22). Kühn [178] also drew attention to chemical reactions between lime, soap, and wire which might account for anomalies in the behavior of some soaps. In particular, the likelihood of soap properties being modified by loosened particles of the lubricant coating was noted—not only viscosity but chemistry may be altered by this means. For example, Lunn [176] reports that a 15% lime-85% soap mixture will deteriorate after drawing steel wire through several holes. The final composition may then include up to 45% solids, consisting of lime from the wire coating and iron and iron oxide from

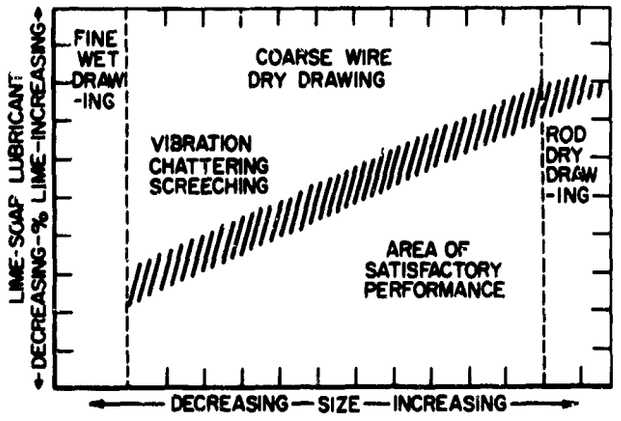

Fig. 7.22. Proposed relationship between drawing performance and lime-soap ratio [142].

the steel surface. Apart from this, it has also been observed that the soap itself undergoes chemical changes [179] due to production of soap components having shorter or longer carbon chain lengths than the original compound. This occurred both in the presence and absence of a lime coating, and this had to be attributed to the effects of pressure.

Lime is usually not employed in drawing nonferrous metals; the soaps of sodium and potassium, often known as the alkali soaps, are much more important because of their solubility.

7.33 Graphite and Molybdenum Disulfide

Graphite and molybdenum disulfide are solid lubricants possessing lamellar structures (Section 4.24) and may frequently be regarded as boundary lubricants, though in some applications they act purely as solid fillers [172]. In wire drawing they may function as lubricant carriers [137], as when graphite-coated wire is drawn through dry soap. Graphite mixed with aluminum powder and added to stearic acid has been recommended for cold drawing [180]. More frequently its high-temperature properties are attractive in those instances where cold working cannot be performed. For example, molybdenum and tungsten are drawn at temperatures between 500 and 700°C [181-183], and a dry film of graphite is almost exclusively used. Other metals drawn at elevated temperatures with graphite include rhodium and iridium [177], and there may be a relatively new field of application developing in the warm drawing of steel [184]. At room temperature, however, graphite is severely limited by problems of removal.

The same considerations largely apply to molybdenum disulfide too. However, whereas graphite will find frequent application at temperatures up to and above 600°C if the exposure time at temperature is short and a suitable carrier is selected, molybdenum disulfide oxidizes at a lower temperature—around 400°C [185, 186]—so that its high-temperature use is limited. Its high-pressure properties are said to be superior to those of graphite, however [187-189], so that in many respects it is attractive in those operations where galling might occur. Some reference is made to molybdenum disulfide in the drawing of stainless steel [190, 191], copper [191], aluminum [192], both high and low carbon steel wire [190-192], and other metals [187, 188], although it is invariably recommended as a solid additive to an oil, a grease, or a soap. The recommended proportions vary between 2 and 5% in soaps or greases, although in special cases up to 40% has been used [187, 191, 193].

Some benefits may also result from applying these layer-lubricants to the plug or mandrel in tube drawing or rolling [194], since here there is often a critical problem in preventing adhesion and die pickup. A serious problem with solid fillers is that aggregation can take place which leads to pockets formed in random areas of the workpiece when an aggregated lump is drawn through.

7.34 Other Lubricants

Many other lubricants have been used in wire drawing, of course, but their compositions are not nearly so easy to group as the soaps and lamellar solids. These can be roughly classified, however, according to the type of operation and the nature of the workpiece material. Wet and dry drawing lubricants will be considered here.

The wet drawing lubricants are expected to provide a boundary lubricant film and, perhaps more important, to extract heat from the die and workpiece. For steels, these lubricants are usually applied to a wire precoated with copper in the case of lacquered or coppered wire [195], or with zinc in the case of galvanized wire, or perhaps with a phosphate for bright wire [195]. These coatings are, of course, added in part to prevent galling of the wire in the dies, but the lubricant is still required to impart high finish to the wire. Thus we find as wet drawing lubricants materials having polar qualities to provide a boundary film on the metal, frequently in a solution or dispersion in water, which provides the necessary heat conductivity.

In this category are found straight soap solutions, of between 1% and 15% by weight soap concentration [15, 16]. These find some application in the drawing of nonferrous fine wire, but usually various alkalis are added to counteract contamination by pickling acid [15]. This lubricant ensures cleanliness of the drawing machines, but is apparently uneconomical [6].

Soluble oils or, more exactly, emulsified mineral oils are used extensively in the drawing of nonferrous fine wire, including bronzes and nickel-chromium alloys, and of metal-coated mild steels [74]. Concentrations range from 2 to 10% by volume [14, 16], and usually additions of boundary and extreme pressure agents are made.

Other emulsions are made from fats or fatty oils dispersed with soap or other emulsifiers. These dilute soap-fat compounds constitute a major type of wet drawing lubricant [14], being used for steels, copper and its alloys, and even stainless steels. Pomp [148] has given a method of preparing a lubricant of this type for the drawing of fine steel wire on continuous drawing machines. Concentrations of 6 to 8% in water are used for medium wire sizes, and 2 to 3% for finer wire. The temperature should not exceed 60°C, or breakdown of the fats can occur [14, 196].

Besides these emulsions which contain a high proportion of water, oils find wide application as wet drawing lubricants. Straight petroleum-base oils are seldom satisfactory and fats or fatty acids, as well as extreme pressure compounds containing sulfur and chlorine, are usually added [14, 15, 177]. These oils are used in the drawing of aluminum and its alloys, for stainless steel wire [16], nickel-chromium steel, and Monel [7], and can contain up to 10% of fats or fatty oils. More reactive oils are used for the more difficult materials. For example, stainless steel tube drawing often requires an oil containing up to 50% chlorine.

In dry drawing, there are three main alternative lubricant types to soap. These are the petroleum greases, the soap-fat paste compounds, and natural tallows. However, soap-fat compounds are diluted with water for use in wet drawing operations, as mentioned above.

A petroleum grease is a mineral oil that has been gelled by addition of soap [17] (Section 4.25), and as a result some of its lubricating ability is lost. Thus it produces a much brighter finish on the drawn bar [175]. Pomp [148] has given a method of preparing this in the drawing shop, but notes that more consistent properties are obtained in ready-made proprietary

greases. Greases have been developed with high concentrations of sulfur and chlorine in order to extend die life, and are used in the drawing of extra clean and bright wire. The grease may also be pigmented with a solid filler such as lime.

The principal application of soap-fat pastes is in wet drawing as emulsions in water, but in the undiluted state they are employed as dry drawing lubricants for extra clean and bright steel wire when the finish from petroleum greases is not acceptable. Other possible applications are for copper and brass rod [84] and in tube drawing [15], where solid fillers may be added.

Tallow is an animal fat (e.g., beef or mutton tallow), and finds substantial use in the drawing of heavy bars.

This concludes the listing of the various lubricant types. In the remaining sections of this chapter the individual metals and alloys will be considered with respect to the lubricants investigated experimentally and employed commercially.

7.4 LUBRICATION OF FERROUS MATERIALS

7.41 Carbon and Low Alloy Steel

Carbon and alloy steel wire is produced from coiled, hot-rolled rods mostly in the as-rolled condition, sometimes also after heat treatment. Hot extrusion is employed very infrequently, and then only for special alloy steels, as the technique of making steel bar and rod stock for wire drawing since the volume of steel wire production is usually high enough to warrant the more expensive but higher productivity rod rolling equipment.

In drawing terminology, the rod or the bar is the product from the primary working process, whether it be rolling or extrusion. The smallest size of hot-rolled rod commonly made is 7/32 in. diameter, although some new mills roll to 1/8 in. The difference between rod and bar is considered to be in the greater accuracy of cross section of rod stock. Wire, of course, is drawn rod or bar.

Experimental Investigations

The ferrous alloys represent by far the largest commercial output of drawn wire. It is not surprising, therefore, that most of the research in wire drawing has been conducted on steels and that the understanding of

lubricating mechanisms in steel drawing has progressed rapidly. Of all published work, two major research efforts are particularly noteworthy: the first was performed in Germany at the Max Planck Institut in Düsseldorf, the second in England at the British Iron and Steel Research Association. The BISRA work culminated in the development of the nozzle-die unit for the provision of a thick lubricant film as discussed in Section 7.27, whereas the German research sought an understanding of the action of lubricants and lubricant carriers in wire drawing.

Lueg and Treptow [137] examined lubricant carriers for carbon steels, and it appeared that borax could be more economical than lime for finer sizes of wire. They also studied various other lubricant carriers in the drawing of medium carbon steel wire at 100 fpm, and found that lime/graphite and lime/MoS_2 performed almost as well as the conventional lime/soap pair, while an alkali/soap pair was better, as assessed by the number of passes possible before annealing and by the friction. The composition of this alkaline carrier was not described in detail.

Figure 7.5 shows the influence of both lubricant carrier and lubricant coating on the coefficient of friction in the drawing of 0.53% carbon steel [51]. There are obvious differences in ability to reduce the friction in drawing, but it is interesting to note that the best conditions were obtained when soap was added to lime.

Further work [41] showed that the type of lime employed had a direct bearing on the lubricating qualities of the carrier; performance deteriorated as oxide impurities and carbon dioxide content increased. Silicates were found to be successful carriers if the reserve of alkali was sufficient to prevent precipitation of silica, which is an abrasive. Lueg and Treptow [41] also found that with soaps as drawing lubricants the magnitude of the drawing stress decreased as the chain length of the fatty acid increased.

Lueg and Treptow [162] have observed the forces obtained in drawing both carbon and stainless steels with a variety of oils, greases, and soaps, and concluded that the higher the saponifiable fraction of an oil-base lubricant (i.e., the fatty acid and ester content), the lower the drawing force. They also found that the addition of extreme pressure agents such as sulfur was necessary since repeated draws imposed requirements of longer lubricant film and die life. In general, oils did not exhibit the same ability to minimize drawing load as did soaps [12].

Dahl and Lueg [12] compared the behavior of phosphate and lime coatings in the drawing of 0.60% carbon steel wire, using a commercial drawing soap as a lubricant. None of the phosphate coatings investigated surpassed the performance of lime coats. Similarly, additions of molybdenum disulfide failed to improve the lubricating qualities of either oil or soap used as a lubricant on limed wire.

In general, the German research described here and in Section 7.3 has provided some guidelines for the selection of lubricants and carriers for carbon and alloy steel wire. However, much work on phosphate coatings has been done elsewhere. For example, Goncharov et al. [145] found very great benefits in the wet drawing of fine steel wire (down to 0.010 in.) at 1840 fpm after phosphating, liming, and dry drawing. Komura [197, 198] examined the behavior of the phosphate coating during wire drawing by means of autoradiography, using the isotope P_{32} in the phosphate bath. Thinning of the phosphate film was not a linear function of reduction in area, as would be expected, but was very much dependent upon the drawing speed and the efficiency of the lubricant. The more efficient the lubricant, the more uniform the thinning of the carrier. The benefits of phosphate coating were also demonstrated in the experiments of Hantos et al. [199]. Mild steel tubes were drawn under industrial conditions with a mineral oil-fatty oil emulsion as lubricant. The total draw force and the mandrel force were much the same with both phosphated and limed tube blanks: however, drawing speeds and total reduction prior to annealing were higher, and bare and hard-chrome-plated tool-steel dies and mandrels could be equally well used with the phosphated tubes. In contrast, drawing of limed tubes at 16-30% reduction per pass was possible only with chrome-plated mandrels. Lubricants of higher viscosity—including a mineral oil, a drawing paste, a soap-aluminum powder mixture, and graphite (applied to the inner surface)—reduced drawing forces on phosphated tubes by not more than 10%, suggesting that the presence of the phosphate coating exerted an overriding influence at the low (6-45 fpm) drawing speeds.

Many other experimental investigations of lubricants for the drawing of steel have been reported (for example, refs. 27, 184, 200-205). In general, soaps have been found to be the most efficient drawing compounds for wire, and this is reflected by their very extensive use in industry.

Industrial Observations

Numerous lubricants have been recommended for drawing steel bar, wire, and tube. The lubricant carriers for steels have been discussed in Section 7.31, and include lime, borax, and silicate coatings, while the sull coating, metallic layers, and the phosphate coating are useful also in preventing metal-to-metal contact. The sull coat, followed by lime, is the traditional method of preparation of high-carbon steel wire prior to drawing.

When lime is unacceptable for some reason, the borax coating finds application. Lime is generally used only for low-speed drawing, while borax is employed for more severe operations. Electrodeposited copper, followed by application of lime or other carrier after plating, is acceptable when the wire will be cold headed after drawing [206], since it can withstand severe operations. Copper is also widely employed in wet drawing; the "coppered finish" of steel wire is very attractive; therefore, market demands for this finish also predetermine that copper will be used to prevent metal-to-metal contact. Similarly, if galvanized or tinned wire is required, the zinc or tin coating alone will be employed as a lubricant carrier.

The phosphate coating is more expensive than many of its competitors, and is economical only when used in continuous lines, as discussed in Section 7.31. Phosphate coatings find considerable application when wire will subsequently be cold headed, and phosphating can be regarded as standard practice in the cold drawing of tubes [207, 208].

The silicates, discussed in Section 7.31, are less widely accepted as lubricant carriers, and it is not known whether they are employed in industry.

In dry drawing, the carriers are most frequently coupled with dry soap as a lubricant. The guidelines for using soap have been discussed earlier in Section 7.32. With reactive substances such as lime, care must be taken to ensure that no unfavorable reactions take place between soap and carrier prior to or during drawing.

In the drawing of steel, sodium and calcium stearates form the basis for the majority of industrial lubricants. As noted earlier, calcium-base soaps are applied as dry powder from a soap box immediately ahead of the die, while the soluble sodium soaps are generally employed for dipping of wire, bar, or tube, which is subsequently dried. The insoluble calcium soap is of a much harder consistency than sodium soap, and has been more widely introduced as drawing operations became more severe [9]. For drawing mild

steel, calcium soaps are not recommended [175], unless the wire has previously been descaled. Otherwise, there may be difficulties in ensuring adequate pickup of dry calcium soap at the very high drawing speeds encountered, besides the obvious problem of die damage due to the presence of scale. Aluminum stearate has been recommended [177] for drawing steel wire which subsequently will be cold headed.

Blended calcium soaps are very important for drawing high-carbon steel wire [9, 175]. These frequently contain sodium soaps and solid fillers such as lime or chalk; the fillers improve the high-temperature performance, while the low-temperature properties deteriorate [142]. Greater solid contents are said to be required for mechanically descaled bar [176], and approximate compositions of calcium stearate with 25% lime are quoted. Frost [171] mentioned that higher lime: soap ratios are used for drawing coarse wire than for fine wire and gave values of 4:1 lime: soap for rod and 1:4 for very fine wire.

Soaps ensure a greater average film thickness in the die than liquid lubricants and, as a result, provide less intimate contact of die and wire. The surface condition of the wire may be relatively poor due to the presence of hydrodynamic pockets or to the occurrence of "free" surface deformation (orange-peel effect). Should such surface be unacceptable, greases or soap-fat drawing pastes are employed [148, 177]. Greases, or tallows, are often used in the drawing of large-diameter bars. These are sometimes pigmented, containing 15 to 20% of solids [209] such as lime, talc, mica, graphite or molybdenum disulfide. Soaps also frequently contain such fillers, and for high-carbon steel free sulfur is sometimes included [5, 182] to provide both mechanical separation and E.P. action in case thinning of the lubricant film occurs.

In wet drawing, finer wires are involved, the surfaces of which sometimes have residual coats of lime, phosphate, etc., from the dry drawing operation. This can be removed if a special finish is required—for example, a galvanized or coppered wire—or more usually it serves to prevent metal-to-metal contact in drawing with a liquid lubricant. Alternatively, rods are bright-drawn in a grease and then finished by wet drawing [148]. Here the grease must be removed prior to wet drawing, for example, by pickling in a bath which also imparts a copper coat to the wire. The practice of drawing wet directly from the rod is seldom followed now.

Soap-fat emulsions are common wet lubricants for steel. Salz [177] gives typical constitutents and concentration ranges as follows:

Soap	10-65%	(e.g., potassium stearate)
Fats or fatty oils	5-50%	tallow
Unsaponifiable oil	0-15%	mineral oil
Fatty acid	0.5-3.0%	stearic acid
Diluent	25-40%	water

For carbon steel wire Salz recommends a 1/2 to 3% solution of low soap-high fat emulsion in water. Excess lime on the wire or its reaction products with the free fats and fatty acids would, however, clog the recirculating system of the wire drawing machine [43]. Bauzenberger [5] considers high fat-low soap emulsions to be more frequently employed in drawing the coarser sizes of fine wire (from 0.050 to 0.020 in. diameter), while low fat-high soap compositions are more suitable for finer sizes.

Straight alkali soap solutions are recommended [5] for very fine wire ($\approx$0.009 in.), but these will also deposit insoluble soaps in the presence of lime, and are easily contaminated. Water-emulsified oils (soluble oils) are alternatives for fine wire drawing, in place of soap solutions or soap-fat emulsions.

Oil-base lubricants are recommended by Salz [177] for the wet drawing of alloy steels. Viscosities between 100 and 300 SUS at 100° F are given for oils compounded with sulfur and chlorine extreme pressure additives as well as fats. Bauzenberger [5], however, notes that oils with viscosities as high as 3000 SUS at 100° F may be used in slow-speed drawing of heavy gage carbon steel when a bright finish is required.

7.42 Stainless Steel

Experimental Investigations

Stainless steel poses some problems in metalworking operations because of its high strength, rapid work-hardening rate, and high adhesion to die surfaces, which can readily lead to galling. The most obvious solution to these problems is to provide a continuous film of soft ductile material which will prevent metal-to-metal contact. However, stainless steel is frequently required to have a bright surface. Drawing with tenacious, highly viscous or solid lubricant films and their subsequent removal can cause undesirable surface deformation. Two of the chief requirements of lubricants then are ease

of removal and ability to provide good surface finish. Consequently, there has been much research into lubricants, lubricant carriers, and coatings for stainless steel.

Lueg and Pomp [210] investigated the drawing of a low alloy steel, a high-speed steel, and an 18-8 stainless steel using lime alone and lime with common salt as lubricant carriers. A dry soap and a commercial drawing grease, to which oil had been added, were the lubricants, and the specimens were given between three and eight drafts without annealing to reduce bars of initially 0.197 in. diameter by various amounts. At speeds of 82 to 213 fpm, lime with salt proved to be the better lubricant carrier, while soap was the best lubricant. As a combination, these allowed eight drafts to a total of 88.4% reduction without process anneal, and without surface scoring of the wire until the eighth draft.

Kuntze and Pomp [11] investigated the effectiveness of an oxide film produced by treatment in an oxidizing saline melt, as well as the more conventional oxalate and lime-salt coatings. These were evaluated in the drawing of stainless steel wire through steel dies to a reduction of about 85% in six drafts using calcium stearate as a lubricant. The effectiveness of the coatings was determined by the evaluation of die wear, drawing forces, friction coefficient, and surface appearance of the drawn wire. The oxide coat was the poorest carrier tested, while the lime-salt coat was the best, in agreement with Lueg and Pomp's results [210], as well as the cheapest. However, they point out that a lime-salt coat of sufficiently even thickness and uniform adherence is difficult to form; this may lead to gage variations and the necessity of replenishing the coating after only a few drafts. Moreover, removal is difficult, and the coating can cause pitting of the wire surface since there is a possibility of chlorine being formed. Therefore, oxalate coatings were judged to be the best since they gave an even layer and did not impair the surface quality of the wire. The higher cost of providing an oxalate coat is, however, a disadvantage.

Lueg and Treptow [162] pointed out that the effectiveness of any coating will be dependent upon the lubricant used: in their work the oxalate coating was unsatisfactory with the two oils employed, whereas the oxalate coating with calcium stearate as the lubricant was excellent in the work of Kuntze and Pomp [11]. Better results were obtained with a coating which was described as an unspecified organic binder with ferric hydroxide. Another significant difference in technique was that Lueg and Treptow's [162] dies were of tungsten carbide, while Kuntze and Pomp [11] relied upon steel dies.

Buch and co-workers [165] obtained favorable results in drawing stainless steel tubes with both oxalates and chloroparaffins. A chlorinated paraffin containing 40% chlorine was the most effective lubricant tested in the work of Halas [211] on drawing stainless steel tubes, while Duplii et al. [212] found soap containing finely crushed free sulfur an effective lubricant for stainless steel tubes. Lancaster and Rowe [26] indicated that methacrylic resins have been successful in preventing metal-to-metal contact, and these are currently in industrial use.

Solid fluorocarbon polymers applied in various concentrations as dispersions in oil, kerosene, toluene, water, and a proprietary solvent, were employed in drawing stainless steel wire by Gerds and Ogle [213]. Some of the lubricants contained molybdenum disulfide also. They were applied by drawing wire through the liquid dispersions, by dipping and air drying to form a solid coating, or by dipping, air drying, and heating to melt the polymer on the wires. A suspension of fluorocarbon polymer with MoS_2 in the commercial solvent was as effective as commercial chlorinated wax, as judged by the drawing load.

It will be noted that there is little published experimental work on the use of plastic coatings in drawing stainless steel. This is surprising since such coatings are widely employed in tube drawing, and it must be surmised that research efforts have been industrially sponsored, and are regarded as commercially confidential.

Graphite [183] and molybdenum disulfide [190] have both been mentioned as possible lubricants for stainless steel, but once again removal problems present the greatest drawback to their industrial use. Some form of carrier is required for these solid lubricants.

Industrial Observations

Recommended lubricants for drawing stainless steel in industry have been listed in references 34, 43, 166, 177, 206, 207, 209, and 214-216. Lead coatings are frequently mentioned, not only for tube drawing [43, 207] but also for wires [34], but can now be regarded as obsolete because of the toxicity of lead, along with the difficulty of complete removal from the surface of stainless steel. Its place is now taken by coatings and carriers which are easier to remove or which need not be removed. Alternatively, improved lubrication obviates the necessity for a carrier in some instances.

The oxalate coating has found wide application, particularly in the more severe operations such as mandrel drawing [166, 206, 215], where it can be regarded as standard tube drawing practice. The most attractive feature of this coating, besides its efficiency in preventing metal-to-metal contact when used in conjunction with soap, is its relative ease of removal. Alkali cleaning removes residual lubricant, while an acid dip will remove the oxalate [163]. Alternatively, a hot caustic wash has been proposed for oxalate removal [217]. Neither method will cause such severe pitting as is evident after the removal of lead, for which the tubes must be immersed in a nitric acid solution for several hours [163]. Material drawn with an oxalate coating is therefore characterized by better surface finish. However, it should be noted that the oxalate coat begins to lose its effectiveness if stored for longer than three weeks [217]. Apparently, oxalate is affected by any increase in temperature to a far greater extent than phosphate coatings [153], and thus drawing speeds are severely limited. Oxalate coatings have been used in some German wire mills on multihole machines, but the finishing speed employed is less than 200 fpm.

Some pitting still occurs when oxalate is removed, and this can cause considerable problems in the drawing of fine tubes. The chief competitors to the oxalate coating are plastic films, which can be removed with organic solvents without any pitting. Hydrodynamic pockets might form on the drawn product surface if the plastic film is too thick on the original stock, but the problems should be minor if the coating is applied evenly by spraying or dipping and if it is no thicker than required for the proposed number of drafts. These plastics are frequently used in conjunction with a chlorinated oil [214] for drawing all sizes of tubes and for rod and bar drawing.

Among the older methods which have now largely been replaced for bar and tube drawing are electroplated copper coatings [213] and a coating of lithopone-shellac described by Bastian [43]. Lime and borax coatings have also been suggested [206, 215], especially in conjunction with metal stearates containing molybdenum disulfide [215]. Water-soluble, heavily pigmented drawing pastes which can be applied by dipping also find some application with lime coats [43, 209].

In wet drawing, heavily chlorinated waxes and oils—usually containing about 40% chlorine—can adequately prevent pickup in many instances without coatings or carriers. These can be used for large wire sizes. In wet

drawing of fine wire, less active lubricants may apparently be used. Salz [177] suggests a compounded oil containing sulfur, chlorine, and fat, of a viscosity of 100 to 300 SUS at 100°F, while Stock [218] notes that there is a trend away from emulsions of vegetable soaps towards mineral oils with E. P. additives. Dahl [166], however, considers that soap solutions and oil emulsions are suitable for all sizes of wire below 0.05 in. diameter.

7.5 LUBRICATION OF ALUMINUM AND ITS ALLOYS

Aluminum poses relatively few lubrication problems in wire drawing and, in consequence, negligible research has been devoted to finding lubricants for aluminum drawing. The material has low strength and is, therefore, extremely susceptible to changes in drawing speed or lubricant viscosity [219]; by increasing either of these parameters, the draw force can be reduced. The standard lubricants are somewhat similar to those used in rolling (Section 6.52), and are chiefly compounded mineral oils. Adequate prevention of pickup can be ensured by careful control of viscosity and drawing speed, and by provision of suitable boundary or extreme pressure additives in the base oil. Compounded oils have been widely recommended for aluminum and its alloys in the literature [14, 34, 43, 68, 177, 215, 220-222].

The concentrations of boundary and E. P. agents in the base mineral oil vary according to different authors. Morton [14] suggests that 7 to 10% fats, fatty oils, or sulfur and chlorine additives are common, while Salz [177] gives 10 to 30% and Bastian [43] 10 to 25% as the normal range. Obviously, industrial practices vary locally, but compounded oils are certainly used more frequently than straight mineral oils because die life is extended and die pickup avoided.

Wide variations in recommended viscosity are found. Heavier oils with viscosities between 1000 and 2500 SUS at 100°F are given [15, 43, 177] for rod sizes, and 100 to 200 SUS for fine wire drawn at high speeds (around 3000 fpm). Perry [34] gives slightly lower oil viscosities of 250 to 450 Redwood 1 seconds at 140° F for rod and 40 to 90 Redwood 1 seconds for fine wire. Nicol [222] notes that two miscible oils having viscosities of 55 and 600 Redwood 1 seconds can be employed, so that the whole range of aluminum rod and wire sizes can be drawn with suitable mixtures of these two oils. The oils can also be used neat: one for high-speed drawing of fine wire, and the other for comparatively slow-speed tube drawing. Such practice is, however, rather

questionable because the presence of even small quantities of the heavier oil could cause excessive staining on annealing. On the whole, narrow cut mineral fractions of the appropriate viscosity should be by far preferable.

As in rolling, aluminum debris accumulates in the lubricant after drawing. According to Cleaver and Miller [68], these are particles of alumina, which at best can function as inert fillers. On the other hand, the abrasion of die materials by alumina particles is more important.

Oil-base lubricants find far more application in wet drawing than water-soluble oils (emulsions) because of the problem of water staining and even corrosion of aluminum, the latter occurring when the pH of the lubricant is above 8.5 [177]. Conventional soluble oils and soap solutions also have the disadvantage that they cause rusting of the equipment and high maintenance cost [223], and they frequently fail to provide adequate protection against pickup. They are sometimes used in fine wire drawing through diamond dies [34].

For dry drawing of bar and rod, dry soaps, greases, or other lubricants can frequently be found when aluminum is drawn on a small scale [34] —for example, in a steel drawing mill—and special lubricants for aluminum are not provided. Such practice should, however, be discouraged because ferrous fines left in the system will be pressed into the aluminum surface and cause pitting corrosion.

Cockcroft [215] states that high-purity soaps are used for bar and tube sizes, often applied by dipping in a hot aqueous solution and allowing the soap to dry. Salz [177] and Wickwire [224] have recommended dry soaps based upon aluminum stearate, which may even be mixed with grease [224] to ensure pickup onto the bar surface. The main disadvantages of dry soaps are that they prevent any smoothing of the surface and that residual films cause discoloration on subsequent annealing [225].

The same can be said of greases, although the consistency of a grease can be varied to the near-liquid state, so that surface polishing will occur. Greases are employed extensively in low-speed machines not equipped with wet lubrication systems [225]. Werner [226] has noted that an undisclosed type of wax dispersion in oil can be used for drawing rod from 3/8 in. diameter to fine wire. The problem of staining is claimed to be overcome since some waxes may volatilize without leaving a carbonaceous residue.

For tube drawing, once again heavy compounded oils have been recommended [201, 206, 207, 209]. Perry [207] has indicated that oils with viscosities of up to 1000 Redwood 1 seconds at 212° F could be required for drawing very large tubes. Alternatively, a dry film of soap or wax [207, 215] has been used.

Perry [207] comments that none of the current lubricants for aluminum tube is entirely satisfactory, although some new lubricants and techniques have been proposed; for example, Gerds and Ogle [213] find solid fluorocarbon materials very successful in wire drawing aluminum, but it should be noted that these are far too expensive for consideration.

Significant improvement in fine wire drawing technique has been achieved by Olsen et al. [126], who applied ultrasonic energy to the liquid lubricant in submerged drawing. It was claimed that by this means aluminum could be drawn to much finer sizes of wire; for instance, very high purity aluminum (99.99%) could be drawn from 0.005 in. to 0.0027 in. through 11 dies taking a 12% average reduction in each die, at speeds between 100 and 150 fpm.

7.6 LUBRICATION OF COPPER AND ITS ALLOYS

7.61 Experimental Investigations

After steel, copper has been used most frequently in wire drawing research, mainly because it is fairly easy to draw experimentally and hence presents few problems to the experimentalist, whose main interest might be correlation of draw force with a drawing theory. Much of this work is conducted at speeds less than 5 fpm [103, 105].

These low speeds are not representative of commercial wire drawing, of course, but frequently it is not the aim of the experiments to do this. Barnes and Cafcas [205] and McFarlane and Wilson [227], for example, were testing the validity of simulation techniques. Barnes and Cafcas found good correlation between a very slow speed wire drawing test and rolling mill trials with brass, using soluble oils as lubricants. This conflicts with the results discussed in Section 5.28 showing that rolling performance could not be predicted by drawing. McFarlane and Wilson found good correlation between a friction test with a hemispherical slider on a disk and tube drawing as far as lubricant performance was concerned. However, drawing was performed with conventional tool materials, while in the sliding test copper

against copper was examined. This was said to compare with a layer of copper deposited on the tools early in the operation, but obviously a true correlation cannot be given unless the simulating test employs materials corresponding to those in drawing.

Lancaster and Rowe [27] used a plane-strain drawing technique with steel dies of circular profile. Copper strips were first indented by the dies, using normal loads of 2 or 1000 kg, corresponding to elastic deformation and bulk plastic flow, respectively, and drawn at speeds up to 6 ipm with soap or oleic acid as lubricant. Soap ensured a lower friction coefficient than oleic acid at both levels of normal load, since it was able to maintain a thick film while oleic acid gave boundary lubrication.

Olsen et al. [126] dealt with a process having more direct application to industry. They applied ultrasonic energy to liquid lubricants in the submerged drawing of fine copper and copper-beryllium wire. This prevented the accumulation of debris in the die and enabled them to draw OFHC copper from 0.015 to 0.0028 in. diameter at 1000 fpm using an average reduction of 30% per pass through nine dies. Further reduction down to 0.0007 in. diameter could be accomplished at a speed of 50 fpm. This technique, if reproducible, represents a significant advance in fine wire drawing technology, where the greatest problems are in preventing fine slivers of copper and other debris from entering the die and causing tensile failure.

7.62 Industrial Observations

Almost all copper and brass wire is drawn with a liquid lubricant, but dry lubricants may be used for the slower rod or tube drawing operations. For example, dry soaps have been recommended especially for brass and bronze [215], but removal by immersion in boiling water is necessary if the wire must be entirely clean for a subsequent operation [228]. Soaps may be applied to tubes by dipping in a suitable hot soap solution. It should be noted that coatings are not required for copper and its alloys in cold forming operations.

Greases containing sodium or calcium stearates have also been employed for bar drawing [215]. In particular, the rod may be passed through a grease or tallow box before entering the first die, and then one may rely upon liquid lubrication for subsequent drafts [43].

By far the most common lubricants for copper-base materials are soap-fat emulsions, with typical composition ranges given in Section 7.4. Salz [177] also notes that for coarse sizes of copper and brass wire a concentration of between 3% and 7% of high fat-low soap compound in water is employed but for fine wire a low fat-high soap compound is preferred at lower concentrations (between 0.5 and 3% in water). These concentration ranges agree with those suggested by Perry [34], Morton [14], and others [228], and are used for most copper alloys. However, the free fatty acid content should be kept to a minimum to avoid staining on storage and to avoid formation of copper soaps which could clog the machines. Also, the pH of the emulsion should be kept within the range 8.5 to 9.6 [34, 68, 228] since higher acid contents will cause instability of the emulsion and increased tendency for staining. Lengthy storage times can also cause problems [229], since the residual film of lubricant on the surface can react with the thin copper oxide film and cause discoloration. An optimum working temperature of between 38° and 54°C has been quoted for these compounds [228]; prolonged exposure to temperatures above 60°C usually results in reduced die life.

These compounds are also recommended for tube drawing, where conditions are more severe. The concentration of solids may then be increased, so that for harder alloys such as bronze or cupronickel, soap-fat pastes containing up to 20% of solid filler are employed [207, 209].

Oil emulsions find limited application in less severe operations, such as the drawing of fine copper wire [228], once again at concentrations up to about 3% in water. They usually contain extreme pressure additives, and the pH will be maintained between 8.5 and 9.6.

Compounded mineral oils suffer from poor cooling ability, but give lower friction, higher die life, and better finish than emulsions. They are generally used at lower drawing speeds to overcome the difficulty of inefficient cooling, and high lubricant flow rate can also alleviate the problem. Compounded oils are found in European practice for drawing rod sizes [34], and are also mentioned [43] for drawing very fine wire (down to 0.001 in. diameter). Oils for fine wire are always of low viscosity; 45 Redwood 1 seconds at 70°F was recommended by Perry [34], particularly for phosphor bronze wire. Perry [207] has also noted that E.P. mineral oils with viscosities of 100 to 300 Redwood 1 seconds at 140°F are sometimes employed in tube drawing.

Mineral oil containing proprietary waxes as boundary additives was suggested by Werner [226], who noted that, after drawing, a thin film of wax residue prevented corrosion of the wire.

7.7 TITANIUM AND ITS ALLOYS

7.71 Experimental Investigations

The great advantages of titanium as a structural material are its exceptional strength-to-weight ratio, particularly at slightly elevated temperatures, and its corrosion resistance. These properties are, of course, extremely attractive but are offset to a large degree by the problems involved in forming titanium and particularly its alloys. The difficulties in cold forming arise from high strength due to development of an unfavorable texture, from a high rate of work hardening, and from a susceptibility to severe die pickup. Lancaster and Rowe [27] showed that in plane-strain drawing, neither soap nor oleic acid prevented severe pickup of titanium onto carbon steel dies, while Rabinowicz [230] demonstrated that many conventional lubricants were totally ineffective on titanium, giving friction coefficients little different from that of the unlubricated metal. This evidence points to the need for a lubricant coating similar to those used on high-carbon and stainless steels.

Several coatings have been proposed on the basis of various research studies. The most common of these is the fluoride-phosphate chemical conversion coating originating at Battelle Memorial Institute [160] and described in Section 4.42. This was developed primarily for cold extrusion, but has obvious application in tube drawing or other operations of equal severity.

The coatings examined for sheet metalworking discussed in Section 11.8, are also relevant here. These include the fluoride-phosphate coating, oxidizing in air for 15 min at 630°C, and sulfidizing for 3 hr in a salt bath based on sulfur and cyanide compounds at 570°C. The Swift cupping test was employed, and coated blanks were drawn dry or with one of three lubricants (two E. P. oils and a plastic dry film compound).

Sulfidizing exhibited the best performance in terms of limiting drawing ratio and surface finish, with adequate performance given by both oxidizing and phosphate coating. A chlorinated oil was found to be the better of the two oil-base lubricants, but the plastic film lubricant adequately prevented metal-to-metal contact without additional surface coatings. All of these lubricants are applicable to wire- and tube-drawing requirements.

White and Miller [161] examined a wide variety of coatings in wire drawing and in rotary and reciprocating wear tests, using a wax, a machine oil, and molybdenum disulfide in both a grease and a lacquer as lubricants. The results showed that suitable fluoride-phosphate coatings could be produced by both high- and low-temperature baths. A sodium hydroxide anodic coating, produced by anodizing for 20 min in a 5% caustic soda solution at 94°C with a current density of 50 asf, gave good performance in the wear tests but was not examined in wire drawing. Possibly the best results in both tests were given by a fluoride-phosphate coating which was modified to produce a thick layer of TiO_2 between metal and coating by subsequent heating at 425°C for 2 hr in air. All these coatings must be used with a lubricant, and of those examined, the machine oil and the lubricants containing MoS_2 gave superior performance.

In the experiments of Larson and Backofen [231], a speed of 0.1 fpm was used in drawing 0.187 in. diameter titanium and 10% Mn titanium alloy wire. For a 19% reduction, a lubricant of zinc stearate gave a low draw force on copper-plated, anodized, and phosphated surfaces with the same lubricant. These coatings also performed well with a suspension of graphite in water, but the authors noted that the relevance to industrial conditions, in which speeds up to 200 fpm were more typical, was limited.

7.72 Industrial Observations

It has been repeatedly stated [215, 231, 232] that in industrial practice copper plating with a metal soap is commonly applied. This is, however, an expensive method of providing a protective coating, and has fallen out of favor as cheaper techniques became available. One of these is oxidizing, which is used in commercial practice [233]. Wilson's technique [233] involved heating to 700°C in an oxidizing atmosphere, and subsequently dipping in lime. A drawing lubricant consisting of five parts soap to one part molybdenum disulfide was recommended. This practice enabled the oxide coat to form during intermediate annealing, and had been extensively employed in tube drawing. Chlorinated wax lubricants are also used.

Formation of an oxide coat is probably the cheapest method of obtaining a protective coating on titanium. However, many others have been proposed, as indicated above, and some of these are also in practical use. For example, the fluoride-phosphate coating has some application in the more

severe operations, such as tube drawing [206, 234]. Anodizing has also been mentioned [232], but is probably applicable only to the lighter operations (for example, fine wire drawing).

Plastic film lubricants have relevance to both bar and tube drawing, and they can be applied by spraying or dipping and removed by solvent degreasing. These include both the chlorinated plastics and the methacrylic resins discussed for stainless steel. However, chlorinated plastics, as well as other halogen-based lubricants, are no longer used in the aerospace industry.

Finally, a lubricant coat almost as resistant to penetration as the plastic films has been proposed recently [235]. Asphalt was applied in a very thin layer to the metal surface by dissolving asphalt in xylene, an organic solvent, and dip coating the part to be drawn. Evaporation of the solvent left a thin asphalt coating. Lithium stearate was used as a lubricant, but additional water cooling of the material was necessary at reductions above 10% and speeds above 10 fpm. This speed limitation is the biggest drawback of such a lubricant, since other coatings allow faster working. Removal, however, was again relatively easy, and could be done by solvent degreasing.

7.8 OTHER MATERIALS

Ferrous materials as well as copper and aluminum alloys have been drawn for many years [236, 237] so that lubrication practices are sometimes steeped in tradition. Nevertheless, the vast quantities of these wires produced have promoted a steady advancement in lubricant techniques over recent years. Many other, newer materials are not produced in such quantities. Consequently, research effort has been rather limited, and practices are regarded as confidential; hence, reliable information tends to be scarce. In this class of materials are most refractory metal alloys and alloys which are, in general, only associated with atomic energy applications. Since these are produced in relatively small quantities, drawing technology is still often limited to a pilot-plant scale.

7.81 Nickel Alloys

Nickel and its alloys are lubricated with techniques similar to those used for stainless steels. Coatings and carriers are necessary to reduce die wear. Hence, the oxalate coating is attractive for bar and tube drawing, as are methacrylic and other resins. Oxalates have shown fair success in drawing superalloys and Monel [163].

Other coatings are lime in conjunction with an oil or with a drawing emulsion consisting of soap, oil, and fat in water [238]; lead used with lime and soap [206]; and a copper coating used with a chlorinated paraffin [239].

Lead, copper, lime, and oxalate coats have all been used with dry soap powder possibly containing zinc or aluminum stearates [5], or with drawing pastes. For wet drawing, however, the copper coat is more common than the others, and fine wire may be drawn, usually submerged, without coating. Improved submerged drawing conditions have been obtained by a high-pressure feed on the dies [238] or by ultrasonically agitating the lubricating fluid [126]. Straight oils or emulsions are used for wet drawing, although extreme pressure additives should be beneficial.

7.82 Beryllium

Toxicity and lubrication difficulties make canning of beryllium mandatory when working it hot above 780°C. Lubrication is then typical of the mild or stainless steel used as canning material.

Beryllium is almost invariably drawn at elevated temperatures to take advantage of increased drawability. The metal is usually worked at between 400 and 500° C, but because the work-hardening rate is low, relatively small reductions (25%) must be taken. Cladding is not necessary, but even so, few lubricants are suitable at these temperatures, and graphite and MoS_2 are commonly used. Heavier sections and tubes may be drawn in the sheath, but thinner products have to be processed bare in order to assure good surface finish.

For lubrication in the drawing of rod, Gross [240, 241] has recommended a mixture of graphite and MoS_2 in a phenolic resin binder, which is coated on the rod, while the lubricant box ahead of the die is heated and contains flake graphite. Gross and co-workers [241] also had fair success in drawing beryllium at 315°C with an oil lubricant.

For tube drawing of beryllium in a mild steel sheath, practicable reductions have been obtained [242] with colloidal graphite as a lubricant. Attempts were also made to draw bare beryllium tube with the same lubricant, but scoring was experienced.

Denny has suggested nickel cladding of all wire stock below 0.300 in. diameter, with lubricants of molybdenum disulfide in water on the wire and fine graphite powder in the die box [243]. Recommended reductions were

12 1/2% using a heated (400°C) tungsten carbide die of 12° included angle for stock larger than 0.020 in. diameter, while diamond dies were recommended for sizes below this.

Among other coating materials which have given fair success is electroplated silver [244], which was used in conjunction with a lubricant of vermiculite in isopropanol for the warm extrusion of beryllium tubes. This was not tested for warm drawing, however, although there is little doubt that such a coating could adequately serve as a lubricant.

7.83 Zirconium

The primary use of this metal is in the production of nuclear power reactor cores for operation at elevated temperature. Either the pure metal or the alloy Zircaloy-2 (which contains 1 1/2% tin and trace amounts of iron, chromium, and nickel) is of concern.

Bastian [43] has commented that zirconium is drawn by methods similar to those encountered for carbon steel. This means that the wire will generally be coated and a lubricant used on top of the coating. Thus copper has been recommended [206], either as an electroplated layer or as the sheath from hot extrusion, and would be combined with a soap, a grease, or an oil lubricant. A copper jacket with traces of oil as lubricant has been suggested for tube drawing of Zircaloy-2.

However, commercial practice is closer to that for titanium alloys [206]. A fluoride-phosphate conversion coating is available, and this is applied by immersion in an aqueous solution containing 0.1 to 0.5% by volume of hydrofluoric and 1% orthophosphoric acid. Conventional lubricants for this type of chemical conversion coating are soaps, although greases, oils, or emulsions might have some limited application. Nelson [245] has reported that a proprietary conversion coating, presumably a fluoride-phosphate, on Zircaloy-2 has given better results than a straight phosphate coat and an oxide layer.

Asphalt in xylene [235], in conjunction with a lithium stearate soap has been successful on Zircaloy-2 wire and tube, though not at speeds above 10 fpm. Finally, Cockcroft [215] has recommended a mixture of insoluble stearates and E. P. additives with a high MoS_2 content for use on uncoated zirconium wire and tube.

7.84 Tungsten

Tungsten is used as a filament material in lamps or electron tubes, and also as the material of various components in missiles and space vehicles. It is most frequently hot worked to take advantage of the increased ductility at elevated temperatures [183] and the corresponding reduction of strength. The ductile-brittle transition temperature is lowered by plastic working, and cold drawing becomes feasible for heavily worked material [13, 246]. The temperature at which the wire is drawn may vary according to local practices and the amount of prior work, but the lubricant is invariably colloidal graphite in a liquid carrier which volatilizes when the wire is heated.

Salz [177] has given a drawing temperature of 980°C, as has Bastian [43], while a carbide die temperature of 380°C has been suggested [238]. Carbide dies are invariably employed for coarse wire; diamond dies are more suitable for finish reductions at room temperature down to 0.003 in. diameter [43].

Graphite in water is frequently recommended as a lubricant, and is applied by spraying the liquid onto the wire, which is subsequently heated to a temperature above that at which drawing will take place [43] and then allowed to cool. A preliminary oxidizing treatment has been suggested [180], so that metal-to-metal contact is doubly prevented by means of a coating, which will also give better graphite adherence, but this practice is not widespread.

Tube drawing is carried out at lower temperatures [246], usually between 425° and 540°C, using carbide dies and a hardened steel bar. A lubricant of graphite in sugar syrup is baked onto the tubes prior to drawing, and the tube is removed from the mandrel after drawing by applying a light pull. The tube does not require expanding by the normal reeling operation since there is a favorable differential thermal contraction.

7.85 Molybdenum

Molybdenum and its alloys are drawn with the same techniques as tungsten [180, 183, 238]. The wire passes through a spray or bath of colloidal graphite in a carrier, which is frequently water, and is then heated to drawing temperature, so that the carrier volatilizes. Similar temperatures are involved, although it has been suggested that small reductions can be made cold [235].

7.86 Tantalum

The traditional method of drawing tantalum is through dispersion-hardened aluminum bronze dies [247], since severe die pickup occurs with steel or carbide dies. Although these dies prevent adhesion, a high rate of wear must be tolerated since the bronze is much softer than hardened steel or carbide dies. Conventional practice as stated by Batista et al. [248] employs beeswax or beeswax-base lubricants in conjunction with aluminum bronze dies. The type of die alloy is important, however, and generally precipitation-hardening alloys are required for their extra strength. The composition used by Batista et al. [248] was 80% copper, 15% aluminum, and 5% iron.

Galling can also be prevented by adding a protective coating on the metal and, as Bastian [43] remarks, the techniques that can be used are essentially similar to those for carbon steels. Thus, asphalt coating [235], anodizing, copper coating, or plastic film coating might find application, as a means of changing the composition of the surface presented to the die. High working pressures would be involved at room temperature, so that graphitic lubricants might be warranted with some of these coatings to provide additional protection against metal-to-metal contact.

7.87 Uranium

Batista and co-workers [248] state that the lubricants found to be most effective in their simulating test, which involved drawing strip through parallel dies under a normal load in the elastic range (as in Fig. 5.10b), were consistent with known practice. These lubricating techniques involved aluminum bronze dies and beeswax, or chrome-plated steel dies and colloidal graphite in water.

Coating techniques using plastics or asphalt [235] would, again, be quite acceptable.

7.9 SUMMARY

A great variety of lubricant requirements are encountered in the drawing of wire, bar, and tube. Drawing speeds and geometrical variables may differ considerably in these processes, so that lubrication may range from purely boundary to near fully hydrodynamic. For example, the wedge-shaped

entry zone in draw dies encourages hydrodynamic lubrication, while the interface between the stationary mandrel and the inner surface in tube drawing often becomes starved of lubricant supply.

Compared to rolling, drawing has the advantage that no minimum friction is required. Therefore, lubricants of any viscosity may be used, provided the surface of the drawn product is acceptable. This has led to the wide-scale adoption of dry soap powder as a lubricant, which acts essentially by a partially hydrodynamic (thin film) mechanism, and the basic problem here is maintaining a uniform supply of the lubricant.

When surface finish is of no great important, the coefficient of friction, as well as the tendency for metal pickup, may be substantially reduced by obtaining nearly full fluid film conditions of lubrication. The methods of promoting these conditions depend upon supply of lubricant under pressure to the die; although designs suitable for soaps have been successful, further development in this direction is certainly desirable.

When drawing speeds are slower or a better surface finish is desired, conditions more removed from hydrodynamic lubrication are sought. Drawing pastes, greases, and heavily compounded oils are usually adequate for slow-speed drawing with the lubricant reducing friction through the formation of boundary or extreme pressure films. For higher speeds, oil-base or water-base lubricants are successful. Here, cooling of the die is as important as reduction of friction, and this is accomplished by supplying large quantities of fluid to the die-wire interface, or by submerging the multiple drawing unit in lubricant. The composition of the lubricant is dictated by the workpiece material, and improvements could no doubt be found somewhat on the lines indicated for rolling in Section 6.10.

Wire drawing presents some special problems to the lubrication engineer. Firstly, very fine wire must be drawn through a series of many dies, and costly breakages can be avoided only by assuring cleanliness of the lubricant. Ultrasonic vibration of the fluid has shown great potential here, and application of recirculating filtration systems which are well established for rolling fluids could no doubt be employed to advantage. Secondly, some materials tolerate only very moderate cold work, and wire drawing must be performed at elevated temperatures. While equipment suitable for elevated temperature drawing exists, lubrication practices could possibly be improved and better hot drawing lubricants found.

Problems in tube drawing arise because drawing speeds are low and because continuous supply of lubricant to the stationary mandrel/tube inner surface interface is difficult. Uniform application of a lubricant effective at low speeds is necessary prior to drawing, and some advances have been made in this direction by various solvent and aqueous techniques. There is plenty of scope for improvement, however, and vibration of the mandrel is one of the attractive possibilities.

The great interest in wire drawing lubricants, in general, seems to have somewhat subsided. Nevertheless, the need remains for further improvements in both the conventional and the more difficult-to-work materials. In particular, the latter are still produced by rather expensive and slow techniques, and a fresh approach to their forming would be desirable. This would include not only a search for improved lubricant systems, but also an assessment of the die-lubricant-workpiece system as a whole.

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Chapter 8

HOT EXTRUSION LUBRICATION

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8.1 INTRODUCTION

Hot extrusion is one of the most important primary metalworking operations. From the relatively simple task of extruding lead the process was gradually developed for copper, aluminum, and steel. During the last few years, it has received considerable attention for the working of refractory alloys, superalloys, and titanium.

This process is attractive because (a) extrusion forces are reduced in that the flow stress of the billet is lowered; (b) elevated temperatures increase the workability of the material without fracture thus allowing higher extrusion ratios; (c) the process is one of predominantly compressive deformation, again enhancing the ductility of the workpiece material, and (d) complex shapes may be produced with modest tool costs. In view of these major advantages, hot extrusion has been the subject of considerable study—both in laboratory-scale experiments and industrial developments—to determine optimum conditions for major parameters such as extrusion ratio, die design and materials, temperature, speed, lubrication, and other operating variables. The purpose of all of this effort is to obtain a sound product of desired dimensions, tolerances, surface finish, and mechanical and physical properties.

Lubricants in hot extrusion (which can also be performed dry) are called upon to reduce friction and hence power requirements, reduce die wear, act as thermal insulator between the billet and the die container, improve metal flow and thus enhance mechanical properties, improve tolerances and overall quality of the extruded product, and reduce cost by allowing higher extrusion ratios, higher extrusion speeds, and increased percent yield of the billet.

In hot extrusion, lubrication of various portions of the die-container assembly may serve a variety of purposes. Thus, it is desirable to have low friction between the billet and the container walls so that extrusion

forces are reduced. Furthermore, good lubrication of the die-billet interface is particularly important if good die life is desired. Die wear can take place either by abrasion as a result of which the die throat diameter is increased or by thermal failure resulting in die washing whereby the throat is reduced in size. It is thus evident that a good supply of lubricant must be provided, both for low friction and for low heat transfer to the die.

On the other hand, the use of a lubricant has the disadvantage of introducing additional costs, including the cost of the lubricant itself and the cost of equipment and operations necessary for applying the lubricant and for removal of the residues.

The desirable properites of lubricants in general have been discussed in detail in Section 5.1. For hot extrusion, Séjournet [1], Sabroff [2], and many others have highlighted the following requirements: chemical stability, or at least a slow rate of decomposition or attack on the tool and workpiece, and—if liquid—good wetting and adequate viscosity to resist high pressures and a moderate change in viscosity with temperature so as to flow in a thick film. Additionally, the lubricant should be a good thermal insulator tc minimize heat losses (most lubricated hot extrusions are completed within 3-4 seconds), should act as protective coating to minimize oxidation during handling and processing, and should be relatively inexpensive and easy to apply and remove.

Profound changes in performance can be obtained in hot extrusion not only through manipulation of process variables such as speed, extrusion ratio, and billet temperature but also through the selection of lubricant-workpiece material combinations.

The most stringent requirement of the lubricant is that it function properly at the high temperatures (Table 8.1) and pressures employed in hot extrusion. The selection of the proper lubricant from the great variety available depends on the billet material, die material, extrusion temperature, and other parameters involved. Some of these lubricants, graphite and glass, are widely used in practice while others are in an experimental stage of development.

Systematic studies to establish quantitative relationship between the material flow, forces, quality of product, etc., and the material and process variables in hot extrusion in terms of lubrication appear to be scarce. The available information is presented in the following sections.

TABLE 8.1

Temperature Ranges Ordinarily Used for Extrusion of Various Materials

Material	Range, °C
Low C Steel	900-1250
High C Steel	900-1150
4340 Steel	1070-1200
304 Stainless	930-1250
1100, 3003 Aluminum	300-550
2024, 7075 Aluminum	360-450
5052, 6061 Aluminum	300-500
Beryllium	800-1100
Magnesium	300-540
Copper	750-950
70/30 Brass	725-850
Phosphor Bronze	540-560
Titanium	650-930
Ti-8Al-4V	870-1050
Nickel	650-1200
Hastelloy X	1000-1200
Cb 752	1200-1450
Molybdenum	950-1900
Tantalum	1000-1250
Tungsten	1600-2200
Zirconium	750-900

8.2 FRICTION AND LUBRICATION EFFECTS

8.21 Friction and Lubrication Mechanisms

Lubrication mechanisms in hot extrusion encompass four basic types: dry sticking friction (Fig. 2.12b), solid or liquid lubrication with sliding friction (Fig. 2.12a), hydrostatic lubrication, and phase-change lubrication. The desirable mechanism for a particular extrusion application depends on considerations involving the workpiece material, billet and die temperatures,

die life, and surface finish of the extruded product. In practice, the choice of lubrication will also depend on the type of extrusion equipment available.

Sticking Friction

In dry sticking friction the outer skin of the billet remains more or less attached to the container walls; the flow of the metal then takes place in the subsurface layers. In general, the extruded product will have a good surface finish and will be free of any contamination that the original billet surface might have had, provided that extrusion is interrupted and a butt left which prevents oxides and other contaminants from entering the extrusion.

Solid Lubrication

Solid lubrication resulting in sliding friction is obtained through means such as oxide layers on the original billet, or solid lubricants such as graphite, molybdenum disulfide and phosphate coatings, and canning materials. These materials maintain an interface of low shear strength between the billet and the container-die so that friction is reduced. The surface of the extruded product depends on the nature of the oxide or the coating, which largely remains on the extruded surface. Canning materials are usually removed after extrusion, and the quality of the extruded surface depends on the physical and mechanical properties of the canning material in relation to the billet material.

Liquid Lubrication

Hydrostatic lubrication can be sustained in ramless extrusion (Fig. 2.11f) or with special container and ram designs (Fig. 8.1) in such a way that the lubricant is trapped in the interface between the billet and the container. Under such conditions, speed does not have any appreciable influence, since the pressure buildup that is necessary to transmit extrusion forces to the billet is obtained by trapping the lubricant by mechanical means. Consequently, the choice of the lubricant is governed more by factors other than lubricating ability; in ramless extrusion, the lubricant must not solidify under the imposed high pressures, while in hot extrusion (Fig. 8.1) it must melt at an adequate rate to flow easily yet it must not decompose at an excessive rate. In the technique described by Sauve [3], the lubricant is maintained under pressure by a metal seal at the die and another specially designed seal behind the billet (Fig. 8.1). If the billet is completely enveloped by the liquid, the hydrostatic pressure generated should be similar to that encountered in hydrostatic extrusion. It is claimed that this

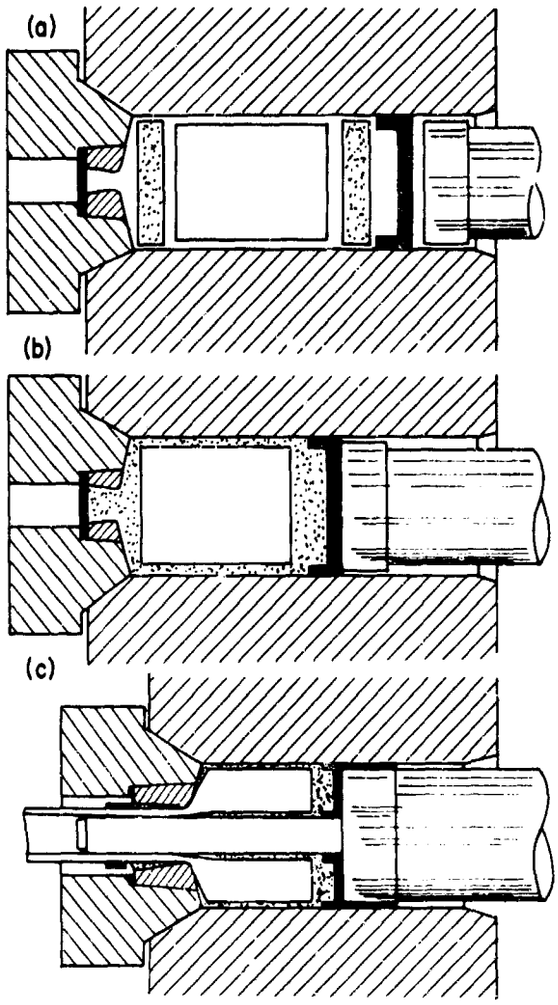

Fig. 8-1. The C. E. A. process for extrusion. (a) Lubricant, billet, and rear seal in position; (b) fitting the pressure pad; (c) extrusion of a tube in progress [3].

patented C. E. A. process (after Centre d'Etudes Nucleaires de Saclay, France) is simple and inexpensive.

When the lubricant is not trapped in the container, a fluid film can be maintained only under rather strictly circumscribed conditions. Due to a lack of systematic experimental data and the scarcity of thorough analytical studies, our knowledge of the exact mechanisms of fluid film behavior in hot extrusion is incomplete. It appears, however, that in lubrication with fluids such as glasses, two mechanisms are in operation, either singly or, under certain circumstances, jointly.

The first is the mechanism of phase-change lubrication in which the glass disk between the die and the billet serves as a reservoir (Fig. 8.2) supplying the required amount of lubricant by gradual melting of the glass at the billet-glass interface. Although it is preferable to use conical dies for better lubrication, the die faces normally include 180°; thus the die-glass-billet system makes its own die angle, somewhat similar to the dead metal zone formed in the extrusion of metals with a 180° die.

A second mechanism of lubrication akin to hydrodynamic lubrication is obtained by precoating the billet whereby the coating supplies all glass necessary to maintain a continuous lubricant film during extrusion. This has assumed particular significance in the extrusion of superalloys and refractory metal alloys, because a glass pad cannot be retained [4] at the usual low extrusion ratios.

Theoretical studies of fluid film (hydrodynamic) lubrication in extrusion are scarce. An analysis by Pan [5] essentially confirmed the expectation that factors controlling hydrodynamic lubrication in general should also be important in extrusion. Thus, the die design, lubricant characteristics, process temperature, and extrusion ratio must be matched. Unfortunately, an explicit solution can be found only if the lubricant supply is known, a condition seldom satisfied in practice. Further work on hydrodynamic extrusion is discussed in Section 10.2.

Temperature and pressure effects on the viscosity of the lubricant must be regarded as important factors in the proper die design for hydrodynamic lubrication during extrusion but, here again, available data are too scarce to allow valid theoretical solutions, at least for the present.

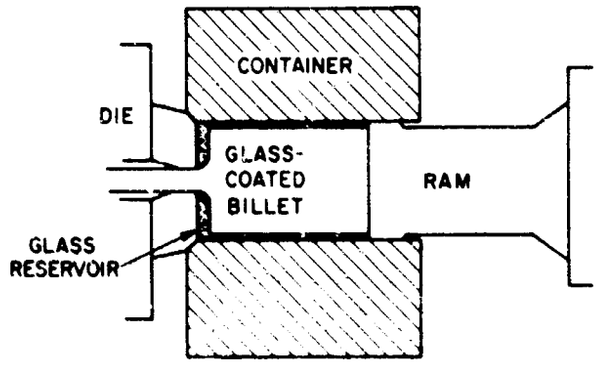

Fig. 8-2. Schematic illustration of glass-lubricated extrusion process.

The relative importance of phase-change and hydrodynamic lubrication is still debated. There is little doubt that the phase-change mechanism predominates with glass pad lubricants used at larger extrusion ratios (typically, 12:1 and over). Séjournet and co-workers regard gradual melting of the glass the most important, and have attempted to determine the optimum glass viscosity from calculations of the time required to soften the lubricant film [6]. Rowe and co-workers have shown with radioactive tracer techniques that almost all of the glass coating present on tube blanks extruded under industrial conditions came from the pad placed in front of the billet [7] and that the glass applied to the billet surface ("tray glass") was useful mostly by its effect of assuring a more uniform coating at the trailing end of extruded bars [8]. In the latter work, rather wide variations in glass viscosity had very little (4-10%) effect on extrusion pressure, even though the glass film thickness was significantly greater with glasses of lower softening point. Similarly low variations in extrusion force with viscosity were found by Vdovin et al. [9] in the extrusion of stainless steel, even though a slight minimum was evident at a glass viscosity of 150 poises at the extrusion temperature. However, best surface finish was obtained with heavier glasses (up to 1000 poises).

There is also general agreement over the importance of die geometry. The influence of die angle (Section 2.43) has been repeatedly confirmed. In general, extrusion forces are lower with smaller die angles [8, 10] but too low angles may lead to a nonuniform glass distribution and included angles of 120-150° are usually regarded optimum [9]. When the billet nose angle is smaller than the die angle, the wedge-shaped gap (Fig. 8.3) traps more

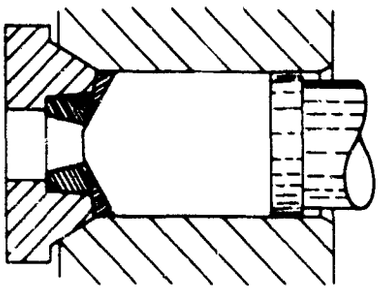

Fig. 8-3. Extrusion of a cylindrical billet with a conical leading face [3].

lubricant and aids in supplying a continuous film [3]. This tended to overshadow the viscosity effects in the work of Rogers and Rowe [11] (Table 8.2). A billet with a square nose should not be used with a conical entry die, because the lubricant pad is extruded first and the sharp billet nose is likely to plow through any lubricant film that may remain.

Speed of extrusion becomes very important because the time necessary for the gradual softening (melting away) of the glass may not be available at too high speeds [11]. On the other hand, too low speeds would allow excessive cooling and, in extreme cases, damage of the die and container by the solidified glass.

8.22 Effect on Material Flow

The role of lubrication in material flow during hot extrusion has been reviewed in detail by Chadwick [12] and by Pearson and Parkins [13]. All techniques discussed in Section 5.4 have been utilized for studying deformation within the hot billet.

Genders [14] was apparently the first to make a systematic study of metal flow in direct extrusion. He showed that the extrusion defect (annular inclusions in the rear end of the extrusion) is due to chilling of the outer

TABLE 8.2

Extrusion Pressures and Coating Thicknesses for Glasses of Different Viscosities [11]

Glass No.	Softening Point, °C	Extrusion Pressure after 2.5 in. Ram Travel, kpsi	Average Coating Thickness, μ	Viscosity at 900°C under Atmospheric Pressure, poises
1	660	128	36	25,000
2	625	126	58	2,500
3	593	125	63	4,000
4	593	123	66	50
5	593	118	77	4,000
6	630	118	102	25,000

Mild steel, 900°C, ram speed 2 ips, 150°C die

surface of the hot billet; the outer skin then accumulates in front of the follower block and eventually forms the defect, resulting in rejects of as much as 30% of the length of the extrusion. When a follower block of smaller diameter than the container is used, the outer skin (skull) is left in the container rather than extruded, but a second, cleaning stroke must be taken for removing the skull.

The extrusion defect (piping) is due not only to chilling of the outer skin, but also to the high interface friction between the billet and the container. This is a matter of force balance whereby the center of the billet moves faster toward the die than the rest of the material. Thus, improved lubrication will minimize this defect, through both reduced cooling and reduced friction.

The importance of the heat-insulating role of a lubricant can be appreciated by examining Fig. 8-4 where the rapid cooling of a hot, bare billet within a few seconds is clearly seen. Apart from initiating the extrusion defect, such uneven temperature distribution also causes nonuniform metal flow and may result in severe internal stresses.

The profound influence of lubrication on metal flow is shown in Fig. 8.5 for a hot steel billet extruded with glass and an aluminum billet extruded without lubrication [15]. The effect of container wall friction (and cooling) is apparent, in that the outer skin of the billet is dragged behind while the

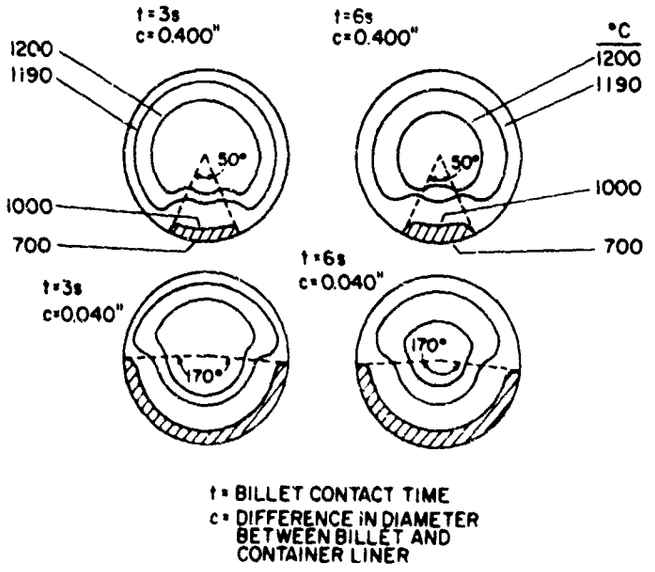

Fig. 8-4 Isothermal lines of a billet lying in a liner. Liner temperature: 200° C. Container diameter: 5.5 in. [1].

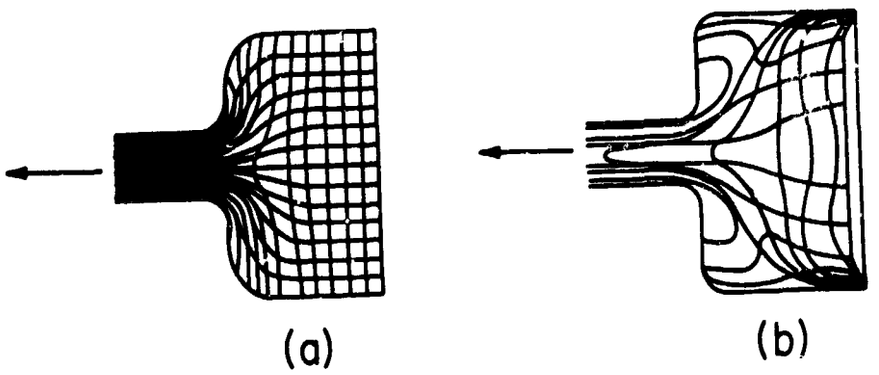

Fig. 8.5. Deformation of the grid after extrusion. (a) Metal flow with glass lubrication; (b) without lubrication [15].

central portions are extruded freely. The dead metal zone in another unlubricated billet is seen in Fig. 8.6.

High friction may lead to a number of undesirable effects. Chadwick [12] discussed some of these in relation to the extrusion of brass rods and sections. In nonlubricated extrusion, a highly sheared zone exists, as shown in Fig. 8.7 by AA'DB'B. When a lubricant of copper oxide scale is present on the container wall, stress concentration at a point such as E is likely to cause rupture; the lubricated surface of the billet then slides over the dead metal zone, whereby the oxide scale or lubricant is drawn into the extruded product. This mechanism produces subsurface inclusions and often causes blistering of the product. Other studies on material flow in hot extrusion have been made by various authors [12, 16-32]. The effect of jacket thickness on flow during extrusion of aluminum is discussed by Moguchin [33] and Panseri et al. [34].

Studies by Blazey et al. [25, 35] on the influence of lubrication on metal flow in tube extrusion have led to similar conclusions. In the absence of lubrication, marker pins originally driven in the surface (circumference) of the billet deformed severely (dark areas on the left side of Fig. 8.8) with no appreciable movement between the billet walls and the container. When lubricants were used for brass billets or an oxide film was present on copper billets, metal flow was concentrated near the die entry; the pins on the walls of the billet were extruded successively (the right of Fig. 8.8). An interesting conclusion is that with good lubrication, surface imperfections on the billet are likely to be extended and remain as imperfections on the extruded

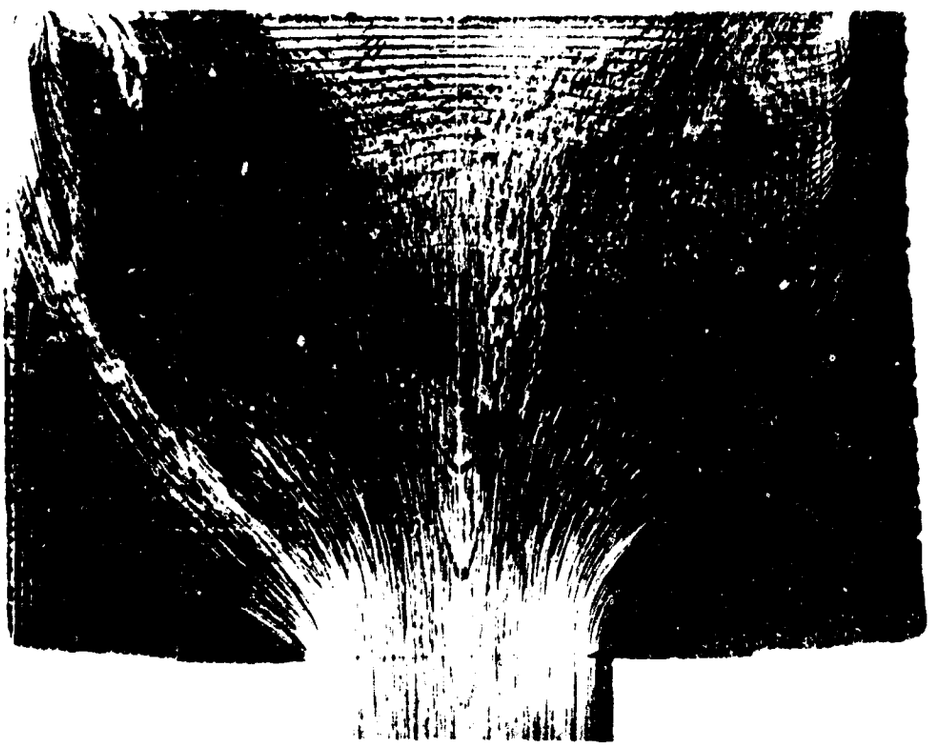

Fig. 8.6. Macrograph of a billet of light alloy extruded without lubricant [15].

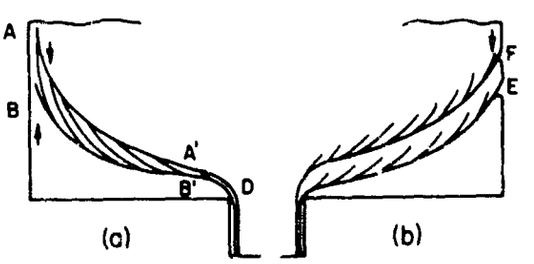

Fig. 8.7. Flow in unlubricated extrusion. (a) Normal conditions; (b) rupture of skin caused by lubricant [12].

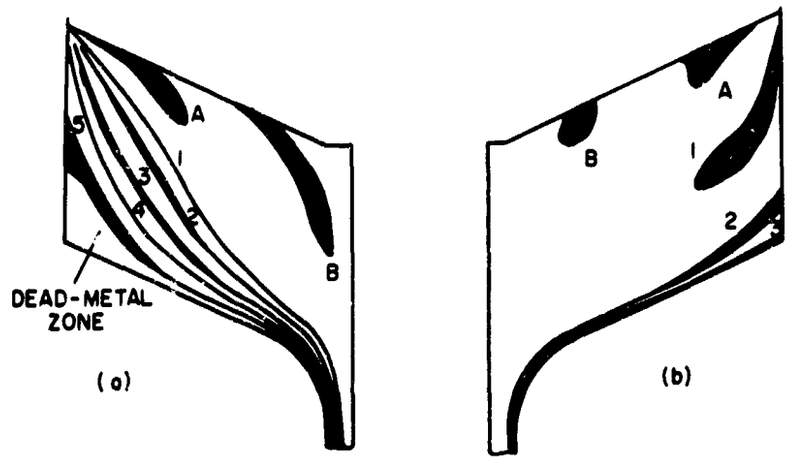

Fig. 8.8. Metal flow in tube extrusion. (a) Unlubricated; (b) lubricated [35].

product; in this sense, unlubricated extrusion is preferable. The deformation pattern in the residual skull (Fig. 8.9) also indicates that, in the absence of lubrication, the original skin remains, with some distortion, on the skull surface whereas for the lubricated billet most of the skin is drawn in and extruded through the die. Blazey et al. have also shown that the difference in flow behavior between copper alloys and copper was due to the lubricating effect of oxides. When copper billets were prevented from scaling, their deformation pattern was the same as that of brass, in agreement with the general behavior of oxides as lubricants (Section 4.28).

In fully lubricated extrusion (such as is assured with glass on hot billets) as well as in indirect extrusion, the surface of the billet forms the surface of the extruded product (Fig. 8.10). The surface quality of the billet is thus important in obtaining an extruded product with good surface finish. (Fig. 8.10 gives an example of a rather low extrusion ratio and 180° dies.)

8.23 Surface Films in Hot Extrusion

The surface condition of the billet to be extruded is important because it affects (a) the surface and overall quality of the extruded product, and (b) the interface friction between billet and container which, in turn, influences extrusion forces and power requirements. The physical and mechanical properties of surface films, with or without superimposed lubricants, are important in determining the thermal behavior of the billet-container system

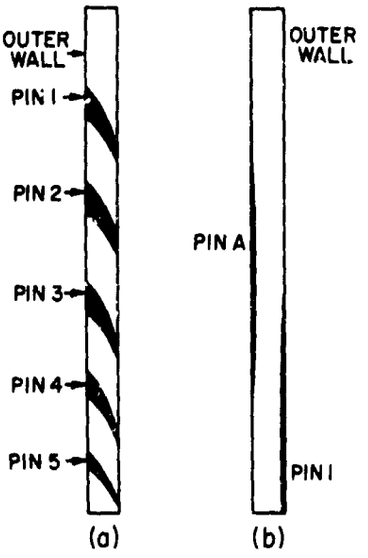

Fig. 8.9. Sections through residual skull showing metal flow. (a) Unlubricated; (b) lubricated [35].

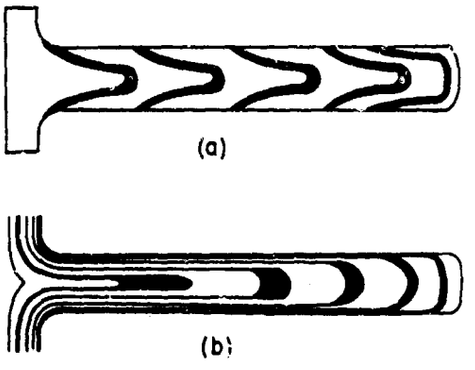

Fig. 8.10. Metal flow in bar extrusion. (a) Lubricated; (b) unlubricated [15, 32].

and the magnitude of friction at the interfaces. The effect of surface conditions on frictional behavior has been discussed with particular reference to extrusion by Chadwick [12] and Séjournet [1]. A great variety of surfaces obtained in hot extrusion have been described in References 36–40.

As pointed out in Section 8.22, a billet with inferior surface finish is likely to yield an extruded product with inferior surface in fully lubricated or in indirect extrusion. On the other hand, in unlubricated direct extrusion,

the surface of the extrusion is likely to come from below the billet surface, particularly when the die angle is large and a dead metal zone is formed; surface quality of the extrusion is thus improved.

Metallic oxides, whether accidentally or purposely produced, are capable of reducing friction in metalworking operations (Section 4.28). We have seen that at high temperatures the oxide of copper gives lower friction than that of 70/30 brass. This is also evident in the direct extrusion of these materials at 800°C (Fig. 8.11); the copper billet exhibits a well-lubricated type of flow [41]. Similar observations have also been made for magnesium [19, 21]. In some cases, such as in hot extrusion of titanium, the oxide layer on the billet serves not only to reduce friction, but also to reduce adhesion between the billet and the die. This function is particularly important since titanium has a strong tendency to adhere to the die surfaces, causing rapid wear at elevated temperatures. Willis [42] and also Male [42] drew attention to the deliberate use of surface oxide films in extruding certain aluminum-magnesium

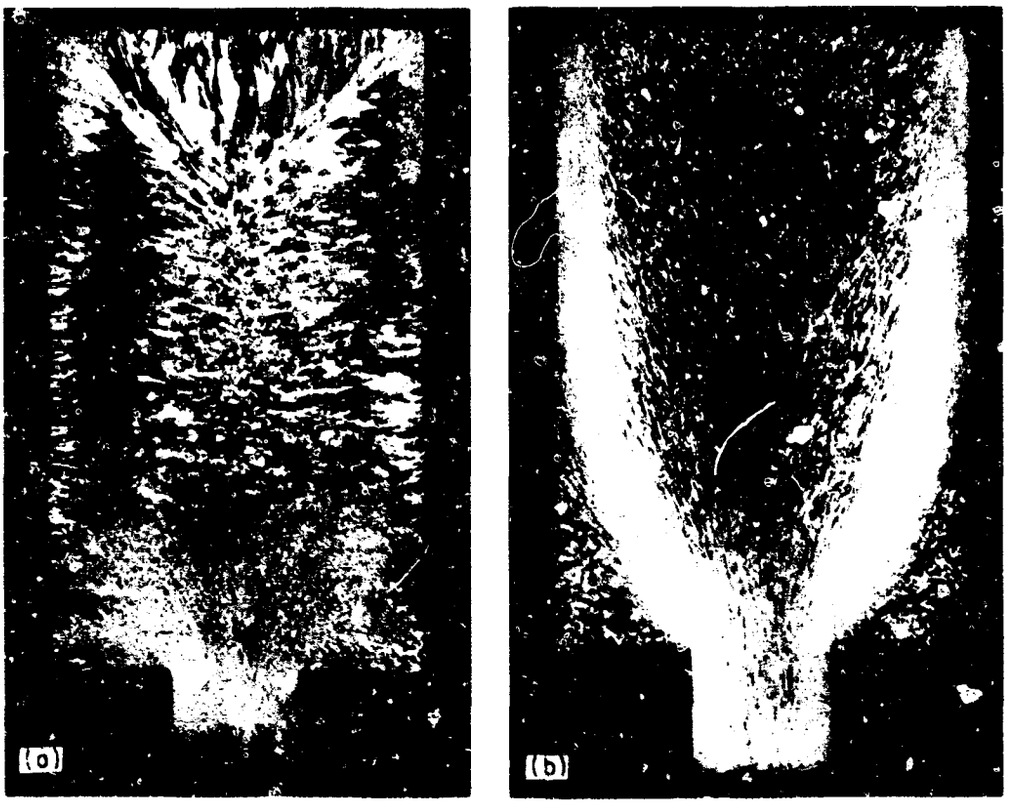

Fig. 8.11. Macrostructure of a billet of (a) copper and (b) of 70/30 brass, partially extruded at 800°C [41].

alloys. Willis claimed that a graphite-20% CdO mixture overcomes the shortcomings of graphite alone, such as its oxidation. Haverstraw [36] investigated the lubricating capabilities of various oxides and other compounds in a simulating test (Fig. 5.10e), but it appears that few of them can approach the performance of phase-change or hydrodynamic lubricants.

It should be pointed out that some oxide layers may be quite hard and abrasive, causing excessive tool and die wear. Also, they may become embedded in the metal surface and cause defects. In general, however, oxides with low friction coefficients are not abrasive. Scale-free billets are desirable in lubricated extrusions for improving the quality of the product and lowering cost [1]. Among the various heating methods available, salt baths, using barium chloride or other salts, are rather expensive and not entirely scale-free. Induction heating with a neutral atmosphere can provide practically scale-free heating, and the short heating times minimize scaling even in air. Glass baths have proved to be quite economical but have not found wide application; the glass used for heating is usually removed before the application of lubricants. Heating in conventional furnaces followed by descaling of the billet with high-pressure water is economical, but the danger of scale pockets remaining on the surface exists.

Controlled atmosphere furnaces are more reliable. Glass (enamel) coating of the billet before placing it in a conventional furnace is a practicable method but only if the glass can maintain a continuous film. New developments in scale-free heating are in progress. Naden [39] has discussed the relative advantages and disadvantages of various heating methods for billets. It might be noted, however, that slight oxidation of the surface is desirable as it assists wetting by glass.

8.24 Friction and Forces in Hot Extrusion

By definition, the coefficient of friction is the ratio of the shear stress to normal stress at the interface. It is well known that the pressures in extrusion are quite high, whereas the shear stress at the interface cannot exceed the yield shear stress of the workpiece material or of the lubricant. Since the yield shear stress of metals is, according to the information available thus far, independent of the normal stress, it then follows that with increasing pressures in extrusion the coefficient of friction will decrease (a situation corresponding to Fig. 2.2, continuous lines).

A survey of the friction coefficients obtained in hot extrusion [32, 37, 43-46] indicates that the values reported are within a range of 0.015 to 0.2. Variations are to be expected since a great number of parameters are involved, such as billet, die and container materials, lubricant, temperature, speed, and die geometry. Some of the variation is, no doubt, also due to errors and difficulties in measuring, calculating, and identifying properly the friction coefficient (see Section 5.24); an additional problem is whether these values represent the conditions at the die or the container or both. The low values obtained in hot extrusion can be explained by the high pressures that cause the coefficient of friction to drop. It is thus important not to be misled by such low values; they do not represent the actual situation correctly for, after all, hot extrusion is a rather severe process and interface shear stresses must be high, unless a full-fluid film of lubrication is maintained. Undoubtedly, interface shear stress would much better describe the situation; however, very few data are available in the open literature.

For practical purposes, it is of interest to know what extrusion forces to expect. For a very rough approximation the extrusion constant K is often acceptable (see also Section 2.43). Extrusion pressure is then

$$P = K \ln (A_1/A_2) = K \ln R_E \qquad (8.1)$$

Forces calculated for low extrusion ratios R_E are likely to be too low, since this expression averages all friction and deformation effects.

Considerable data are available on forces and the extrusion constant for conventional as well as refractory metals and superalloys. Depending on the material, the lubricant, temperature, and other process variables, extrusion constants as high as 160,000 psi have been obtained. The maximum pressure is usually set by the strength of the tooling (punch, container, and die) and seldom exceeds 180,000 psi. Most of the reported values lie between 60,000 and 140,000 psi [12, 13, 36-38, 40, 47-53]. The effect of lubrication on this constant has rarely been studied. Haverstraw [36] showed that in extruding Mo-0.5% Ti at 1870°C and at an extrusion ratio of 10:1, the breakthrough pressure ranged from 88,000 to 151,000 psi, depending on the lubricant. For 4340 steel at 1150°C and a ratio of 40:1, the pressure ranged from 99,000 to 156,000 psi. Cherniy et al. [54] found that, depending on the glass lubricant, extrusion pressures varied by up to 50% in extruding stainless steel at 1250°C. In contrast, the extrusion pressure changed by only

20% in the work of Rogers and Rowe [8] even though the glasses used varied widely in their composition; obviously, process conditions other than lubrication are also important. In studies by Shaw, Boulger, and Lorig [16] the total work done (inch-pounds) in hot extrusion of unalloyed titanium, 4340 steel, and 2014 aluminum was calculated from measured forces and tabulated against the type of lubricant used (Figs. 8.12 and 8.13). It will be noted that forces were reduced with conical dies and that lubricating the die did not affect forces appreciably. Furthermore, with conical dies the breakthrough pressure was only slightly higher than the average extrusion pressure.

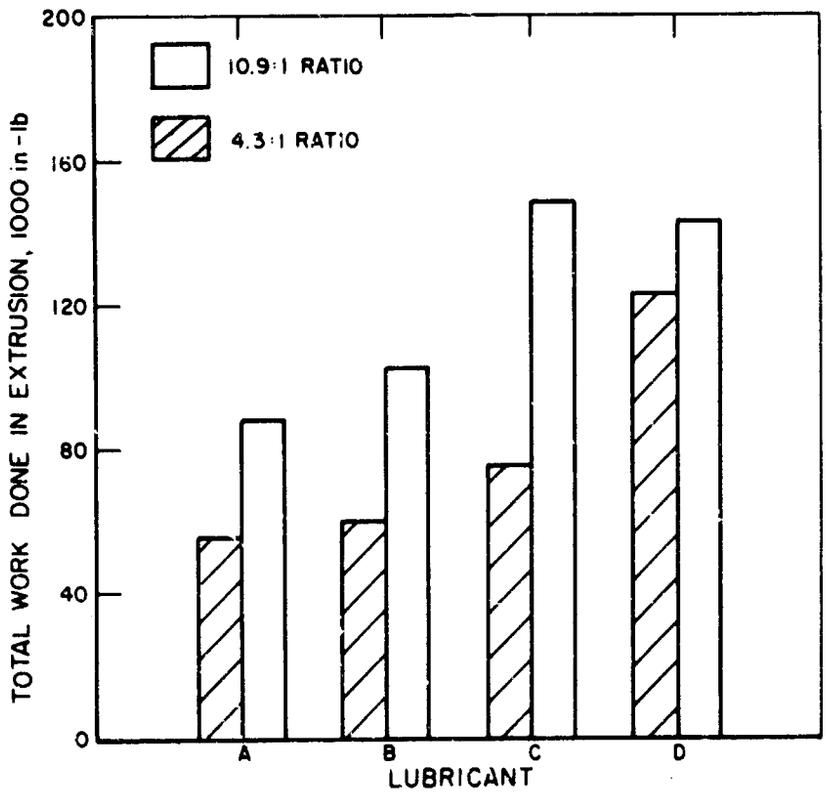

Fig. 8.12. Work done during extrusion of unalloyed titanium at two extrusion ratios, with four different lubricants. Extrusion temperature: 950°C. (A) Graphite in aluminum grease; (B) graphite and molybdenum disulfide in heavy oil; (C) graphite and mica in calcium grease; (D) molybdenum disulfide and mica in calcium grease [16].

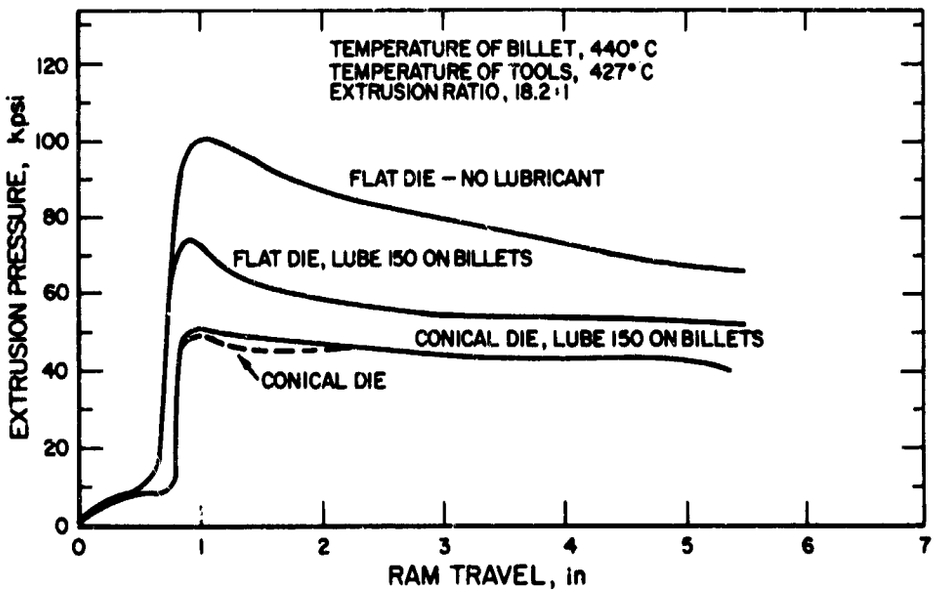

Fig. 8.13. Extrusion pressures for several methods of extruding 2014 aluminum alloy in a 3.2 in. diameter container. Billet diameter: 3 in.; Lube 150 is tetrafluoroethylene resin. Billet treatment for dashed curve: etching in hot 10% sodium hydrochloride for 4 min, rinsing, dipping in hot aqueous suspension of colloidal graphite. Flake graphite in oil applied to container and die [16].

To separate the force at the extrusion die from the total extrusion force, others [10, 40] have used the measurement system described in Section 5.24 where the die support was modified to serve as a load cell equipped with strain gages. In experiments [10] conducted with OFHC copper at 425°C (unlubricated and lubricated with graphite grease) and 1018 steel at 980°C (unlubricated and lubricated with Corning 0010 glass), it was observed that lubrication reduced the container friction forces much more than it did the deformation force on the die. The calculated friction coefficient between the billet and the container was about 0.1 for copper unlubricated and about 0.036 for the lubricated condition. The value 0.1 is too low for unlubricated flow; however, the calculated shear stress at the billet-container interface was the same as the shear strength of the copper billet, indicating sticking. This example further amplifies the importance of using a shear stress value rather than a coefficient of friction for describing the nature of the interface between the die and workpiece in metalworking operations such as extrusion. The

dependence of deformation pressure on the extrusion ratio is shown in Figure 8.14 where a linear relationship is obtained between pressure and the natural logarithm of the extrusion ratio, i.e., true strain. In agreement with theoretical considerations, the intercept with the ordinate is not at the origin (see Section 2.43).

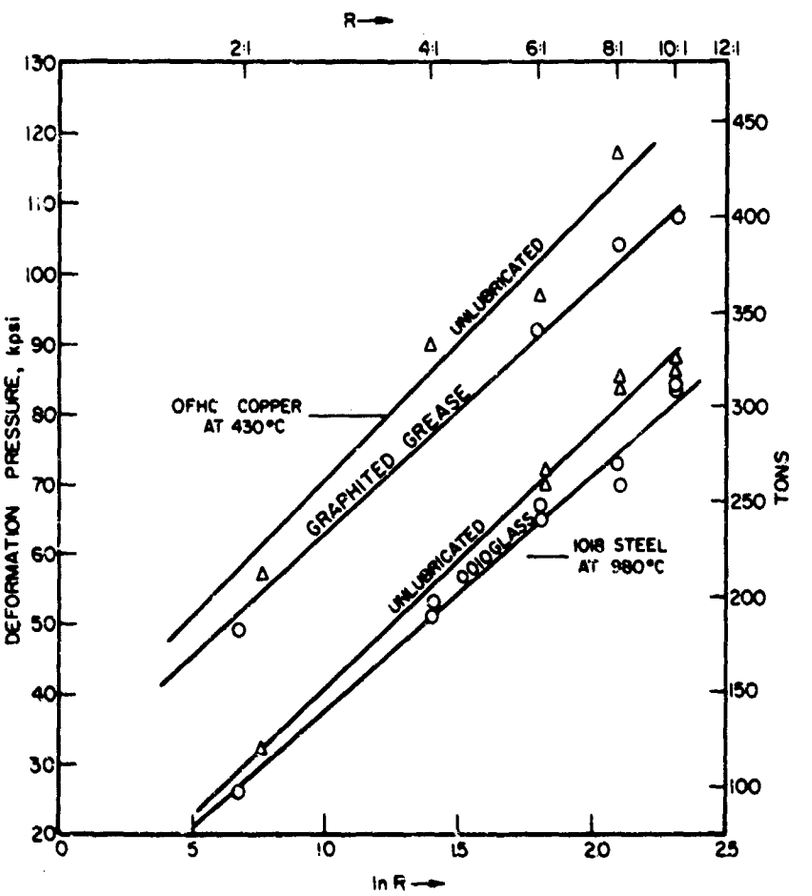

Fig. 8.14. Extrusion pressure as a function of natural strain for a die half-angle of 45° [10].

8.3 LUBRICANT TYPES

The general characteristics of the major lubricating elements in regard to hot extrusion are discussed below.

8.31 Graphite

The properties of graphite are discussed in Section 4.24. Partly because of its lamellar structure, it is an effective lubricant when bonded properly to the surface. It does not, however, interact significantly with metal surfaces and affect boundary lubrication. Bonding to the surface may be achieved with resins, or by mechanical interlocking such as by rubbing. In most instances, however, graphite is most conveniently applied in a carrier, the most common ones being oil, grease, or water. Upon application on a hot surface, the carrier usually burns off or the water evaporates, leaving a coating of graphite on the surface. Oil-graphite lubricants usually contain up to 35% graphite. The lubricant is applied to the die and the container either by spraying or swabbing.

In spite of the extensive use of glass (see below) there are instances where it is worthwhile to use graphite lubrication in hot extrusion [39, 42]. In tube extrusion, lubrication of the mandrel by graphite has also been suggested. Contact time at temperature is important to avoid excessive oxidation.

It is essential that the graphite be of high purity. High ash content and other abrasive impurities impair its lubricating characteristics. The ease with which graphite is bonded to a surface depends on the dimensions of the individual particles. Fine particles not only ease suspension in a carrier, but also allow thin films to be formed when fine graphite is rubbed vigorously on the metal surface [55]. Smith [56] points out that the adhesion of small quantities of solid lubricant, such as graphite, to metal may be beneficial in subsequent plating or coating operations by assuring better wetting with paint.

The following main advantages of colloidal graphite in extrusion of tubes and sections in aluminum, copper, brass, and other alloys have been listed by various authors: it reduces friction, improves the surface finish of the extruded metal, prevents metal-to-metal contact, and eliminates pickup. It is unaffected by elevated temperatures at which lubricating oils carbonize, although it will oxidize if the temperature is sufficiently high.

These claims, however, have to be modified for many applications. Metal pickup is prevented only when a thin but fully continuous film can be maintained. Carbon pickup occurs (perhaps forming chromium carbides) when graphite is used in extruding stainless steels. The carburized layer has to be removed either mechanically or by pickling. On some metals, such as aluminum, the use of graphite can cause localized galvanic corrosion [42].

8.32 Molybdenum Disulfide

This material has a lamellar structure similar to graphite, and has found application for specific extrusion tasks. With iron it forms iron sulfide, which may be undesirable. Also, it would not be suitable for use with stainless steels or high-nickel alloys, because of the danger of inducing hot shortness through the formation of a low-melting sulfide eutectic at the grain boundaries.

8.33 Other Lubricants

A number of lubricants that act through a variety of mechanisms have been experimented with.

Thermoplastic resins, such as acrylics, and thermosetting resins such as phenol formaldehyde polymers have also been identified as promising lubricants for hot extrusion [57]. These resins decompose at elevated temperatures, leaving carbonaceous products. It appears that it is the decomposition products that contribute to improved lubrication. Other promising materials are epoxies, polyimides, and polybenzimidazole. This is a rapidly developing field but still in the experimental stage. At this time, no single composition has found as wide application as graphite or glass, but some may finally prove practically useful, especially when mixed with graphite, MoS_2, or other solid lubricants. Thus, Roux [58] described a patented dry lubrication system for hot extrusion and other operations. The lubricant is essentially composed of an organic substance that is porous, nonabrasive, and a thermal insulator, mixed with lamellar graphite and other "appropriate" substances. It is claimed that it can be used on all metals, leaves no residue, and provides good dimensional tolerances.

Infusible solids such as lime and slate assured adequate lubrication in the work of Rogers and Rowe [11], provided that they were in the form of a

friable pad, properly trapped in the die. Lubrication by these substances was attributed to controlled wear of the pad.

In an extensive program aimed at developing new lubricants for the hot extrusion of aerospace alloys, the following materials have been found to be promising: metal phosphates, borates, chlorides, fluorides, sulfates, and organic resins (melamines and acrylics) containing inorganic solids [36, 59]. Some of these materials are relatively expensive, and a direct comparison with glass lubricants was not available.

Another new type of lubricant (composition not disclosed except that it contains ferric oxide crystals) was developed for the hot extrusion of carbon and alloy steel bars and tubes between 1100° and 1250° C. A number of claims have been made regarding the properties and behavior of this lubricant, and its adaptability to various extrusion conditions [60].

Occasionally, nonglassy substances that melt at a controlled rate have been used. Common salt (NaCl) melts at about 800°C and was found useful at temperatures of 900-1100°C [1, 11, 61]. Lithium fluoride behaves in a similar manner, and both may be used at higher temperatures if 10-20% solid lubricant such as slate is added [11]; these lubricate when too rapid melting of the salt would cause film breakdown. Barium chloride has also found some limited application [62]. Experiments with salt baths as lubricants have been reported for small-scale hot extrusion of steel [16].

8.34 Glasses

The successful use of glass in hot extrusion has led to the appearance of extensive literature.

Historical Development

Séjournet [32, 63, 64] gives a brief history of the development of glass-type lubricants for hot extrusion, which started with efforts at the beginning of World War II to extrude steel. The lubrication practices that were successful for nonferrous alloys soon proved to be quite inadequate for steels. Experimental studies indicated that a lubricant that was liquid at the extrusion temperature was ejected through the die at the beginning of the operation. Lubricants, such as talc, which were solid at the extrusion temperature, acted as thermal insulators but increased die wear by abrasion. It was then

concluded that the lubricant should become viscous at the operating temperature, so that gradual melting away should provide a continuous thin film. The idea of using glass and glass-like materials then occurred to Séjournet and his co-worker, Labataille. The first experiments were conducted in Paris in 1942; the use of glass on a commercial basis began about 1950 [65]. Over the years, the glass lubrication technique was further developed and perfected, whereby it is now standard practice for the hot extrusion of steels and many other materials, although for short lengths of steel graphite is often used.

Advantages and Drawbacks

There are certain advantages in using glass lubrication. At high temperatures glass is one of the best thermal insulators; thus it protects the container and particularly the die from excessive heat buildup and prolongs die life. It can be easily applied to the billet after the latter comes out of the furnace. It also protects the workpiece from oxidation during handling and processing. By varying the composition of the glass, it can be used over a wide range of temperatures. With use of a glass pad, it may be kept feeding through the die, allowing long extrusions to be made. Glass is stable at the high extrusion temperatures, and it does not react excessively with steel during the time normally required for hot working operations.

Glass lubrication is standard practice for the extrusion of alloy steels and stainless steels, and for those shapes of carbon or mild steels which cannot be economically hot rolled.

Glass, for all its benefits, has also some drawbacks. The most obvious is that, compared with conventional lubricants, it is quite expensive to remove from the extruded product. Furthermore, the disposal of the materials used for removal (such as sodium hydride and hydrofluoric acid) is particularly difficult. This latter aspect might be more of a deterrent in the consideration of glass as a lubricant than the cost of removal. Since glass lubricates by maintaining a thick film on the surface, the surface finish of the extruded product is not likely to be better than that of the billet although this is true to some extent for all efficient lubricants (Section 8.22). The billets must be, practically speaking, free from scale; otherwise the extrusion will have much poorer surfaces than if another lubricant (e.g., graphite) had been used. Any possible reaction of glass with metal surfaces must also be taken into account.

Glass has been repeatedly compared with graphite as a lubricant in extruding steel tubes [39, 66, 67], and the following additional advantages have been pointed out: The good heat insulation of glass helps to avoid transverse breaks on tubes; thinner and smaller-diameter tubes can be made (i.e., greater extrusion ratios are possible); no carbon pickup occurs; and the extrusion of long steel sections and hollow shapes with comparatively sharp corners becomes practicable on a production basis.

Desirable Properties of Glass as a Lubricant

The properties of glass that are reported to be important in its function as a lubricant are: thermal conductivity, specific heat, viscosity-temperature curve, coefficient of linear expansion, surface tension, and reactivity with metals and alloys.

If glass is supplied to the extruded surface by gradual melting, then the basic property indicating the rate of heating of the lubricant is thermal diffusivity, which is given by:

$$K = \frac{\lambda}{cp}$$

where λ is the thermal conductivity of glass, c is the specific heat and ρ is the density [15, 32, 68]. A low value of K would be desirable; it appears, however, that the value of K does not vary greatly with different glass compositions [63]. Radiation adsorption is also important [11].

As for the viscosity-temperature curve, a low slope should assure optimum melt-away performance. An overall range of 10^2 to 10^3 poises viscosity at the billet temperature is usually suggested for steel. For extrusion of light alloys, a viscosity range of 10^3 to 10^4 poises has been recommended for a temperature range of 350°C to 500°C. In very general terms, glasses softening at approximately two-thirds of the billet temperature have been recommended [11]; softening is taken as a viscosity of $10^{7.6}$ poises. A simple indentation test has been suggested by Rogers and Rowe [8] for assessing the rate of softening and surface interactions. A large difference in the coefficients of linear expansion between the billet material and the glass enables easier removal of glass by methods such as quenching. It has been suggested that glass lubricants should have a linear expansion coefficient of 6 to 100 x 10^{-7}/°C [68], although it appears that this range covers practically all glasses. Since thermal expansion is typically around 9 to 20 x 10^{-6}/°C for metals, a wide possibility of mismatching exists.

Surface tension is important in that the glass lubricant should be able to wet the billet surface uniformly for thorough lubrication. Wetting characteristics can be improved by 1-2% oxidizing additions [69]. Reactivity is an important consideration, especially if rapid corrosion or contamination of workpiece or die materials results. Reactivity test results with some glasses are given by Haverstraw [59]. Glasses containing lead, for instance, should not be used for alloys containing nickel [70]; fortunately, most of these glasses have too low a softening point for nickel. Because of its toxicity and also to avoid the pollution of pickling waters [71], lead content is limited in some countries to below 5%, or even to zero. In forming aluminum and magnesium alloys, the use of lead glass would contaminate the scrap and introduce lead in these alloys upon remelting [12]; fortunately, commercially available lead glasses have too high a softening point for these alloys.

In the extrusion of metals for nuclear reactor applications, glass lubricants should be free from elements having a high neutron cross-section, such as boron [72]. This makes selection of a suitable glass for these applications difficult, because most of the suitable ones do indeed contain boron.

Compositions

No one glass can be used with all metals, because of factors such as widely differing extrusion temperatures, thermal expansion, wetting characteristics, and the nature of the oxide scale formed on the metal surface and its affinity to dissolve in the glass. The glasses used range from a simple boron oxide to the soda-lime silicate, borosilicate, and phosphate types. Viscosity requirements have not been clearly established. Viscosity-temperature curves of glasses have generally been measured only at atmospheric pressure, a condition that does not truly simulate extrusion conditions. However, recent work on two glasses at high temperatures has indicated that, up to a pressure of 180,000 psi, pressure has no appreciable effect on viscosity [73].

While pure glasses generally exhibit Newtonian flow behavior, the addition of a solid dispersed phase changes this behavior so that viscosity is dependent on shear rate. Another factor which could be important in changing the behavior of the glass lubricant is the effect of oxide scale from the billet or die. Solubility or rate of reaction between the two could affect the wettability and viscosity behavior of the glass. If the rate of solution is slower than the rate of oxide formation, a solid phase will exist in the glass, changing

it to a non-Newtonian lubricant. This could be further complicated by the high pressures resulting from extrusion. Also, oxides dissolved in glass could possibly affect its removal properties [74].

A further consideration for glass as a lubricant is the fact that, depending on the composition, glass begins to devitrify or crystallize within a certain temperature range [75]. Thus, if glass is to retain its vitreous nature it should not be held within this temperature range for any length of time. However, it is only important that glasses should remain vitreous during extrusion; after extrusion devitrification of glass could considerably aid in its removal.

A great variety of glass lubricant compositions have been developed for use with various billet materials and extrusion temperatures [43, 76]. Since the viscosity-temperature characteristics of glasses as lubricants are very important, considerable work also has been carried out to develop compositions for optimum performance and for use within specific ranges of temperature. Many patents have been issued on compositions and use of glass and other materials for high-temperature lubrication.

In many hot extrusion applications, ordinary window glass may be used [32], and compositions suitable for more special purposes are available among the commercial glasses. Table 4.6 gives the basic composition of some glasses suggested for various extrusion temperatures [40]. According to Sejournet [1], silicates are suitable for temperatures above 1100°C; for intermediate temperatures the mixtures are predominantly borates, and for low temperatures they are predominantly phosphates. Natural silicates such as basalt have also been used for the extrusion of nickel-base superalloys [62].

A great variety of glass compositions have been used in hot extrusion by a number of individual research workers. While approximate compositions are frequently given, they are seldom sufficient to characterize the glass since minor constituents, usually classified as "other oxides," could play an important part in lubricating performance. In view of the diversity of available information, various studies are summarized below.

(a) In the extrusion of steels and high strength alloys, varying degrees of success have been reported using different glasses. Plain soda-lime glass has only limited application mostly for steel; for very hard alloys, such as nickel-base superalloys, glasses containing small quantities of boron oxide

combined with other oxides were found to be suitable [70]. A number of glass compositions for various applications are also given in References 69, 77, and 78.

(b) Extensive studies on the hot extrusion of refractory alloys using glass lubricants have been carried out [37, 38, 47]. In this work, the glass is applied to the billet prior to heating; the method of preparation is given in Table 8.3. The recommended viscosity range is between 100 and 500 poises at the desired extrusion temperature.

(c) A lubricant based on a mixture of alkali tetraborate in a K_2O-Na_2O-P_2O_5 base is available under the name of Phosphatherm and, being water soluble, is readily applied to the surface of the material. It is claimed that at the temperature of deformation the surface of the metal is transformed into a phosphate, which provides a firm key for the superimposed glass-like layer, the viscosity of which drops less rapidly than in regular glasses [79, 80].

TABLE 8.3

Preparing Glass Lubricants [40]

Spray Mixtures
1. Dry mix 200 ml of -100 mesh glass (all glasses except 7900, -325 mesh) with 1/4 to 1/2 ml of sodium alginate.
2. Add glass and alginate to 150 ml of distilled water (16 to 32°C); mix slowly and thoroughly.
3. Spray immediately after preparation before glass settles from the suspension.

Brush Mixtures
1. Heat 375 ml of distilled water in a beaker to 38°C.
2. Add 1 g of Carbopol 934 to heated water and mix thoroughly.
3. Add NaOH solution (7 to 12 pellets or 1 g NaOH in 59 ml of distilled water) to Carbopol 934 solution to neutralize to pH 7.
4. Add 400 to 700 ml of -100 mesh glass to neutralized solution and mix thoroughly with electric mixer.
5. This mixture may be stored.

(d) Instead of using glass alone as an extrusion lubricant, a number of glass-solid lubricant mixtures have also been developed. These consist of a particulate solid lubricant material dispersed in a glass having a wide viscosity range at the extrusion temperature. Solid lubricants including graphite, molybdenum disulfide (which decomposes at extrusion temperature), and boron nitride have been dispersed in soda-lime silicate or sodium borosilicate glass for the extrusion of titanium alloys. The best results were reported with mixtures containing 10% or less of the solid lubricants [81]. The improvement with solid lubricant additions may be due to by-products; thus, additions of graphite to glass produce carbon monoxide forming a glass foam. It is also possible that the solid lubricant provides boundary lubrication in the event of excessive thinning or breakdown of the liquid film.

(e) For extruding refractory alloys above 1650°C, a glass cloth impregnated with tungsten disulfide in an epoxy or similar carrier has been suggested [82]. The cloth is coated with a slurry of carrier and tungsten disulfide and is cured at about 120°C for about 10 min.

(f) Recent developments in glass lubrication include the concept of using different glasses to establish viscosity gradients between the die/container and the surface of the hot billet. A patent [83] proposes several layers of different viscosity glasses to control melting of the glass lubricant. It would appear, however, that this would be very difficult to achieve in practice without mixing the different glasses. Another patent [84] describes the coating of a steel body with a slurry of softer glass powder followed by the application of an outer wrapping of a cloth of harder glass, such as a high-silica glass.

For the extrusion of hollow articles, Séjournet et al. [85] described a method of coating the bore of a heated hollow billet with two different glasses along the length of the bore. The glass of higher viscosity (80% SiO_2, 12.5% B_2O_3, 2% Al_2O_3, 3.3% Na_2O, and 1.4% K_2O) is applied to the rear of the bore, and the low-viscosity glass (71.5% SiO_2, 1.5% Al_2O_3, 14% Na_2O, and 13% CaO) is applied to the front. However, Rowe claims that no success, either experimentally or industrially, has been obtained with this technique [62].

Methods of Application and Operation

There are various methods of applying glass in hot extrusion, and each method has a profound effect on the lubricating mechanism and on lubricant performance. The techniques include the following: (a) The cold billet is precoated by spraying or swabbing the surface with a suspension of the glass lubricant. (b) The hot billet is rolled on a table that is covered with a powdered or a fiber glass which then adheres to the surface of the billet. Although this is a common and practical method of applying glass, it does not always provide uniform coating on the billet. (c) A pad of glass is placed between the die and the billet to provide a reservoir of liquid glass, as shown in Fig. 8.2. The thickness of the glass disk is usually 1/4 to 1/2 in. The pad is used in conjunction with (b) above. (d) In extruding tubes, either the mandrel is covered with a woven glass sock (expensive) or the hollow billet is sprayed with a glass lubricant (which can also be deposited with a scoop).

Cast glasses (now obsolete) were originally used as pads for extrusion dies and as tubes for mandrel lubrication [65]. These, however, cracked on sudden contact with the hot billet. Eventually, mixtures of glass powders were introduced in various forms such as multicellular glasses, glass pad or powders, wool, fibers, and cloth. The strength of the pad is important to avoid fracture; appropriate strength can be achieved by using a binder of sodium silicate or bentonite clay. Powdered glass bonded with a solution of sodium silicate and preformed into molded glass lubricant sleeves has been described in a patent [86] for steel extrusion but does not appear to be used extensively.

The relative advantages of various glass forms are discussed by Sejournet and Delcroix [63]. Only glass pad or powder is in general use, and is readily available. Particle size is important; very fine size is not desirable—a 100 mesh size is the most suitable. Glass made into pads should normally have a higher softening point than the powder over which the billet is rolled [8]. Foam glass is not readily available in different compositions, and it tends to collapse during the initial stages of pressure application, making lubrication uncontrolled. In a study of foam glasses for the hot extrusion of steel [87], commercially available foams were found to have too high a viscosity, containing typically 70% SiO_2 and 15-18% Na_2O. Also, the graphite that is used as a foaming agent impairs the wetting of the metal by the glass. It is pointed out that foam glass can be more effectively used as a carrier for glass powder.

Removal of Glass

A major criticism of glass lubrication has been the difficulty of removing the glass after the operation has been completed. To remove the strongly adherent glass coating, quenching in water is a normal practice, followed by pickling the product in a solution of hydrofluoric acid of 5-10% concentration or in sodium hydride. Mechanical methods such as shot blasting, vapor blasting, or reeling are also effective.

Because the removal of glass is an important problem, techniques have been developed to reduce the thickness of the coating to 10-30 μ. Thin coatings are, however, somewhat unreliable; a more dependable thickness range is 30-100 μ [62]. The thickness of glass depends on factors such as extrusion speed, die profile, and dwell time in the container. Suitable additions (such as carbonaceous materials) to the glass pad produce extensive foaming at the die exit, which disposes of most of the glass on the extruded billet. Potassium palmitate, in additions of up to 20% by weight, was found to promote sufficient foaming with various glasses without affecting the extrusion pressure [11].

8.35 Canned Extrusion

Canning or jacketing is practiced to: (a) reduce friction and adhesion between the billet and the die and container, (b) to protect the billet from atmospheric or lubricant contamination during heating, extrusion and cooling, (c) to prevent contamination in the extrusion of reactive or toxic materials.

The typical canning technique is rather simple (Fig. 8.15). The space between the billet and the can is sometimes evacuated through a tube which is then crimped and welded, as shown in the example of the rather complex canning developed for extruding tungsten tubes (Fig. 8.16). In canned extrusion it is important that the metal flow be smooth and streamlined in order to reduce defects in the product. This can be achieved by fitting a truncated cone nose to the can-billet composite, matched to the extrusion die with an included angle of about 90-120°.

Canning a billet with a lower strength material reduces the interface shear stress and thereby the extrusion forces. Unckel [88] showed that pressures could be reduced by about 35% in extruding a high-strength

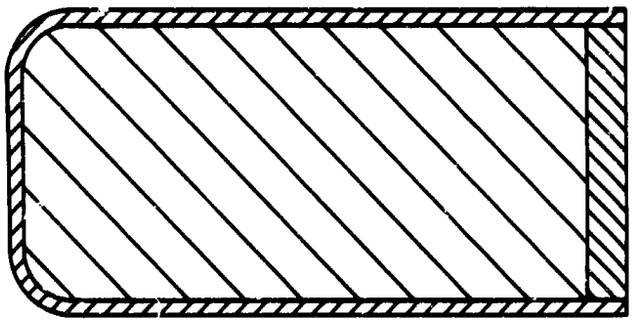

Fig. 8.15. Typical canning technique in extrusion.

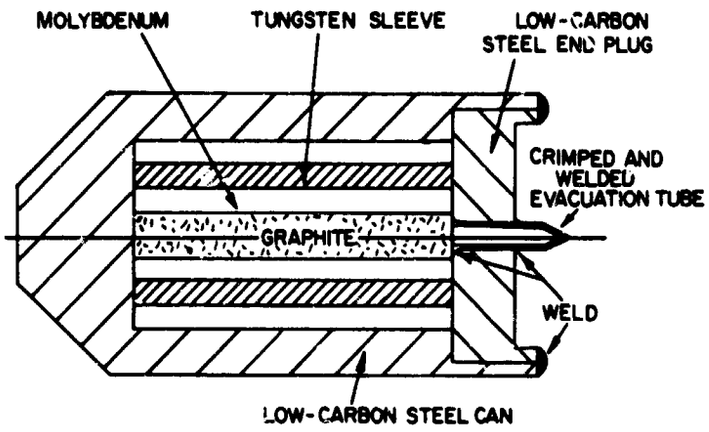

Fig. 8.16. Composite billet for extruding tungsten tubes at 1210°C [131].

Al-Cu-Mg alloy canned in pure aluminum. In this way extrusion defects are also eliminated and the metal flow is very smooth. However, the can material must not be too soft.

Moguchin [89] found that the canning materials with at least 1/2 to 1/3 of the strength of the billet material gave satisfactory results; softer cans flow unevenly and cause periodic thinning of the extruded product.

Chemical characteristics are also important in that little or no reaction should take place between the billet and can materials; in particular, the formation of eutectics or brittle constituents and contamination of the billet material should be avoided. Sometimes it is found advantageous to place a thin sheet of diffusion barrier between the billet and can materials.

If the strength ratios permit, cans are usually made of low-carbon steel or copper tubing, although unalloyed molybdenum has found application for high-temperature extrusion of refractory metal alloys. Billets can also be clad by a variety of depositing techniques, including electrolytic, thermal, and thermochemical [90] methods; examples will be found in Sections 8.5 and 8.9. Methods assuring good adherence of the can to the billet give better performance, more uniform flow; for example, electrodeposited copper was found successful where a loose can of copper failed [91].

One problem with canning is the rough surface that the extruded billet acquires. It is suggested that very coarse-grained castings should be grain-refined first by forging or bare extrusion [53]. After extrusion the can is removed by machining, peeling, or by pickling; the latter is preferred.

Canned extrusion is also used extensively for powder metals giving extruded products of high density and good physical properties [53]. The special applications of canning are given in References 33, 52, and 72.

8.36 Cladding

Cladding, a term sometimes used also for canning, is essentially a co-extrusion process where the clad material, unlike canning, is not removed after extrusion. It is used in applications such as fuel elements for reactors, conductors for the electrical industry, and heat exchangers for the chemical industry. Thus the purpose of cladding may be mechanical, electrical, or chemical; in all instances, a metallurgical bond is usually required. Examples of cladding are uranium dioxide pellets extruded in stainless steel or zirconium alloy cans, copper-clad stainless steel and uranium clad with aluminum or magnesium-base alloy. Stainless steel clad with mild steel, and composite stainless steel-mild steel tubes have also been extruded.

8.4 LUBRICANTS FOR FERROUS MATERIALS

Among the great variety of lubricants discussed earlier, only glasses and mixtures containing graphite appear to have found their way into production practice in steel extrusion. As far as can be ascertained, glass is in general use, following developments by Séjournet, for the extrusion of steel and stainless steel tubes, bars, and sections in longer lengths. Dies are of 180° included angle; smaller angles are mostly restricted to experimental work. The reasons for this appear to be economic. Dies with included

angles less than 180° would require billets with truncated nose. Such billets have to be specially machined and the material left in the container would be of greater volume, thus making the process rather uneconomical. On the other hand, the extrusion process is improved with the use of conical dies and, if a deformable (graphite) follower block is fully extruded, end losses are minimal.

When extruding through "square" (180° included angle) dies, a glass pad is invariably used, in conjunction with a glass coat applied to the billet after heating. With conical entry dies (included angle usually 90°-120°), the glass or other lubricant is often preapplied to stainless steel billet surfaces. Container liners, dies, and tube mandrels are made of conventional hot-working die steels and are usually heated to the range 260°-430°C. In choosing die materials, the primary consideration is heat resistance and long life; occasionally, the working surface of the die is rough machined and then coated by a plasma or other deposition technique with a zirconia or alumina coating of approximately 0.010 to 0.040 in. thickness. The purpose of this coating is primarily that of reducing heat transfer, and little consideration seems to be given to influencing the lubricating mechanism by a selection of an optimum die-lubricant-workpiece system.

Graphite-bearing compounds are often used in the extrusion of shorter lengths. The primary purpose of the lubricant is then that of reducing friction; heat transfer is rapid but is counterbalanced by short contact times resulting from fast work strokes. Die angles of less than 180° are commonly preferred for reducing extrusion forces. Die and container materials are again of the conventional hot-working die steel type.

Extrusion presses operate at fairly high speeds (typically, 300-1200 ipm) to limit cooling. Extensive literature is available on steel extrusion, some of the more informative articles may be found in References 32, 54, 60, 63, 65, 66, 92, 93. Precipitation-hardenable stainless steels are extruded with procedures similar to those developed for steel [94].

A number of experimental studies have been carried out on 4340 steel to determine optimum lubrication practices. The first systematic study is due to Shaw, Boulger, and Lorig [16] who measured forces in extruding 1 in. diameter billets at 1180°C with an extrusion ratio of 4:1 and an included die angle of 130°. All lubricants containing graphite, with or without additional

solid materials, gave fairly uniform extrusion pressures. Very high pressures were developed when MoS_2 was used alone in a calcium grease, probably because it decomposes at these high temperatures. Extrusion pressures were not reduced by additions of boron nitride, vermiculite, and talc to a conventional lubricant. A number of glasses were tried, but pressures were higher than with grease-type lubricants containing graphite. This should not be taken as a generalized conclusion, because the billets were abnormally small compared to those used for the production of long lengths.

In another study [36] results from extrusion trials at 980°C indicated that a mixture of magnesium metaborate and graphite, applied prior to extrusion in an aqueous slurry, promoted relatively low extrusion pressures, close dimensions, and good surface finish.

Preliminary evaluation of rather limited data on the extrusion of short lengths indicated that glass lubricants may be unnecessary when the liner is coated with a graduated alumina-nickel-ceramic [95]; the practicability of such a solution remains to be proven.

Proprietary glasses have been found useful for extruding structural shapes of this steel [96] under the following conditions: Billet temperature of 1260° C, fast billet transfer, Al_2O_3 -coated steel dies, and a ram speed of 8-15 ips. It would appear, however, that the alumina coating will wear off rapidly, and provisions for rapid and low-cost recoating would have to be made.

8.5 LUBRICANTS FOR LIGHT METALS

8.51 Aluminum and Its Alloys

For best surface finish and freedom from defects, aluminum and its alloys are usually extruded without any lubricant.

Some references have, however, been found on the use of graphite-base lubricants. A spray consisting of colloidial graphite and caustic soda has been found suitable for the lubrication of the die land [97]. The caustic soda dissolves any aluminum remaining in the die from the previous extrusion, while the graphite serves to lubricate the next extrusion. In practice such local lubrication is usually frowned upon because uneven material flow may cause subsurface defects (lamination).

In small-scale laboratory tests on extruding 2014 aluminum alloy at 440°C, lubricants reduced forces considerably [16] (Fig. 8.13). Tetrafluoroethylene resin was applied to the billet only, while an organic grease containing "extra-fine" flake graphite was applied to the die and the container. As would be expected, conical dies produced a more uniform macrostructure and appeared to minimize grain growth. In larger scale experiments with 3 in. diameter billets, tetrafluoroethylene resin primer was applied to the billet to serve as a lubricant [16, 98]. The surface of the extrusion was not bright, in contrast to that obtained with flat-faced dies and no lubrication. It should be noted that lubricated extrusion with flat-faced dies usually leads to extensive subsurface defects, by a mechanism similar to that discussed in conjunction with Fig. 8.7.

Various materials were tested as lubricants for the extrusion of aluminum cable sheath [99]. A polymerized oil coating was the most effective in reducing adhesion of aluminum. The coating was produced by dipping the parts in high-temperature motor oil. On heating to about 350°C by a radiant heater, a partly polymerized, partly carbonized hydrocarbon was produced which was very adherent and hard and had a black glossy finish.

8.52 Magnesium and Its Alloys

The powdery oxide formed on magnesium alloys possesses lubricating properties, as shown by metal flow studies. Flow is of the well-lubricated type [19, 21] similar to that of copper at 800°C [41].

In the experimental extrusion of AZ80A magnesium alloy [98] the application of tetrafluoroethylene resin primers to the billets reduced extrusion pressures markedly. Surface cracking observed with flat-faced dies was reduced by conical dies; the latter also permitted higher extrusion speeds.

8.53 Beryllium

Commercially pure beryllium can be extruded within a temperature range of 400° to 1100°C. Bare extrusion is safe only below 750°C. In the temperature range of 400°-650°C, MoS_2 may be used as a lubricant, although it shows no significant advantage over graphite [100, 101]. The products of this "warm extrusion" are of good quality and high dimensional accuracy. Also, small-diameter thin tubing was readily warm extruded between 430° and 540°C with colloidal graphite and MoS_2 lubricant [101]. Electrodeposited

or spray-deposited silver has proved useful as a lubricant in the warm extrusion of hot-pressed or pre-extruded beryllium bars [72]. The silver can be removed by dissolution in nitric acid.

Glass lubrication has not been successful in the hot extrusion (above 750°C) of bare beryllium [101, 102]. The main reason is that, in the event of lubricant breakdown, the contact of beryllium with the die causes rapid wear. Frit and salt lubrication also failed because of the difficulty of removal and poor surface quality of the extruded product.

The most common method for hot extrusion is canning in mild steel [102-104]. This serves to minimize oxidation of the billet and health hazards due to loose beryllium and oxide dust, in addition to reducing die wear. For further reduction of friction, the steel jacket may be coated with an 0.020-0.030 in. thick copper film by electrodeposition [105]. A lubricant between the copper coating and the container is also used. One lubricant mentioned is a mica-base compound, but special lubricants containing asbestos have also been suggested [102].

Beryllium powder has been extruded encased in steel jackets [106]. Tools and liner were lubricated with bentonite-base grease with graphite in suspension.

In using steel cans the upper limit of temperature is 1065°C, beyond which alloying occurs between the steel and beryllium [72]. Although not reported, glass would appear to be a practicable lubricant for the extrusion of longer lengths.

8.6 LUBRICANTS FOR COPPER AND BRASS

In general, copper and its alloys are extruded dry or with a lubricant consisting of graphite-oil or graphite-grease mixtures. Glasses are occasionally used, as have been graphited grease [10], resin-bonded graphite, and barium chloride [62]. (See also Section 8.24 and Fig. 8.14.)

8.7 LUBRICANTS FOR TITANIUM AND ITS ALLOYS

Lubrication is particularly important in the hot extrusion of titanium because of its severe galling characteristics which can result in excessive die wear and loss of dimensional control of the extruded product. To protect the highly reactive titanium billet surfaces from atmospheric contamination, heating must be done with special care, preferably in an inert atmosphere

or in vacuum; otherwise, a protective coating of a glassy type must be applied prior to heating.

The two basic types of lubricants used in the hot extrusion of titanium alloys are grease and glasses. Solid additives such as graphite, MoS_2, talc, mica, soapstone, and asphalt are incorporated into the greases. To provide adequate lubrication, it has been suggested that solids in greases be about 50% by weight.

Glasses are also used by most extruders of titanium, the technique being similar to that of extruding steel [107, 108], although different glasses are needed since extrusion temperatures are usually lower. Molten salts (LiF and NaCl) gave reasonable results in experimental work [11].

Copper jacketing (canning) of titanium is also practiced, copper being a suitable material because of its good ductility particularly at the temperature of titanium extrusion. A thin layer of steel is used between the billet and the copper can to avoid contamination. The lubricants used in this case have been grease and graphite mixtures [109]. This process is suitable for extruding long lengths of uniform quality.

A number of publications deal with experimental lubricants and lubrication methods. In extruding unalloyed titanium heated to 905°C in an argon atmosphere, at an extrusion ratio of 4.3:1, with tools heated to 480°C, lubricants containing graphite were found [16] to give lower forces and improved surface finish compared with those containing MoS_2 but not graphite (Fig. 8.12). Aluminum soap greases as carriers appeared to require lower forces than bentonite-thickened grease or calcium-soap grease. Graphite mixed with powdered glass improved the lubricating properties of the glass (although application must have presented some problems). Also, it was observed that an oxide layer on the billets reduced forces below those obtained with billets that were heated in an argon atmosphere; however, the resultant contamination of the surface may be objectionable for most applications.

Further experimental lubricant mixtures were investigated in the extrusion of a Ti-3Mn-1Cr-1Fe-1Mo-1V alloy [110] at 870°C with a die of 130° included angle. Of the four mixtures tested, three were based on a calcium-base grease because its oxidation products were considered less abrasive than those of other high-temperature soaps. Mica was added to all of the lubricants to improve their insulating properties, and graphite and/or MoS_2

for better lubrication. The fourth mixture, a bentonite-grease base lubricant (containing 25% flake graphite, 15% MoS_2, and 5% mica) was found to produce the best surface finish, the least amount of pickup, and the lowest extrusion pressure. The surface finish was found to depend greatly on the consistency of the lubricant mixture. Lighter mixtures produced a more uniform distribution of the lubricant, avoiding excessive accumulation of the lubricant and giving a smoother surface finish.

A variety of structural shapes of Ti-155A, MS 821, Ti-7Al-4Mo, Ti-4Al-3Mo-1V, and Ti-6Al-4V alloys were extruded with 1/16 in. web thickness in 20 ft lengths [48]. Split ceramic coated dies and a composite glass wool/granular glass die pad was found suitable for extrusion at 980°C. Lubrication and jacketing procedures in extruding a variety of titanium alloys are given in References 37, 50, and 111.

8.8 LUBRICANTS FOR NICKEL- AND COBALT-BASE ALLOYS

Nickel- and cobalt-base superalloys have assumed great industrial significance in recent years, particularly for jet engine applications. All extruders use glass lubrication with procedures similar to those developed for extruding steel. Successful extrusion of these alloys is possible only with accurate temperature control, since the working temperature range is usually narrow. Canning of the billet has been reported [112], and basalt has also been used [62].

Some superalloys possess rather high strength at the extrusion temperature and if, for this or any other reason, low extrusion ratios are used, the glass pad placed in front of the billet would be extruded. Therefore, lubrication with glass coats applied prior to heating the billet becomes important. Generally good results have been obtained with sprayed glass in the extrusion of Udimet 700 at 1080°-1160°C and Inconel X and IN-100 at 1180°C [37]. Also, a magnesium metaborate-graphite mixture (Section 8.4) was reported to give good overall results for nickel-base alloys. Waspaloy and René 41 have been extruded without difficulty with 0010 glass lubrication [113].

Powder billets of René 41 have been extruded using glass lubricants within a temperature range of 1125°-1260°C with the container at 480°C. The extrusion ratio ranged from 8 to 16:1 [114].

8.9 LUBRICANTS FOR REFRACTORY METAL ALLOYS

In the extrusion of refractory metal alloys, lubricants such as graphite and some glasses are used for the temperature range of 980°-1320°C. For higher temperatures, glasses with viscosities ranging from 100 to 500 poises at the metal temperature have been considered to be the most useful. These may be either sprayed or brushed [113]. It appears that glass pads would be quite effective—provided, of course, that the extrusion ratio is sufficiently high. Canning or coating with a low shear strength, ductile metal is widespread. Dies are frequently coated with Al_2O_3 or ZrO_2.

8.91 Columbium

Columbium-base alloys are extruded within a temperature range of 1035-2040°C, using glass lubrication and/or canning with mild steel, copper, or molybdenum, as appropriate for the extrusion temperature. For extrusion temperatures between 1035° and 1370°C grease, graphite, or glass have proved to be adequate; above this temperature range lubrication of uncanned billets is apparently difficult [115]. Also, commercially available glasses have been found to be corrosive for these alloys above 1200°C, hence cladding with mild steel is suggested [116]. Unfortunately, glasses used in many studies were of a proprietary nature [117-120]. For columbium-tungsten alloys glasses have been used with varying degrees of success [37]. The alloy B-66 (Cb-5Mo-5V-1Zr) has been extruded successfully using molybdenum jackets at extrusion temperatures of 1540°-1760°C [37]. Glass with a softening point of 1000°C was found acceptable in the extrusion of a Cb-20% W alloy at 1650°C [11].

8.92 Molybdenum

Unalloyed molybdenum does not present undue difficulties, and a variety of lubrication techniques—including glasses preapplied to the billet, and compounds containing graphite or MoS_2 applied to the die and container—seem to give acceptable products. It is quite likely that the oxide of molybdenum, liquid or vapor at the extrusion temperature, contributes to lubrication.

A great number of reports deal with the extrusion of molybdenum and its alloys. Unalloyed arc-cast molybdenum has been successfully extruded at temperatures of 1100° to 1370°C using Corning glasses 0010, 7052, and 9772 [49]. For a Mo-0.5% Ti alloy, a temperature of 1930°C and a lubricant

mixture of magnesium metaborate and graphite in water (Section 8.4) gave a low extrusion pressure and good control of dimensions and surface finish [36, 59]. The use of molten salts such as lithium chloride has also been reported [62]. A variety of molybdenum alloys have been extruded with a great number of glass compositions such as are listed in Table 4.6 and given in References 37, 47, 49, 50, and 121-123. The results have been generally good. In some experimental work proprietary glasses have been used [50, 96, 124]. In addition, the container and the die have been lubricated with compounds such as graphited grease, MoS_2 in grease or volatile carrier, MoS_2 + Pb, or aqueous dispersion of graphite. In view of the great number of variables involved, it would be virtually impossible to make quantitative statements about the results obtained. It is obvious, however, that carefully selected glass compositions perform well in the hot extrusion of molybdenum alloys.

8.93 Tantalum

Tantalum and its alloys are extruded within a temperature range of 980°-2040°C, using glass lubrication and/or jacketing with molybdenum or—at lower temperatures—mild steel. Various glasses such as Corning 0010, 7052, 7740, 7810, and 9772 [37, 49, 51, 125] gave generally good results. In other studies proprietary glasses have been used [126, 127], in one case combined with molybdenum powder. For a Ta-Hf alloy the optimum extrusion temperature has been found to be 2040°C, and for a Ta-Cb alloy 1870°C. A ZrO_2 die facing and glass 7810 performed satisfactorily at 1870° C and above; and Al_2O_3 die facing and glass 7740 were adequate below this temperature [125]. Cladding not only has advantages as a lubricant but also offers protection from atmospheric contamination. In the extrusion of tube blanks of Ta-W-Hf alloy, mild steel cans were preferred over molybdenum since extrusion could be performed at 1260°C or less [116].

8.94 Tungsten

The available information indicates that tungsten and its alloys are extruded within a wide range of temperatures, from 1600°C to as high as 2200°C, with lubrication techniques involving glass and/or canning with molybdenum jackets [38]. Varying degrees of success have been obtained depending on the particular alloy and the type of glass used [37, 49, 51, 122, 123, 128, 129]. Glasses applied to the billet and Fiske 604 (a graphited

grease) applied to the dies also gave good results [37], in one case in conjunction with a molybdenum jacket. Arc-cast tungsten ingots have been extruded at 1930°C with the billet rolled over a Pyrex glass wool mat containing a proprietary glass [130]. Glass lubrication was also reported for the extrusion of tungsten tubing [131]. Uniform coatings of 0.010-0.020 in. thick unalloyed tungsten have been applied on W-25% Re tube billets providing ample oxidation protection and lubrication. It is stated that the relatively low deposition temperature (550°-580°C) and short time probably did not alter the alloys or permit diffusion between the billet and cladding materials [90].

8.10 LUBRICANTS FOR OTHER METALS

8.101 Zirconium

Zirconium, like titanium, has a tendency to gall when in contact with extrusion dies and containers. When the billets are heated in air, an oxide film forms which, in combination with a graphite-base lubricant, can function satisfactorily. Salt bath preheating combined with glass lubrication has also been successful. The disadvantage of these methods is that they result in contamination of the billet and, thus, create adverse effects on properties [72]. Thevenet and Buffet [132] reported the application of techniques identical with the Séjournet process for the hot extrusion of zirconium and Zircaloy-2 tubes at 750°C. Spray coating of the billet with glass before heating in a gas-fired furnace has been described by Halapatz [133] for the hot extrusion of Zircaloy-1.

Jacketing of zirconium billets is also possible provided the jacketing material has an extrusion constant similar to the billet material and it does not react with zirconium at the extrusion temperature. Copper can be used up to 800°C, steel up to 900°C [72].

8.102 Vanadium

Vanadium is one of the more readily extruded materials. Hot extrusion has been described by Lacy and Beck [134]; clippings of vanadium sheet were sealed in vacuum in a steel container and extruded at 1100°-1150°C at a ratio of 10:1 to 18:1, using a graphite-oil lubricant.

8.103 Uranium

The successful extrusion of uranium alloys has been described by Lorenz et al. [135]. The alloys were heated to 815°-970°C (depending on the alloy) in a chloride bath and extruded at ratios up to 35:1, using MoS_2 as the lubricant. The dies were made of chromium-plated steel. The use of glasses or barium chloride has also been reported [62].

Pardoe [72] discussed uranium extrusion, emphasizing atmospheric contamination and oxidation problems. Cladding with copper and heating in an inert atmosphere such as argon or helium or in molten salt baths are suggested. The choice of the extrusion temperature is also important since marked changes in hardness take place at different temperature ranges with allotropic transformations. Pardoe also gives details of the coextrusion and clad extrusion of uranium for nuclear reactor applications.

Uranium-zirconium composite extrusion has been carried out at about 680°C with evacuated copper jacketing and a lubricant composed of graphite resin containing MoS_2 [136]. Various techniques have been described by Kaufmann et al. [137] for the hot extrusion of UO_2 fuel elements. Iron and copper have been used for the heavy outer can; and cladding materials (inner can) have been stainless steel, tantalum, and molybdenum.

8.11 LUBRICANTS FOR HIGH ENERGY RATE HOT EXTRUSION

In view of the great interest in high energy rate metal forming processes, hot extrusion studies have also been carried out at high deformation rates. Some results from the limited amount of work done to date are summarized below.

Tee shapes (2 in. x 1 in. x 0.050 in.) of Ti-6Al-4V, AISI 4340, and 304 stainless steel [138] were extruded through ceramic-coated dies at an extrusion ratio of 17:1. The dies were lubricated with graphite; billet lubrication was not used. The container was sprayed with a graphite-alcohol mixture. In further studies, glasses, greases, and other compounds were evaluated as billet lubricants; however, no conclusive answer as to the best lubricant was obtained.

In the direct extrusion of various materials [138] graphitized molybdenum disulfide was the most satisfactory lubricant for all materials. This lubricant was applied to both the die and the punch, but not to the billets.

Sintered tungsten powder billets were extruded [139] at 1800°C at ratios of 6.25:1 and 9:1. The liner was protected with thin molybdenum sheet. A mixture of graphite and MoS_2 was used to lubricate the tooling, and all billets were extruded without any protective coating.

Arc-cast billets of Mo-25W-0.1Zr [122] alloy were extruded with Corning 7052 glass. The die and the container were lubricated with colloidal graphite in water. Another arc-cast alloy, W-0.6Cb, was extruded at a ratio of 4:1 and a temperature range of 1600° -1800° C, using 100 mesh Corning glasses 7052 and 7810. The die and the container were lubricated with colloidal graphite in water [122].

It would appear that the small billet size and the high extrusion speeds limit cooling; therefore, graphite and/or MoS_2 could be expected to perform reasonably well.

8.12 SUMMARY

As evident from the extensive literature available, lubrication in hot extrusion has indeed been the subject of scrutiny at both the experimental and the industrial levels.

In spite of the many efforts made, our knowledge of the mechanisms of lubrication in hot extrusion is still incomplete and in some cases rather controversial. Although graphite suspensions are quite attractive as lubricants, the introduction of glass lubrication has been, by far, the most important development. Yet, in spite of its success in many applications, the mechanism of glass lubrication and the physical characteristics governing it are not fully established. It is increasingly clear, however, that for higher extrusion ratios a glass pad of sufficient strength is of great importance. This glass pad serves as a reservoir of gradually melting glass lubricant, thus enabling long lengths of extrusion to be produced. On the other hand, when the extrusion ratio is rather small—as is the case with some refractory metal alloys and superalloys—the problem of maintaining a glass film without a pad becomes serious; this, in turn, requires a reconsideration of the die geometry and the billet coating in order to insure a more or less full-fluid lubricant film throughout the extrusion cycle. There is still some controversy whether, at sufficient extrusion speeds and with proper selection of die angles, a lubrication mechanism of the hydrodynamic type can be maintained. With appropriate techniques, hydrostatic lubrication similar to that existing in cold hydrostatic extrusion can be assured.

The review presented in this chapter has also shown the importance of the lubricant and die angle on material flow and properties of the extruded product. It is also clear that, probably because of the difficulties involved in conducting experiments at elevated temperatures, the available literature does not always give a clear picture as to the interrelationships between lubricant performance and other process and material variables. In some cases one could even question the accuracy and validity of the data published, particularly when they pertain to such difficult topics as the coefficient of friction, interface shear strength, and forces in hot extrusion. Neither is the proper interpretation of data an easy matter, especially when the temperatures, pressures, and speeds are as high as those in the hot extrusion of some materials. Further complications enter the picture when one realizes that data on forces, die wear, and the surface finish obtained in tests of short duration do not necessarily give a correct indication of the long-term performance of the lubricant, particularly with regard to die life. On the other hand, it would appear that full-scale die life tests with the large number of variables concerned could hardly be run, at least not economically.

There is no doubt that this is a fruitful field for more research and, perhaps because of the great difficulties involved, all the more rewarding potentially. It is hoped that the survey presented in this chapter will form a background for further work as well as to serve as a guide to answer some of the more practical questions concerning lubrication in hot extrusion.

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Chapter 9

FORGING LUBRICATION

Serope Kalpakjian

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9.1 INTRODUCTION

In forging, the lubricant is called upon to perform some or all of the functions described in Section 5.1, with particular emphasis on the following:

(a) Reduce sliding friction between the die and the forging in order to reduce forces and aid die filling. It is conceivable, however, that die filling may be promoted by high friction in the flash gutter.

(b) Act as a parting agent, or prevent local welding and subsequent damage to the die and workpiece surface, to assure good surface quality on the finished product.

(c) Possess insulating properties so as to reduce heat losses from the workpiece and minimize the temperature fluctuations in the surface of the die which would lead to premature failure by thermal fatigue and to surface cracks in less forgeable materials.

(d) Develop a balanced gas pressure to assist quick release of the forging from the die cavity.

(e) Wet the surface uniformly, otherwise local breakdown becomes inevitable at some places, while the accumulation of excess lubricant causes partial filling in other parts of the die cavity.

(f) Be nonabrasive so as to prevent erosion of the die surface.

(g) Be free of residues that could accumulate in deep impressions and not develop by-products that pollute the environment.

The relative importance of the above-listed and sometimes contradictory properties will vary according to the local conditions and the specific task. Lubricants fulfilling some of these requirements have been developed over the years. It is found in practice that, for hot forging, the most common lubricant is graphite suspended in grease, oil, or water [1-7]. A great variety of other lubricants, proprietary or made up of basic ingredients, have also found use. The oxides of some metals fulfill a useful function as

parting agents, while some metals, such as tungsten and molybdenum, form soft or liquid oxides which function as lubricants. Considering the great variety, it is not surprising that many lubricants used in industry for hot forging are held confidential. Most open-die forging requires no special lubrication; natural oxides on the workpiece material serve as lubricants. Cold forging lubrication practices are similar to cold extrusion or wire drawing, and appropriate information is given in Chapter 10.

In view of the great variety of lubricants available and the complexity of the process itself in terms of such variables as die geometry, workpiece material, forging temperature, and speed, systematic studies are necessary in order to identify factors that contribute to successful lubrication in forging. In the following sections, the available general information is presented first, and specific information pertaining to particular workpiece materials is dealt with later.

9.2 FRICTION AND LUBRICATION EFFECTS

9.21 Effect of Friction on Deformation

The compression of cylindrical specimens between flat parallel platens has been frequently employed for investigative purposes of the effect of friction on deformation in forging processes. The most obvious manifestation of friction in such a test is the barreling of the specimen (Fig. 2.16). As discussed in Section 2.52, changes in the original end diameters of the specimen are a further, sensitive indication of friction when partial sticking prevails over the end face.

Although friction is recognized to be a significant factor in governing barreling and end face expansion, cooling of a hot workpiece in contact with a colder anvil may cause the same changes as increasing friction would. Separation of the cooling and friction effects is extremely difficult; therefore, much of the work relevant to the shape changes in forging has been restricted to room-temperature experiments. These will be considered first, followed by a discussion of hot forging experiments.

Friction Effects Without Cooling

In spite of the fact that barreling has been commonly observed in upsetting, only recently have there been some attempts made for a quantitative evaluation of this phenomenon. Kulkarni and Kalpakjian [8] have shown that

the profile of barreled 7075 aluminum alloy specimens of H_o/D_o ratio of 1.5 to 0.75 upset at room temperature can be approximated very closely by an arc of a circle, R_c. A useful quantity expressing relative curvature was found to be $H_{ur} = H_f/R_c$ where H_f is the final height of the specimen. H_{ur} increased with increasing reduction and increasing friction (Fig. 9.1) while speed of deformation and aspect ratio did not seem to have any appreciable influence. The precise effect of lubrication was difficult to study since the friction coefficient has been shown to be a function of reduction in height (Section 9.22). Additional data on barreling, as a function of reduction and lubrication, have been obtained also by Latham, Cockcroft, and Tweedie [9]. Using a single sheet of PTFE on copper specimens, Hsu [10] has shown that barreling can be virtually eliminated. This is attributed not only to the good lubricating characteristics of PTFE but also to its action as a pressurized fluid producing a net outward force at the ends of the specimen.

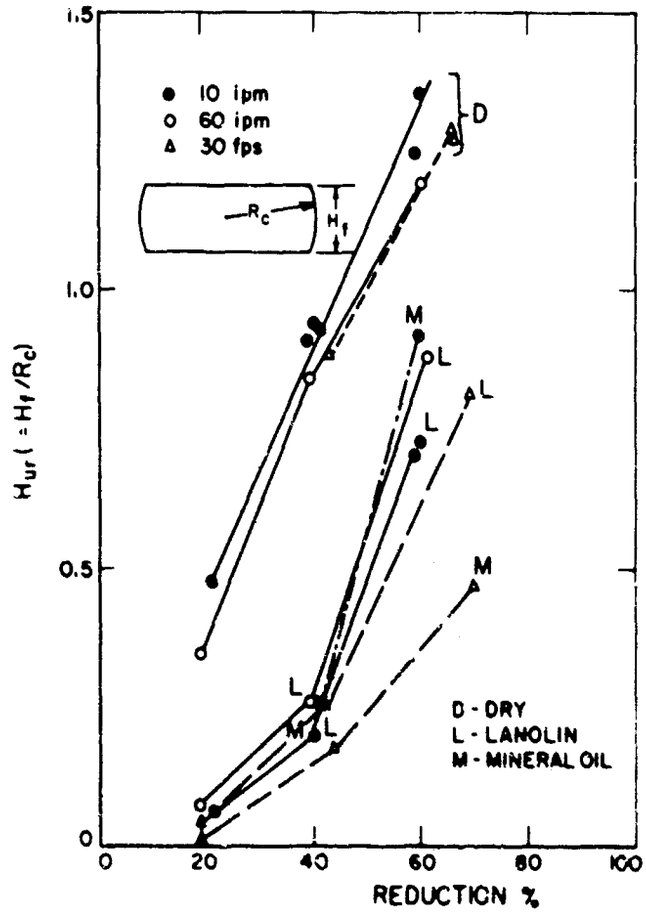

Figure 9.1. Relation of ratio H_{ur} to reduction when upsetting with hydraulic press (10 and 60 ipm) and drop hammer (30 fps) [8].

Studies by researchers at MIT [11] on triangular specimens again showed the influence of lubrication and reduction in height on the bulging of the specimens. With increasing reduction, the originally triangular cross section approached that of a circle because the material always flows in the direction of least resistance.

Among factors that influence the degree of barreling is the platen or die geometry. Barreling can be avoided by using conical platens; this occurs when the coefficient of friction is equal to the tangent of the inclination angle of the conical platen (Fig. 5.4b). Several researchers have obtained data on the effect of the platen angle on the degree of barreling, but information on the effect of various lubricants as a parameter does not appear to be available.

Combined Effects of Friction and Cooling

While the foregoing discussion pertains basically to a constant temperature throughout the die-workpiece system (isothermal forging), it is evident that a hot billet in contact with cool platens will exhibit a greater degree of barreling. This is due to the fact that the upper and lower end faces of the cylindrical specimen are now at a lower temperature than the central portions of the specimen, hence they will exhibit a greater strength and, thus, greater resistance to deformation. However, there is also the possibility that the die-workpiece interface could actually be heated by friction (particularly at high speeds) and exhibit a lower resistance to deformation. Under these conditions, it would be difficult to predict correctly the mode of deformation since this depends on how far the reduction of strength due to interfacial heating is able to counterbalance the frictional resistance which induces barreling and nonuniform deformation.

Schey [12] has shown that in the hot forging of steel, even with graphite lubrication, the end faces increase their area by folding the cylindrical side surfaces against the die interface (Fig. 9.2). Sticking friction prevails over most of the end face, and folding over of the side surfaces is the sole deformation mechanism for a substantial part of the compression process [13]. Specimens of a H_o/D_o 1:1 aspect ratio show very little spread of the original end surfaces at 50% reduction, and even higher reductions are needed to initiate sliding with specimens of greater initial aspect ratio. In fact, perceptible sliding begins only when, irrespective of the initial aspect ratio, the instantaneous aspect ratio reaches 1:4—that is, the diameter of the deformed specimen is four times greater than its height (Fig. 9.3). Much

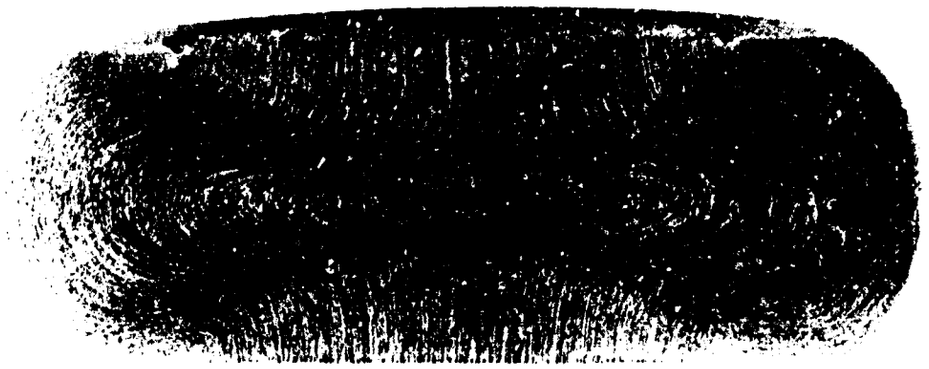

Figure 9.2. Material flow in hot upsetting of steel with sticking friction [12].

published work that employed simple compression for lubricant testing was not carried to such heavy deformations, and the expansion of the original end face was not measured. It is reasonable to assume, therefore, that a fair portion of information on barreling scattered throughout the literature should be viewed with reservation. The deformed specimens have seldom been sectioned nor the end faces carefully inspected, and the shape development due to true barreling and that due to folding over of the side faces cannot be separated.

In plane-strain compression there is no external sign of the effect of friction in the major direction of deformation; however, a cross-section of hot-formed specimens reveals that a sticking zone develops without a lubricant just as in cylindrical upsetting, whereas a completely uniform laminar flow may be achieved with a glass [14]. Lateral spread, although small, noticeably increases with increasing friction.

9.22 Lubricating Mechanisms

In addition to the basic mechanisms of lubrication discussed in Section 3.4, there are particular situations which are unique to forging and related compressive deformation processes. The major considerations are the existence of squeeze films, breakdown of lubricating films, the effect of surface finish, and the effects of relubrication and vibration.

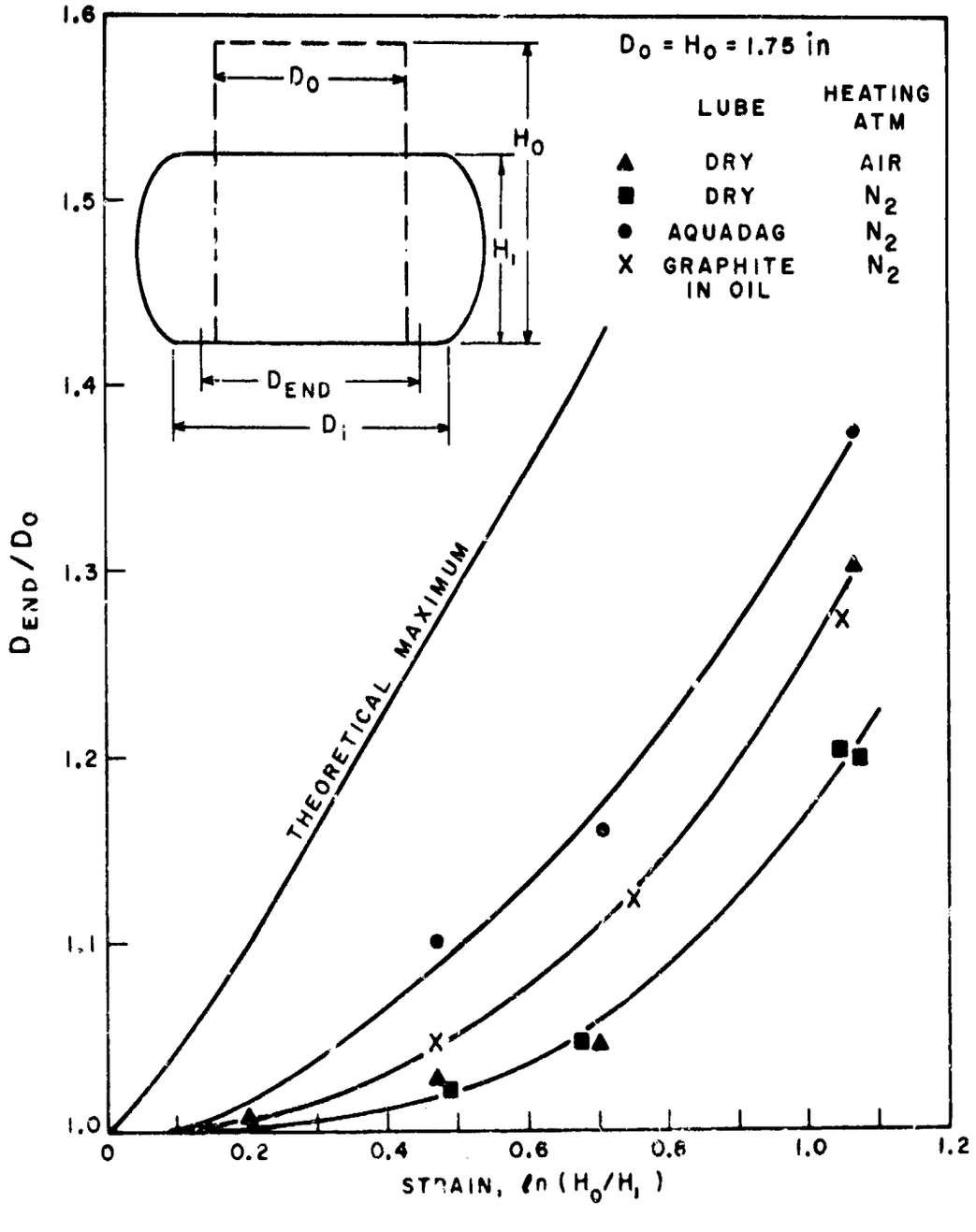

Figure 9.3. Variation of original top end-face diameter (D_0) with strain for simple press upsetting of steel. Speed: 30 ipm [13].

Full Fluid Films

Although partial or full sticking friction and dry or boundary lubrication are the most commonly observed mechanisms in forging and related processes, there can be situations where full fluid film lubrication exists.

Irrespective of the viscosity of the lubricant, fluid films can be established easily by mechanical trapping with suitably profiled specimens as shown in the extensive work by Butler [15-17]. However, when such films are present in the tool-workpiece interface, the deformed surface does not fully conform to the die surface, resulting in a generally dull, matte appearance due to the deformation of individual grains. For this reason, the coarseness of the finish is influenced by the lubricant and by the original grain size of the material; the coarser the grain size, the rougher the finish.

With a viscous fluid as a lubricant, full fluid film separation between the tool and workpiece can be obtained only by a normal velocity component between the two approaching surfaces. The pressure in such "squeeze" films is given by the following expression [16, 18]:

$$p = \frac{3\eta v (R^2 - r^2)}{t^3} \qquad (9.1)$$

where p is the pressure in the fluid, η its viscosity, v the normal approach velocity, R the radius of point considered, and t the thickness of the fluid film at this point. In this simple treatment, viscosity is assumed to be independent of pressure. The predicted pressure distribution is shown in Fig. 9.4 (Stage A). The pressure can be sufficiently high to cause plastic deformation of the disk in the central region, thus assuring full fluid lubrication (Stage B) while the periphery will be exposed to boundary contact conditions. Once the periphery is sealed (Stage C), the lubricant is trapped and is capable of transmitting high pressures, irrespective of viscosity [19].

Although this is a simplified analysis, it does indicate the importance of velocity in upsetting. As a specific example Fig. 9.5 shows a plot of the interrelationship of film thickness t, disk diameter 2R, and normal velocity v to cause plastic deformation in annealed copper disks.

Mechanical Entrapment

Even when the viscosity of the lubricant and the sliding speed are not sufficiently high to produce a full fluid film, lubricant may be trapped in microscopic surface pockets of the workpiece surface. This would create

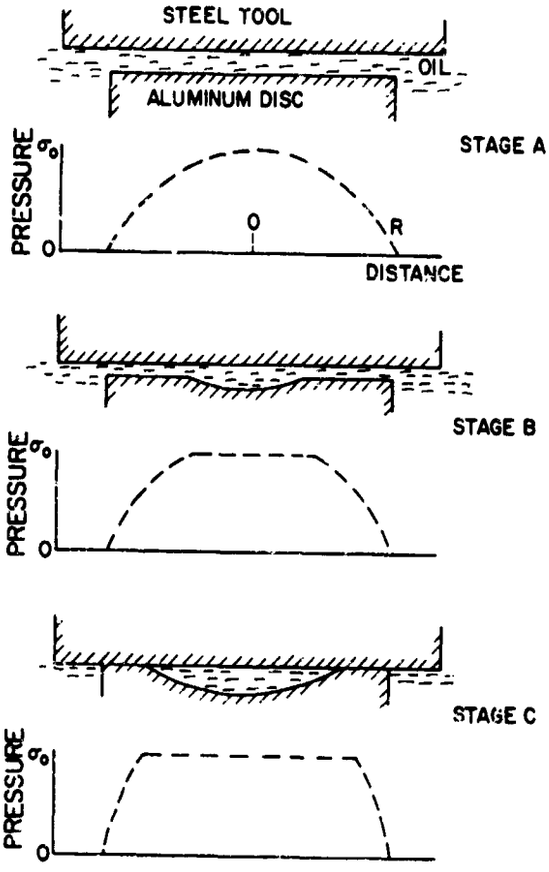

Figure 9.4. Development of hydrostatic squeeze film during the deformation of a circular disk covered by a lubricant [19].

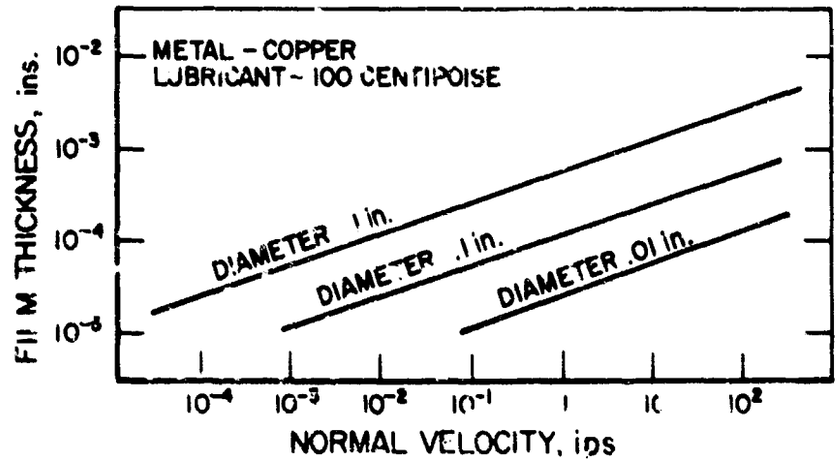

Figure 9.5. Plot of the squeeze film thickness at which plastic deformation through the lubricant film commences [19].

hydrostatic pressure of sufficient magnitude to support a considerable portion of the normal load, and the low shear strength of the trapped fluid would give low coefficients of friction. An analytical study by Kudo [20] is based on an interface model of a grooved surface using the plane-strain theory of plasticity for a rigid, perfectly plastic material. It is valid only for the instant when deformation begins; a solution for the more complex situation for bulk material flow has not been developed yet. The effect is, however, well established in practice and in experiments [15-17].

Wilson and Rowe [21] have commented on the role of macroscopic surface roughness and the entrapment of lubricant at the interface. Specimen surfaces were prepared either with serrated pyramidal hollows or pyramidal hills. In compression tests with a film of oil at the interface, it was observed that the pyramidal hollows were more effective in reducing friction: A substantial portion of the load was found to be supported by pockets of oil in the hollows. They state that a finely spaced hollow pattern will result in no pickup and that surfaces containing closely spaced pockets or valleys, rather than individual prominences, perform better in terms of both friction and pickup. The studies by Butler [22] and Wiegand and Kloos [23] also point to the importance of surface roughness in upsetting experiments. It has also been shown that shallow grooves machined in the end faces of cylindrical specimens reduce friction substantially in lubricated compression, as observed by Loizou and Sims [24], and also by Thomsen et al. [25].

The die surface is also an important factor (Section 5.66). Rough dies puncture lubricant films and raise friction and wear. Smooth dies are better for unlubricated forging, but very smooth dies may cause insufficient lubricant retention.

Squeeze Film Breakdown

A squeeze film, once established, does not necessarily survive throughout the course of compression. Pearsall and Backofen [26] have made detailed studies of lubricant film breakdown at the periphery of cylindrical specimens. In compressing commercially pure aluminum specimens with overhanging platens, lubricant-film failure takes place at the periphery; a sticking zone is thus formed the size of which increases with increasing reduction [27, 28] (Figs. 9.6 and 9.7). It has been observed that with increasing plastic deformation, the lubricant film becomes thinner at the periphery while a reservoir of lubricant is formed within the platen-specimen

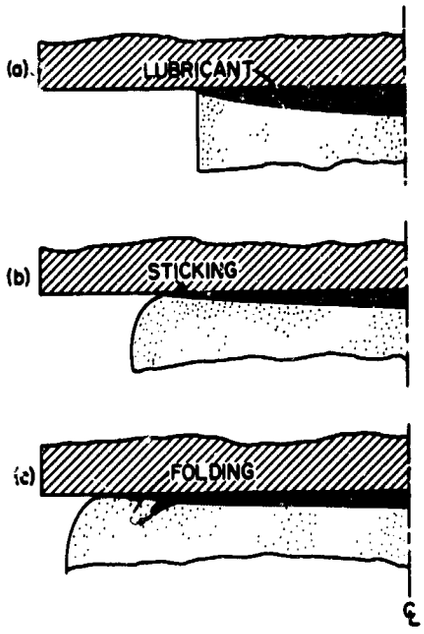

Fig. 9.6. Squeeze film breakdown and the development of folds in the compression of cylinders between overhanging platens [27].

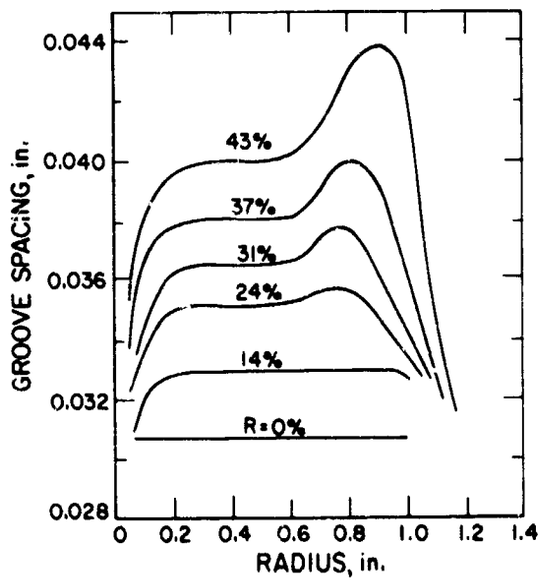

Fig. 9.7. Variation of spacing between spiral-cut grooves, initially equidistant, in the compression of aluminum specimens lubricated with lead foil [28].

interface. As reduction continues, the amount of lubricant at the periphery is exhausted and the platen comes in direct contact with the specimen, leading eventually to sticking. As the sticking zone increases, it leads to a fold formation, as shown in Fig. 9.6. It was found that the initiation of the sticking zone was not influenced by specimen geometry or size, but by the reduction in height and the lubricant. It had been suggested earlier [26] that lubricant failure began after a critical amount of sliding had occurred at the periphery. Further tests indicated, however, that the amount of sliding could not be the sole criterion for lubricant film breakdown.

Sata et al. [27] also suggest that film breakdown is a function of process geometry. In plane-strain compression between narrow parallel anvils, the tools indent the specimen and create new surfaces at the edges of the tool. The film is fully trapped, and there is great resistance to lubricant-film breakdown. The same condition would apply in piercing. On the other hand, in compression with overhanging platens, the new surfaces contact the overhanging platens, possibly contributing to the start of a sticking zone.

Replenishment of Squeeze Film

Because die surfaces almost always move normal to the workpiece surface in forging and related operations, breakdown of the original squeeze film proceeds until a sticking zone develops, unless special steps are taken to replenish the squeeze film periodically. This may be accomplished by cyclic loading; its effect on deformation resistance and, hence, friction, has been investigated by various authors. As discussed in more detail in Section 7.28, there is no evidence to show that high frequency (ultrasonic) vibration of the tool face actually reduces the flow stress of the workpiece material, but for our purpose it will suffice to consider only the frictional effects of vibration.

Since the breakdown of the squeeze film results in boundary contact and, possibly, in metal-to-metal contact with consequent metal pickup, improvements due to replenishing of the lubricant film may be expected on two counts. First, with a liquid lubricant friction is lowered because a hydrodynamic film is maintained; secondly, avoidance of lubricant film breakdown also prevents pickup.

Indeed, a study with cyclic loading [29] has indicated that reduction of the deformation resistance is most marked in upsetting if (a) the lubricant contains a reactive additive, (b) the tool and workpiece have a strong

tendency for cold welding, and (c) the load release or amplitude of vibration is sufficiently large to separate the microwelds and thereby expose the new surfaces of the broken junctions to the reactive lubricant. An example is shown in Fig. 9.8 for 2 in. diameter, 0.5 in. high aluminum specimens upset with caproic acid as a lubricant.

Recent developments in metalworking have involved the vibration of the tools at various frequencies. In upsetting tests it has been found that, due to a reduction in friction, barreling is reduced or eliminated and also upsetting forces are reduced [30-34]. The effect is more marked when the applied lubricant is rather poor, in agreement with the above explanation of cyclic loading.

The beneficial effect of frequent lubricant application has also been studied by Tanaka et al. [35]. With a total reduction of 60%, it was noted that if upsetting was interrupted and the lubricant reapplied more than three times, lubrication did not improve any further; presumably, a sound squeeze film was already attained by the threefold application.

9.23 Coefficient of Friction and Interface Shear Strength

Extensive literature is available on the effect of lubricants and other process parameters on friction in various types of compressive deformation [11, 12, 16, 27, 28, 29, 35-41]. The friction coefficient (or the shear strength) at the interface between the die and the workpiece is found to be a

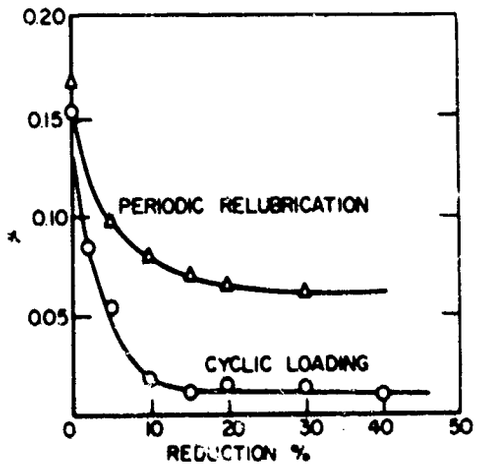

Fig. 9.8. Variation of coefficient of friction with reduction in the compression of aluminum disks [29].

function of not only the lubricant, but also specimen material and geometry, surface finish, temperature, percent reduction, type of loading, and also the location at the interface.

Variation of Friction Across Contact Area

Among the more systematic studies is that due to Van Rooyen and Backofen [28] who, with the oblique pin technique described in Section 5.25, measured the coefficient of friction in cold upsetting of aluminum, iron, and copper. Lubricants included lead foil, molybdenum disulfide, soap, Teflon (PTFE), and mineral oil (medicinal paraffin) with and without fatty-acid additions. Some generalized conclusions may be drawn from this work.

Lead foil of 0.002 in. thickness interposed between anvil and specimen surfaces presented an interface of roughly constant and very low shear strength (c lines in Fig. 9.9). Because the low friction also resulted in an almost constant interface pressure, the coefficient of friction remained practically constant.

Data obtained by Unksov [42] on the normal stress and shear stress distribution along the interface led to similar conclusions. In plane-strain compression of lead specimen of various aspect ratios, the interface shear stress appeared to remain generally constant along the width, both for lubricated and unlubricated conditions.

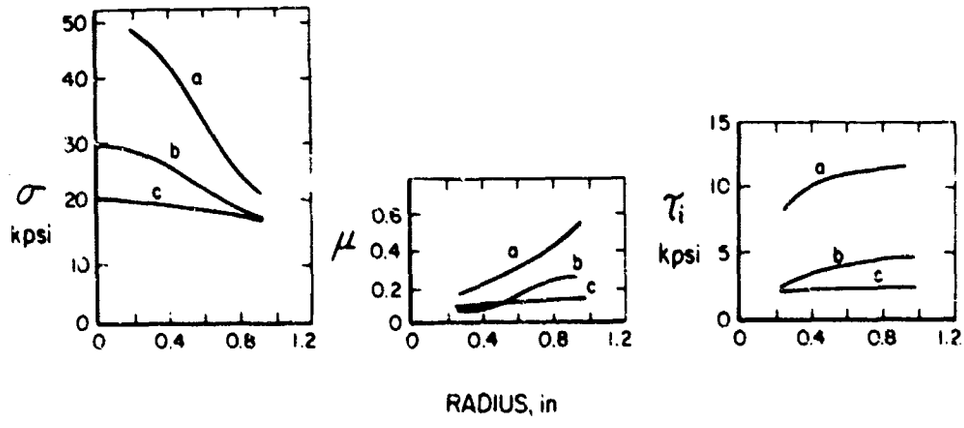

Fig. 9.9. Variation of interface pressure, friction coefficient, and interface shear stress with radius for three lubrication conditions. $D_o/H_o = 4$. (a) Unlubricated; (b) oleic acid in mineral oil; (c) lead foil at interface. Material: commercially pure aluminum. Reduction: 10% [28].

The nature of lubrication provided by various lubricants was followed by Van Rooyen and Backofen [28], who investigated the variations of interface shear stress and coefficient of friction as a function of reduction in height. In upsetting aluminum specimens between dry platens (Fig. 9.10), the interface shear strength increased more rapidly than would be expected from the strain-hardening characteristics of the workpiece material (line τ_o). The reason for the generally higher level and more rapid rise remains obscure. Friction expressed in terms of a coefficient of friction decreased because of the more rapid increase in interface pressures. With a mineral oil as a lubricant, interface shear stress increased rapidly as a result of a thinning out of the initially trapped squeeze film and subsequent boundary contact. The presence of a powerful boundary additive caused an initial drop in shear stress, attributed to adsorption of the fatty acid on the fresh aluminum

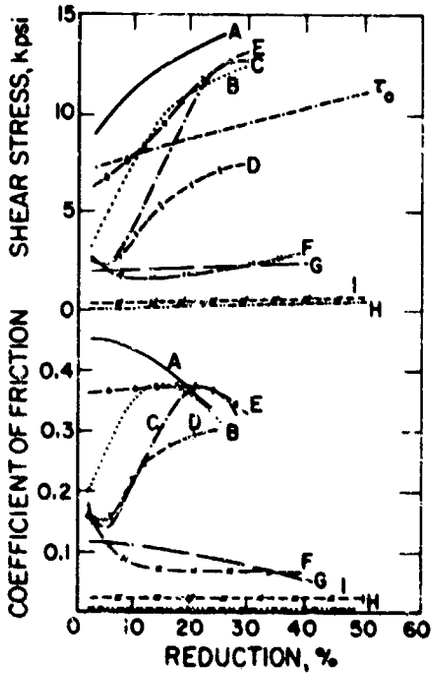

Fig. 9.10. Variation of interface shear stress and friction coefficient at 3/4 in. radius position. $D_o/H_o = 4$. Material: aluminum. (A) Dry; (B) oleic acid in mineral oil, 5%, abraded surface; (C) same as B, etched; (D) lauric acid in mineral oil, 1%, etched; (E) mineral oil, etched; (F) molybdenum disulfide; (G) lead foil; (H) Teflon; (I) soap [28].

surfaces exposed by expanding the end face area. On further compression, interface shear stress rose very rapidly, most probably because of peripheral lubricant breakdown (it is, however, not clear why lauric acid should have been more effective than oleic acid). The initial drop observed with molybdenum disulfide is attributed to alignment of the lamellar particles, leading to an optimum, low shear strength orientation. Exceptionally low shear stress and friction was obtained with Teflon, and almost as good results with specimens that had been first given a chromate-phosphate coating and were then dipped in hot molten soap. These substances behaved like the lead foil except that their shear strength is substantially lower.

Similar observations apply to Armco iron and copper specimens (Fig. 9.11). Neither of these materials, however, show as high adhesion to the anvil as aluminum; therefore, the average value of the coefficients of friction

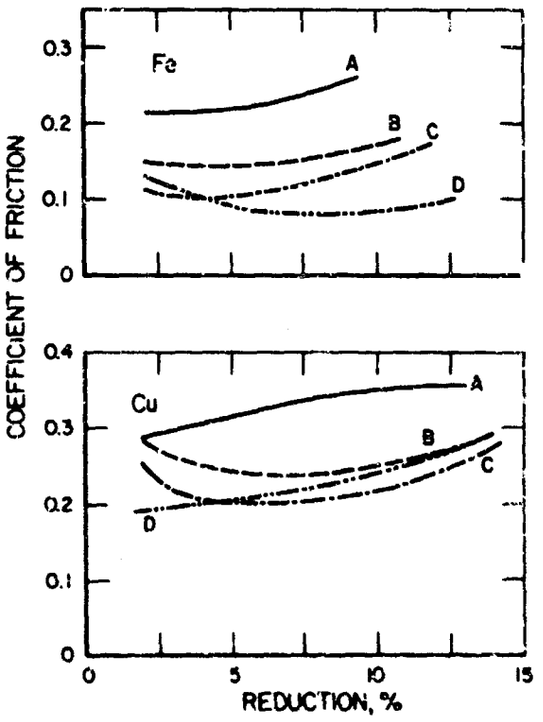

Fig. 9.11. Variation of friction coefficient at 3/4 in. radius position. $D_o/H_o = 4$. Materials: iron and copper. (A) Mineral oil, abraded surface; (B) lauric acid in mineral oil, 1%, abraded; (C) oleic acid in mineral oil, 5% abraded; (D) same as (C), oxidized surface [28].

is lower and variation with reduction in height is also much more moderate. Fatty acid added to the mineral oil lowered friction and maintained it at more constant levels, particularly on iron. The beneficial effect of a thin oxide film is quite marked on the iron, probably because it promotes reaction of the oleic acid to form a soap. The absence of such effect on copper is less readily explained, but the improvement obtained by prior boiling of the specimen in water is in agreement with similar observations made in boundary lubrication studies.

The changes in friction observed during upsetting will also depend on the speed of deformation. Thus, in situations where the interface consists of an element such as lead foil, speed effects in upsetting will show up as an increase in the shear stress of lead due to its strain-rate sensitivity. On the other hand, if the interface consists of a boundary lubricant, increasing speed would lower stresses by inhibiting junction formation or growth, as shown by Pearsall and Backofen [26].

Detailed evaluations of friction from point to point at the contacting surfaces are rare. Most frequently, the effect of lubricants is determined by their efficiency in reducing the average pressure, as calculated from the total force divided by the contact area. An example of such an approach is shown in Fig. 9.12, which is essentially a technological description of lubricant qualities, including its ability to expand with the end face and resist peripheral breakdown. If desired, these data can be converted into coefficients of friction, for example, with the use of curves given in Fig. 2.20. It should be noted, however, that instead of reductions in thickness, instantaneous R/H ratios must be determined. Calculations can be very misleading if the strain hardening in cold working or potential recrystallization during hot working is not considered. In either case, the true yield strength prevailing at a given reduction must be inserted.

Tanaka et al. [35] investigaged the coefficient of friction in upsetting specimens of commercially pure aluminum, copper, mild steel, and 18/8 stainless steel from room temperature up to 400°C. An overall inspection of the results indicates that no general conclusions can be drawn, except that higher viscosity substances reduce friction. A more detailed examination of these results will be found in the appropriate discussions of cold-forging these workpiece materials (Section 10.4, 10.5, 10.6, and 10.7). The reasons for the observed variations in friction are, no doubt, due to a large

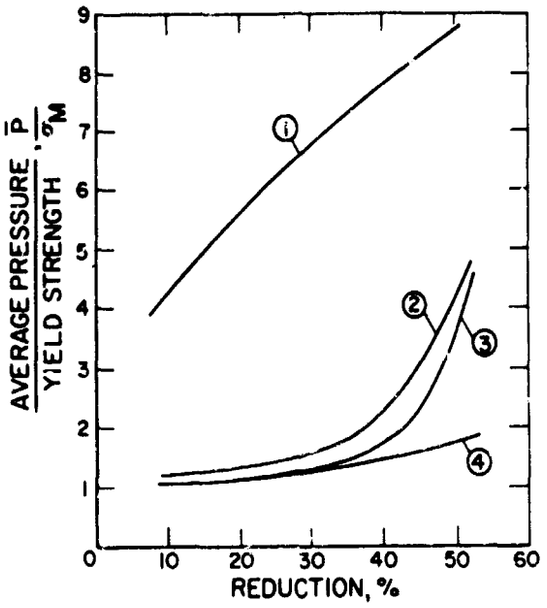

Fig. 9.12. Effect of friction on the reduced interface pressure. 7075 aluminum alloy specimens of $D_o / H_o = 16$. (1) No lubricant; (2) sulfurized fatty oil blend on oxide base; (3) sulfurized fatty oil blend; (4) calcium oleate on chromate-phosphate base [11].

number of often counterbalancing effects of temperature on viscosity, reaction between lubricant and specimen surface, decomposition of lubricant, and others.

Coefficients of Friction Derived from Simulating Tests

In addition to compression tests other types have also been used to determine the effect of lubricants on friction. Much of the fundamental work on lubrication has been performed in simple laboratory apparatus involving sliding contact between a rider (pin or disk) and a flat surface (Fig. 5.10a). Pressures may be readily increased to the point where local plastic deformation occurs during the passage of the rider and new surfaces are exposed by damage. While the deformation mode is substantially different and lubricant entrapment through the squeeze effect is not possible, some of the results can be applied to forging if the limitations are recognized and accounted for.

The application of this test to simulate nonisothermal hot forging creates a number of problems. When the flat surface is chosen to represent the workpiece and the rider to represent the die, rapid heating of the relatively small rider beyond any reasonable die temperatures will soon lead to complete breakdown. Conversely, when the rider is chosen to represent the workpiece, the deformation of the rider and its rapid cooling renders doubtful results. Nevertheless, this test has possibilities for investigating lubricants under controlled conditions of speed and temperature. The lubricating capability of many oxides important in drop forging was first investigated by this technique.

Among the simplified forging tests (Section 5.25) plane-strain compression would be attractive because the contact area remains constant. However, it suffers, like others, from lack of discrimination at high friction. The ring upsetting test has found wider application. It may be used even when friction is relatively high and, though there is still insufficient evidence to judge whether chilling of the end faces could be discounted as an important effect in hot ring-upsetting tests, it would appear that the effects are less disturbing than in most other tests. Chilling does take place in production forging too; the important point is that chilling should be kept within reasonable bounds even when small, fast-cooling specimens are used for experimental purposes.

9.24 Thermal Insulation by Lubricant

In hot-working operations the capability of a lubricant or a surface film to thermally insulate the workpiece is an important consideration. A rapidly cooling interface is a potential source of trouble, particularly when forging billets into thin and deep die cavities and when the workpiece material is sensitive to cracking. Thus, some titanium alloys and especially nickel-base superalloys have a rather narrow hot-forging temperature range and cracking may easily occur if the end faces are allowed to cool.

It has been shown that a thick oxide layer on the workpiece enhances the filling of a die cavity [43], although such an approach would produce an objectionable surface finish. The example given in Table 9.1 shows that, under a constant load, the percent reduction in height of a specimen in compression increases with increasing thickness of mica insulation.

TABLE 9.1

Effect of Mica Insulation
During Press Forging of Steel [43]

Insulation Thickness, in.	Specimen Thickness After Forging, in.
0	0.215
0.010-0.015	0.184-0.176
0.030-0.045	0.134

AISI 4340 billets of 0.5 in. diameter, 0.5 in. height at 1230°C, dies at 315°C.

In view of these observations, greater emphasis is now being placed on the insulating capability of lubricants. Cook and Spretnak [41] obtained quantitative data on the temperature drop as a function of time for various interface materials (Fig. 9.13). Cooling measured in air started from removal of the specimen from the furnace, whereas the cooling rate for the three lower curves was measured from the time the upper platen made contact with the specimen. It will be noted that, as expected, glass is an effective insulator, while an otherwise good lubricant (a graphited grease) actually aided heat transfer and led to a substantial temperature drop in a matter of a few seconds. Initial cooling is very rapid when the surface is dry or covered with a noninsulating lubricant. It is to be remembered, of course, that with increasing deformation speed, forging will approach more and more the adiabatic process, in which case there will be substantial increase of temperature, both in the bulk of the workpiece and also in the interface, depending also on the frictional characteristics of the tool-workpiece system and the lubricant. Unfortunately, no reliable data exist on the actual interface temperatures during deformation.

9.25 Typical Average Coefficients of Friction

It will be clear from the preceding discussion that an average coefficient of friction has no deep meaning and can be taken merely as an indication of lubricant efficiency, provided that process conditions are comparable. Obviously, friction values quoted for elevated temperature work will suffer

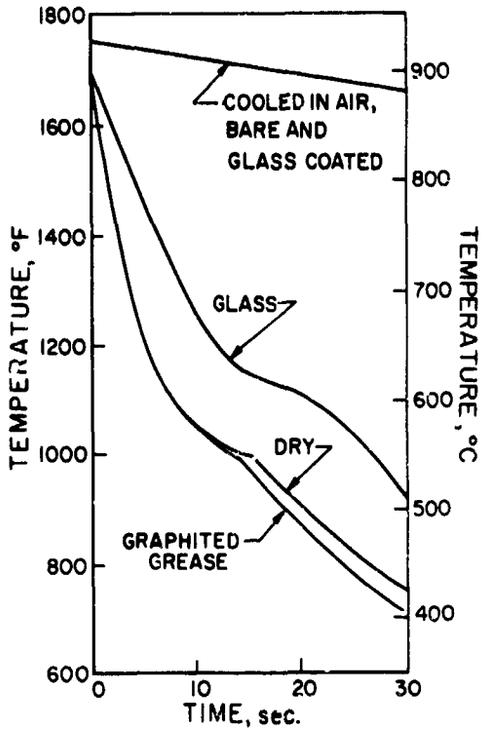

Fig. 9.13. Temperatures measured at approximately 3/16 in. below the top surface of AISI 1018 steel specimen cooled from 980°C [411.

from unknown effects of cooling, while those pertaining to room temperature deformation will seldom be valid for a wide range of geometries, interface pressures, reductions, and approach velocities. Surface preparation and the method of lubricant application can have an overriding effect [44], and many published data have uncertainties introduced by ill-defined process variables.

In considering data contained in Tables 9.2 to 9.4, it will be noted that a coefficient of friction of 0.06 to 0.1 is fairly typical of lubricated compression at room temperature, while the dry friction values are usually in excess of 0.1 [14, 44, 45]. For reasons discussed in more detail in Section 6.21, it is likely that true dry friction values would normally be even higher. The presence of minute contaminants, residues of cleaning fluids, and adsorbed films from the air all contribute to lubrication in ostensibly dry conditions; some evidence of this will be seen later in the detailed experiments on various workpiece materials. In forging at elevated temperatures, sticking

TABLE 9.2

Values of Coefficient of Friction in Plane-Strain Tests [44]

Material	Lubricant	Coefficient of Friction		
		Max	Min.	Mean
70/30 Brass	Dry	0.1	0.025	0.063
	Paraffin	0.11	0.025	0.067
	SAE 10	0.11	0.025	0.067
H.C. Copper	Dry	0.11	0.09	0.1
	Paraffin	0.15	0.09	0.12
	SAE 10	0.14	0.05	0.095
	Paraffin + 5% lead oleate	0.13	0.05	0.09
C.P. Aluminum	Dry	0.25	0.105	0.177
	Paraffin	0.23	0.165	0.2
	SAE 10	0.09	0.05	0.07
	Paraffin + 5% lead oleate	0.1	0.01	0.055
Mild Steel	Dry	0.25	0.17	0.21
	Paraffin	0.23	0.14	0.18
	SAE 10	0.12	0.04	0.08
	Paraffin + 5% lead oleate	0.1	0.02	0.06

TABLE 9.3

Values of Coefficient of Friction in Ring Upsetting (Dry) [45]

Material	Smooth Dies	Rough Dies
Mild steel	0.17	0.31
Aluminum	0.18	—
α-Brass	0.10	0.15
Copper	0.17	0.30

TABLE 9.4

Values of Coefficient of Friction in Plane-Strain Compression [14]

Specimen		Anvil Material	Coefficient of Friction at	
Material	Temp., °C		L/h =3	L/h = 4
3003 Al	R.T.	WC	S	0.32
7075 Al	450	WC	0.29	0.26
		TZM (Mo alloy)	S	0.26
		4340 (steel)	0.27	0.24
Alclad 7075 Al	450	WC	0.16	0.15
		TZC (Mo alloy)	0.16	—
		4340	0.24	0.19
4130	1200	WC	S	S
		4340	S	S
Beryllium	725	WC	0.18	0.16
		TZC	0.10	—
		4340	0.10	0.12

L = width of anvil; h = thickness of compressed specimen;
S = sticking.
With dry, 300°C anvils.

friction is commonly observed although, as shown in Table 9.4, reasonably low friction may be assured by choosing a die and workpiece material combination that shows low adhesion at the working temperatures. The relatively low values recorded for 7075 aluminum alloy clad with pure aluminum must be attributed to the lower shear strength of the cladding; the low values found with beryllium are probably a result of easy shear at the interface of the material of hexagonal structure. In other instances, the oxide film formed on the workpiece material must have helped to keep friction fairly low.

In wedge indentation tests, Kudo [46] has calculated coefficients of friction of less than 0.1 for molybdenum disulfide lubrication, while for dry conditions the coefficient has ranged from 0.2 to 0.4, depending on the roughness of the wedge.

9.26 Simplified Forging Tests

Several simplified forging tests are described in Section 5.25 for the evaluation of various lubricants. The most comprehensive work to date is due to Tolkien [47], discussed in detail in Section 9.5, which extended to measurements of die filling, forging forces, ejection force, and gas pressure in the die cavities. Dimensional changes of the die and the workpiece due to wear were also among the important factors evaluated.

Adhesion of hot forgings to the die surfaces can cause overheating of the dies, reducing their useful life. It has also been observed that the ejection force increases with the number of forgings: this is mainly due to the fact that some of the material from the workpiece surface is deposited on the active die surface and adhesion is increased. It has been observed that adhesion does not set in at once but is a cumulative process whereby an originally smooth die surface begins to become rough by accumulation of material from forgings. After a while it is necessary to clean the die surfaces and remove the built-up material.

Using radioactive techniques, Bowden and Tabor [48] have shown that metallic transfer takes place after only a single blow in upsetting (Section 3.25). Specimens of aluminum, brass, copper, and mild steel were compressed in a drop hammer; the weight of material transferred per blow was of the order of 10^{-6} gram. The transfer is generally from the softer workpiece material to the harder hammer, although the reverse has also been observed. In general, transfer occurs both ways, albeit at varying rates. The amount of material transferred greatly increases when slip occurs between the die and specimen surfaces. Some work on wear of drop-forging dies using radioactive tracers has been reported by Smith et al. [49].

9.27 Speed Effects in Forging Lubrication

The deformation speed can have a profound influence on the forging process. As speed increases:

(a) The time of contact between the hot forging and the cooler die decreases, hence heat loss is reduced. The dies and die lubricants are protected against prolonged exposure to heat, and better die filling can be obtained since the billet does not cool as rapidly.

(b) At speeds above 40 fps, inertia effects can also aid in better die filling.

(c) The liquid lubricant can begin to behave in a hydrodynamic manner, further reducing friction, depending, of course, on the particular die configuration. Squeeze films are likely to form.

(d) It is possible for interface temperaures to increase rapidly leading to a thin molten layer of interface, which again acts as a good lubricant; no direct evidence of melting is available, however.

(e) The process may approach adiabatic deformation; in hot-short materials incipient melting of the workpiece can take place with detrimental results.

(f) The yield stress of most workpiece materials increases, particularly at elevated temperatures unless, of course, concomitant heating counterbalances the effect. Consequently, interface pressures rise.

A material such as lead exhibits a speed effect in that its resistance to deformation increases with increasing strain rate and, when used as a lubricant, the frictional stress increases. In room-temperature ring upsetting tests with aluminum and brass, Male [50] has shown that the speed effect is most marked with lubricants of low viscosity. While the coefficient of friction with graphite did not change with speed, the friction with paraffin and lanolin was influenced by speed—the higher the deformation speed, the lower the coefficient of friction. Changes in deformation speed may cause a reversal in the order of merit of lubricants (Fig. 9.1). At low press speeds, the thickness of the hydrostatic squeeze film is governed by viscosity, and lanolin is a better lubricant than the low-viscosity mineral oil. At high hammer speeds, the mineral oil gives lower friction, probably because the shear strength of lanolin increases at the high shear rates.

Jain and Bramley [51] studied the effect of speed in simple axisymmetric hot upsetting of solid and ring specimens with a variety of lubricants (graphite, molybdenum disulfide, glass dispersion, etc.). Results showed that, over a wide range of lubricating conditions, increasing the forging speed (a) reduces the coefficient of friction, (b) reduces the maximum load when the final reduction is above 40-50%, and (c) reduces the energy required for deformation when the reduction is above 85-90%. The dies were not heated, and the speeds ranged between 0.07 and 40 fps. Many of the lubricants were diluted in carriers, such as water or oil, which had to be evaporated on

contact with the dies leaving a smooth film of the solid lubricant. It is emphasized that actual conditions in closed-die forging are not necessarily analogous to these particular test conditions.

Schey and Wallace [52] have carried out extensive tests on lubrication and speed effects in steel forging at 1180°C using ring compression, upsetting, piercing, and closed-die forging, with dies heated to 100°C. Of the lubricants tested, a graphite-water mixture gave the lowest friction coefficient at press speeds, while for hammer speeds graphite in oil gave the lowest friction. Owing to extensive cooling of the workpiece in the cooler dies, die filling in closed-die forging was generally better in hammer than in press forging. The liquid carrier is an important variable. At low speeds water suspension appears to be best, whereas at high speeds an oil-base suspension which does not evaporate readily is desirable as it enables the formation of a hydrodynamic film.

Lubricants relying on surface reactions, particularly E. P. additives, may suffer if sufficient time is not allowed for generating protective surface films of low shear strength; however, some of this may again be offset by the higher temperatures which accelerate reaction rates. On the other hand, lubricants with a definite breakdown temperature are likely to suffer more at higher striking velocities; again, the harmful effect of speed may be counterbalanced by the short time available to initiate or to complete breakdown.

Obviously, it is difficult to generalize the effects of speed on lubrication in view of a number of factors whose interaction is not yet clearly understood.

9.3 COLD AND WARM FORGING LUBRICANTS

Practically all types of lubricants with varying chemical and physical characteristics have been tried and used in cold forging, for both experimental and production purposes. Lubricants include mineral oils, animal oils, vegetable fats, soaps, waxes, suspensions of graphite in water or oil, white lead, etc. While many of these lubricants have been successful for forging nonferrous metals or mild steel with small reductions, stronger materials and more severe deformations have led to problems with die loads, pickup, surface finish of the product, and die life. Further work brought considerable success with pretreatments of the workpiece surface. These coatings, as well as details on cold forging lubricants, are discussed in Chapter 10.

More recently there has been increasing interest in working at temperatures higher than traditional cold working and lower than hot working. "Warm working" of steel at 500-600°C has the advantage that forces are reduced relative to cold working, yet oxidation is slow enough to assure a good surface finish on the product. Lubrication practices are not well developed yet; the temperature is higher than would be tolerated by cold working lubricants, and present practices employ essentially variants of hot working lubricants. Further development is obviously needed.

9.4 HOT FORGING LUBRICANTS

The choice of a suitable lubricant in hot forging depends on a number of variables such as the workpiece material, the complexity of the forging, type of operation, temperature, ease of application and removal of the lubricant, insulating properties, and the volume and toxicity of the gases generated at forging temperatures.

Over the years a great variety of lubricating materials have been used, such as sawdust, mica, grease, asbestos, salt water, molybdenum disulfide, glasses, and graphite in various carriers. By far, the most common lubricants in commercial practice are based on graphite. Currently under investigation and development are such materials as organic polymers, oxides, phosphates, bromides, fluorides, carbonates, sulfides, etc. The suitability and behavior of the major types of hot forging lubricants are discussed below.

9.41 Graphite

The most common lubricants for hot forging are based on graphite. Important factors are the amount and type of graphite and the characteristics of the carrier fluid. Depending on the type of graphite, concentrations vary between 5 and 40%, the average being about 20%. High purity of the graphite is important as abrasive impurities can be quite harmful. Specifically, the ash content should be low since ash, particularly if it contains silica, can be abrasive. Upon burning, flake graphite produces 5 to 10% ash, but amorphous graphite may produce 15 to 40% [53]. It is also desirable to use fine particle size, although size may be less important than ash content. Some investigators have found that semicolloidal graphite can be more effective than colloidal graphite [47, 54], although the effect of graphite quality on friction

is not clearly established yet. For light metals a trend towards the use of coarser flake graphite has been noted [55]. The oxide layer on the billet does not absorb the coarser graphite as easily as it does colloidal graphite; therefore, it gives cleaner forging.

Commercially used carrier fluids for graphite are water or aqueous mixtures, light mineral oils, black oils, heavy fuel oils, and volatile solvents. The important physical characteristics are the type of residue after burning, viscosity, and flash and fire points. Water is often preferred since it leaves no residue and keeps die temperatures under control, but difficulties are experienced in wetting dies that get hot in high production rate forging. Oils burn off and leave a carbonaceous layer which could serve as a parting agent; the fumes generated create a nuisance but better wetting of hot dies is achieved. For die temperatures in excess of about 400°C, special techniques are needed. One development has been reported for lubricating dies heated to temperatures up to 1100°C [56]. No wetting could be achieved with oil-base lubricants, and the only lubricant that gave any improvement over dry dies (with the iron oxide as a lubricant) was graphite with potassium iodide (KI) as a carrier. On application the KI flashes off, leaving a uniformly distributed graphite film.

Graphite-oil lubricants sometimes contain further additives such as solid inert fillers, molybdenum disulfide, salt, resins, soaps, etc., to increase the effectiveness of the lubricant. The exact reason for various combinations is often difficult to fathom.

One remark is called for in connection with gases resulting from burning of the lubricant. A moderate amount of gas pressure is desirable in order to help eject the forging from the die. Also, the explosive nature of the combustion promotes descaling on the workpiece. However, in dies with deep cavities, this is suspected to cause damage to the die surface by accelerating heat checking and gross cracking. It is also important to note that the liberated gases may be health hazards; in this respect, aqueous suspensions may be perferable to oil suspensions.

9.42 Other Lubricating Materials

Various other materials that have been used or are being investigated are briefly discussed in the following:

(a) Molybdenum disulfide oxidizes at a lower temperature than graphite, but lubricates even in the absence of adsorbed films and does not contain abrasive contaminants, at least below 400°C; above this abrasive oxides may be formed. It is more expensive, however. It has been used extensively, either singly or in combination with graphite. For precision forging of certain steels and alloys, colloidal MoS_2 in water, oil, or mineral spirits have been successfully used, temperature determining the choice of the carrier [57].

(b) Sawdust is probably the first hot forging lubricant ever used. Its function appears to be to provide a more or less continuous gaseous film while the breakdown products (such as carbon and resinous substances) provide some protection as a lubricant and parting agent.

(c) Chlorides, such as common salt or $BaCl_2$ used in salt-bath heating, are occasionally applied to the die in an aqueous solution; the water evaporates and the chloride, melting on contact with the hot workpiece, acts as a lubricant. A number of sulfides, fluorides, phosphates, borates, silicates, carbonates, and oxides, etc., are being investigated most of which, however, fail to match the performance of graphite [58]. Some of these compounds form liquid films, and are particularly useful where squeeze films can be formed, but are likely to roughen the forged surface.

(d) Talc and mica sometimes replace graphite in suspensions with oil. Other solids used are vermiculite, white lead, and alumina powder which serve as thermal barriers in closed-die forging and also possibly function as lubricants.

(e) Solid metal films, deposited on forging blanks to prevent oxidation of the part, also act as lubricants on account of their lower shear strength. Examples are copper film on titanium, and silver and pure nickel on high-strength nickel alloys. Graphite may be used for additional lubrication on top of the metal coating.

(f) Liquid oxides such as those formed on tungsten and molybdenum also function as hot-forging lubricants, in which case no other additional lubricants are used (see Section 8.23).

(g) Glass has also been used in hot forging of steels, high-nickel alloys, and titanium alloys, especially in situations where atmospheric protection and thermal insulation are critical. There are, however, disadvantages in using glass in that it can impair dimensional accuracy by being trapped in deep recesses of dies for intricate forgings, too inaccessible for removal. Another problem with glass lubrication is the surface damage encountered when the temperature of the interface between the die and the workpiece is below the softening point of the glass. The large temperature gradient that exists between the bulk of the forging and the flash further complicates the use of glass as a forging lubricant. In addition, there is great variation in relative sliding velocities on the surfaces of a forging; it is rather difficult, therefore, to find a glass with a sufficiently wide, useful viscosity-temperature range to suit all requirements. The glass must be chosen so as not to attack the workpiece or die surface.

(h) The canning technique used in hot extrusion (Section 8.35) finds limited application in the hot forging of some metals. Unlike extrusion, however, it is difficult to obtain finished parts with the proper configuration from canned forging blanks. For this reason, many forging plants use proprietary coatings, metallic spraying, or electroplating techniques. The forging lubricant is then chosen to suit the cladding (canning) material.

9.43 Application

In forging operations, the dies are usually either sprayed or swabbed with the lubricant after each forging and sometimes even between successive blows on the same forging. The amount of lubricant is not only a matter of economy; too much lubricant may be as undesirable as too little if excessive lubrication leads to faulty products.

The method of lubricant application is important. It has been shown that spraying with a uniform layer of lubricant is preferable to swabbing. In many cases, the method of application has been found to influence lubrication to a greater extent than the type of lubricant used [58]. Techniques have been developed to spray the lubricant on forging dies, such as the one described by Tolkien [59]. Automatic die lubrication also has proven to reduce reject and rework rates, the top die being lubricated after every strike [60].

Hot forging dies are sometimes pretreated with graphite. This is usually done by cleaning the die surface with a solvent to remove oil or grease, heating the die to about 100°C, and brushing the surface with colloidal graphite in water. After the water evaporates, the surface is buffed, resulting in high polish and an adherent thin film of graphite. Another method is painting the die surface with colloidal graphite diluted in either carbon tetrachloride or trichloroethylene. After the fluid evaporates, a hard adherent surface is obtained which also provides protection against corrosion.

The efficiency of the lubricant system is improved if adhesion between die and workpiece is reduced. Borocizing of the dies has been reported as an effective means of reducing die wear [61]. Another older technique reduces seizing (adhesion) by tempering the die under controlled conditions after machining. The oxide layer thus formed on the dies serves as a parting agent and also provides a bond for the lubricant.

9.5 LUBRICANTS FOR STEELS AND STAINLESS STEELS

General information was given in previous sections of this chapter; specific, quantitative results of the effect of lubricants on forging pressure and coefficient of friction will be given here, followed by a discussion of general lubrication practices.

9.51 Experimental Studies

In the past, the principal difficulty in obtaining values of coefficient of friction and evaluating lubricants has been lack of sufficient pressure and temperature in experimental setups. More recently, some relevant data have been generated in various types of tests.

Laboratory Studies

Upsetting of a cylindrical specimen is one of the most common methods used in evaluating lubricant performance, and a wide variety of data is available for hot upsetting.

Breznyak and Wallace [58] screened a large number of experimental lubricants by upsetting 1018 steel at 1175°C. They concluded that commercial lubricants containing colloidal graphite gave the best results. The lowest friction coefficient (0.13) was obtained with a high-temperature silicone-base resin paint containing graphite. Breznyak and Wallace also studied the "sticking" characteristics of lubricants in a punch adhesion test

in forging. Commercially available lubricants of colloidal graphite in water with solid additives (not specified) gave the best results—that is, the least release load on the punch. They concluded from the available data that the adhesion characteristics of a lubricant-die-workpiece system are not necessarily controlled by the same parameters as those controlling the coefficient of friction.

In production forging experiments by high energy rate Crawley and Wills [62] observed that among a great number of commercially available lubricants the top ten in performance contained graphite. Seven of these had flake graphite, one had amorphous graphite, and the other two were listed as graphite without any designation as to particle size. The authors state that probably the most satisfactory lubricant was a 15:1 aqueous solution of flake graphite which was economical and efficient as a lubricant and was also effective in die cooling.

The effectiveness of graphite lubrication in forging steel at elevated temperatures has been shown by many workers and is well proven by industrial practice. Low coefficient of friction values were obtained by, among others, Cook and Spretnak [41], who performed upsetting tests on 1018 steel rings and cylinders at 980°C (Table 9.5). With dry anvils, the friction coefficient was of the order of 0.35-0.38, a range of values which was also

TABLE 9.5

Data for Compression of AISI 1018 Steel Rings at 980°C [41]

Lubricant	Reduction in Height, %	Decrease in Internal Diameter, %	Coef. of Friction	Solid Cylinders	
				Reduction, %	Stress, kpsi
Dry	35	26	0.35	33	41.4
Dry	52	54	0.38	50	60.2
Fiske 604	35	11	0.12	33	32.4
Fiske 604	53	26	0.12	50	43.0
Glass	36	7	0.105	33	36.8
Glass	53	36	0.18	50	38.6

2 in. OD, 1 in. ID, 0.67 in. high.

obtained by Male [63] for mild steel at the same temperature (Fig. 9.14). It will be noted that friction shows a maximum, attributable to the changing strength of the scale (iron oxide) film, discussed in more detail in Section 4.28.

Instead of calculating the friction coefficient, the effectiveness of a lubricant may be judged simply from the height reduction of a cylindrical specimen under constant load or from the stress required for a constant reduction in height. This method was used by Gouwens [56] for assessing the effect of three lubricating conditions on upsetting 4340 steel at 1230°C. A lubricant consisting of KI and flake graphite appeared to be quite effective, although at die temperatures around 1000°C the result was not different from that under dry conditions.

Plane-strain tests on 4130 steel with tungsten carbide and 4340 steel dies again showed that effective lubrication, such as is provided by a glass, can reduce compressive stresses by one-half as compared with the dry condition [14].

Simplified forging tests have been used extensively to evaluate lubricants in the forging of steel. particularly those tests that measure die filling as a criterion of the effectiveness of a lubricant. Shaw et al. [64] have shown that, in experiments with 403 stainless steel, a preparation consisting of a sodium grease (Paraplex G 60) containing 25% by weight extrafine flake graphite produced the best die penetration for a billet temperature of 1175°C and die temperatures of 370°-600°C.

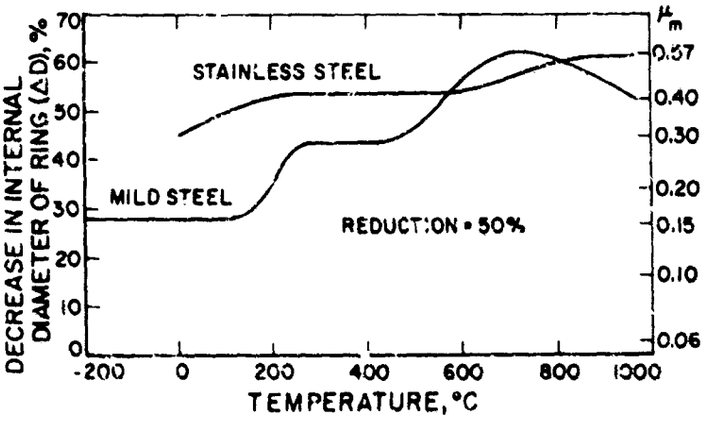

Fig. 9.14. Coefficient of friction in ring upsetting mild steel and 18/8 stainless steel specimens with dry, room-temperature dies [63].

Small-Scale Production Trials

In simplified forging tests with steel, Tolkien [47] measured the total force in the forging of a flat cylindrical workpiece as well as the force required for ejecting it from the lower die half. Since the forging was essentially a flat disk somewhat similar to a gear blank, die filling was achieved mostly by spread over the end faces (Fig. 5.6d). The total forging force was therefore regarded as an indicator of sliding friction, and the ejector force was taken as a measure of sticking friction. A die used for forging a part with a concentric hub was adopted for measuring the gas pressure generated with different lubricants. In an extension of this work a third die shape was used for judging the effect of lubricants on die wear under production conditions [65]. Square billets of 2.2 lb weight were preheated inductively to 1150°C. The die temperatures were in the range of 150°-200°C, and the initial striking velocity was between 16 and 20 ips. Forging was interrupted every 500 pieces, and a lead impression was forged in the die set. This lead impression was then used for checking dimensional changes and surface finish.

The efficiency of the lubricants in reducing sliding friction was judged from the amount by which the maximum forging force decreased in comparison to the unlubricated forging force. Colloidal graphite and molybdenum disulfide applied in an aqueous solution gave the greatest (approximately 30%) reduction in force, followed by an aqueous solution of sodium carbonate (20%), while colloidal graphite and molybdenum disulfide in oil gave only 8 to 10% reduction; a polyalkylene glycol was the poorest (4%).

Sticking in the die, as judged from the ejector force, was negligible with aqueous graphite solutions, the ejector force amounting to about 1% of the force required in dry forging and about 15% with the other materials; polyalkylene glycol did not reduce sticking friction at all. Sawdust was a rather poor lubricant for both sliding and sticking friction. Aqueous solutions and polyalkylene glycol gave little rise in internal pressure during forging, but mineral oil mixtures raised pressure by 70% and sawdust by 110% above that measured without a lubricant.

In the production runs with various lubricants, the increase in the diameter of the deepest part of the die cavity was used as a measure of die wear. Sawdust proved to be the most effective wear-preventive agent, followed by colloidal graphite in mineral oil; colloidal graphite in water was hardly better than water alone. The originally smooth (80 μ in. peak-to-peak

roughness) surface finish of the dies rapidly deteriorated to approximately 800 to 2000μ in. finish with sawdust and went to double this roughness with colloidal graphite in water. An oily suspension of colloidal graphite gave the best results with a typical finish of 800 to 1600μ in. (peak-to-peak roughness) after 2500 pieces. The roughness was measured on the surface of the lead imprint perpendicular to the direction of material flow, in a zone where heavy sliding over the die surface occurred.

As expected from the pressure increases given by various lubricants, unfilled edges were experienced primarily with sawdust and occasionally with mineral oil or graphited mineral oil. A summary of the results is given in Table 9.6, which shows the order of merit of different lubricants from various viewpoints. It is evident that there is no overall optimum, but any choice involves a compromise that must be arrived at with due consideration of actual production conditions.

Knauschner [66] studied geometrical factors affecting die filling during hot forging in a simplified die, with die temperature and lubricants as major variables. The lubricants included colloidal graphite in water, mold dressing (of undisclosed composition), electrode carbon, and sawdust. With die temperatures ranging from 20° to 600°C, die filling was independent of temperature when sawdust was used as a lubricant. With graphite in water

TABLE 9.6

Comparative Performance of Some Forging Lubricants [47]

Lubricant	Sliding Friction	Sticking Friction	Gas Pressure	Die Wear (dimensional change)
Sawdust	4	4	1	1
3.6% Colloidal graphite in water	1	1	5	3
4% Colloidal graphite in oil	3	3	2	2
Polyalkylene glycol	5	5	4	4
17% Na_2CO_3 in water	2	2	3	5

Best performance is marked by 1, poorest by 5.

or with electrode carbon, die filling at low die temperatures was poorer than sawdust, but matched it at die temperatures above 300°C. The mold dressing was the best lubricant for die temperatures of 500°C. Interpretation of these results is rather difficult, particularly because compositions are not given. It is conceivable, however, that the temperature-independent performance of sawdust is due to some degree of thermal insulation afforded by this substance.

Breznyak and Wallace [58] point out that field tests conducted on some selected experimental lubricants (aqueous solutions of graphite, plus proprietary solids ranging from 5 to 32.5% prepared by commercial suppliers) showed substantial improvement. They promoted increased metal flow, reduced sticking, decreased flashing and smoking, and increased die life. However, the results were not always unequivocal, and further production trials appear to be necessary before more definitive conclusions can be drawn.

9.52 General Practice

A great variety of lubricants are used in the hot forging of steels. The most common ones are graphite suspensions, oils, sawdust, and salts. Oil and graphite suspensions are recommended for shallow impressions where lateral flow is required [7], although this generalization is not necessarily valid for all forging speeds and die temperatures. Because they act as parting agents and also prevent excessive lateral flow into the flash gap, sawdust and salts have also been recommended for dies with deep recesses. Colloidal graphite powder dispersed in water has been successfully used in forging intricate shapes of steels to close tolerances [67]. The choice of the carrier is often governed by considerations other than minimum friction, as discussed in Sections 9.41 and 9.43.

For austenitic stainless steels the most common lubricants are oil-base graphite suspensions, although glasses are often used for forgings involving back extrusion. Because they do not form a scale during heating, these steels have a tendency to seize in the forging dies, hence the choice of a good lubricant is critical. In order to avoid the problem of carburization of the forging, thorough cleaning before reheating is necessary [7]. Lubrication techniques for precipitation-hardenable stainless steels are essentially the same as those for austenitic stainless steels. A smooth, thin coating of lubricant is recommended for thin walls [68].

9.6 LIGHT METALS AND THEIR ALLOYS

9.61 Aluminum

Experimental Studies

A considerable body of data is now available for aluminum and its alloys. Since the temperature range of hot working sometimes extends close to room temperature, separation of experimental data is difficult and this section contains, by necessity, some room-temperature work too.

Under unlubricated conditions the great tendency of aluminum to adhere to the die surface is reflected in high friction, both at room and elevated temperatures. The calculated friction coefficients vary between 0.3 and 0.6, partly because of the method of deriving these values and partly because of the often poor surface preparation and control of adsorbed films.

For lubricated situations, data available from various sources [35, 38, 44, 64, 69] indicate a rather close agreement in that the coefficient generally ranges between 0.06 and 0.2 in upsetting and in plane-strain compression, both at room and at elevated temperatures (Figs. 9.15 and 9.16, Tables 9.7 and 9.8).

At room temperature, friction drops with increasing viscosity of mineral oil lubricants, and boundary additives are very effective. In plane-strain compression tests on aluminum-1 1/4% manganese alloy, Guminski and

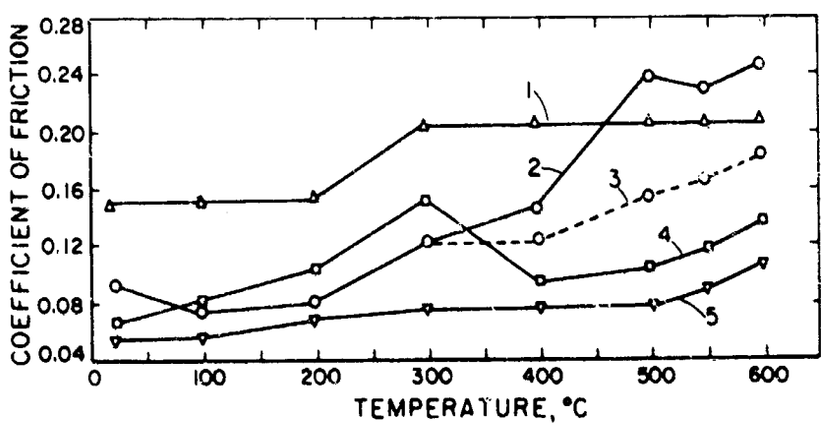

Fig. 9.15. Effect of temperature on the coefficient of friction for various lubricants with super-purity aluminum. L/h = 6. (1) Cadmium oxide; (2) molybdenum disulfide; (3) molybdenum disulfide in nitrogen atmosphere; (4) graphite; (5) graphite with cadmium oxide [69].

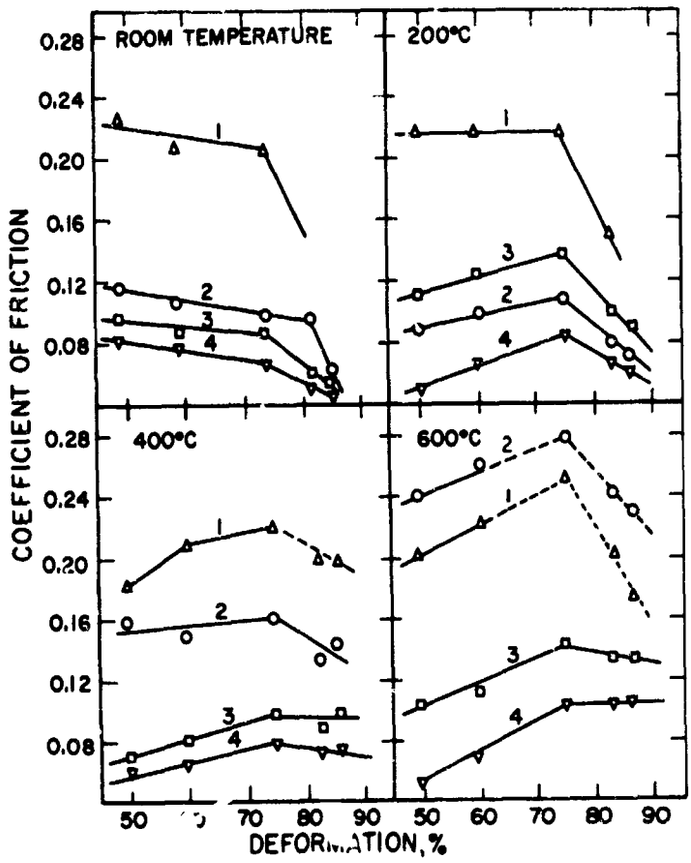

Fig. 9.16. Effect of percentage deformation on the coefficient of friction for various lubricants with super-purity aluminum. (1) Cadmium oxide; (2) molybdenum disulfide; (3) graphite; (4) graphite with cadmium oxide [69].

Willis [70] have shown that the amount of reduction attained for a constant load depended on the number of carbon atoms in the molecule of the lubricant (Fig. 9.17). Reduction increased with chain length and with polarity of the additive. They observed that, for the same number of carbon atoms, branched molecules gave lower reduction than the longer straight-chain molecules. Also, saturated acids and alcohols gave higher reductions than unsaturated ones. All of these results are in good agreement with the expected behavior. The percent reduction obtained with the same load stabilized only after a detritus formed which would then act as solid filler in the lubricant. However, as pointed out by Guy [71], this effect is also a function of die surface finish; detritus is trapped and becomes effective only if the direction of grinding marks on the die is perpendicular to the major

TABLE 9.7

Effect of Various Lubricants in Pressing 2014 Aluminum Alloy Disks between Flat Dies [64]

Commercial Lubricants[a]	Average Values for Test Series			
	Final Thickness, in.	Final Diameter, in.	Forging Pressure, psi	Friction Coef.
Silicone grease	0.103	2.2	36,000	0.16
Flake graphite in oil	0.101	2.2	36,000	0.15
25% flake graphite + 15% MoS_2 + 5% mica in bentone grease	0.095	2.3	33,400	0.13
Colloidal graphite in oil	0.091	2.3	32,000	0.12
Colloidal graphite in water	0.086	2.4	30,000	0.11
35% flake graphite + 5% mica in calcium-base grease	0.067	2.7	23,500	0.06

[a]Commercially available under various trademarks.

Billet size: 1 in. diameter x 0.5 in. high. Billet temperature: 440°C. Die temperature: 370°C. Load: 138,000 lb.

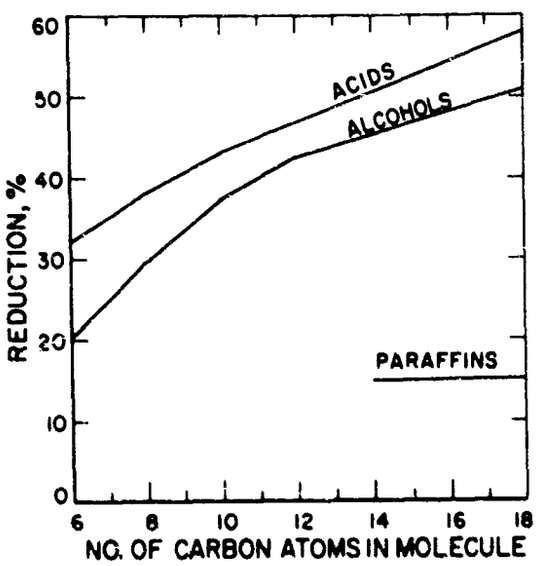

Fig. 9.17. Reduction index of various straight-chain saturated compounds examined in the form of 2% solutions in a commercial petroleum fraction of 275-350°C boiling range. Material: aluminum-1 1/4% manganese alloy [70].

TABLE 9.8

Calculated Values of Coefficient of Friction in Upsetting Aluminum at 400°C Using Various Lubricants [38]

Lubricant	Coefficient of Friction
Unlubricated	0.48
Mineral oil + 10% graphite	0.095
Mineral oil + 20% graphite	0.09
Suspension of colloidal graphite in oil	0.102
Ceresin	0.165
Ceresin + 10% graphite	0.093
Silicone lubricant + 10% graphite	0.18
Thermostable esters + 10% graphite:	
Dioctyl propionate	0.058
Tetraphenyl phosphate	0.106
Dioctyl sebacate	0.141
Graphite + gelatine + casein + table salt + water	0.144

direction of material flow (as it would be on plane-strain compression dies ground in their length). Guy showed that, with dies specially ground in the direction of material flow, detritus had no effect on friction.

Although the exact variations of friction with temperature may be subject to some uncontrolled variables, the general trends found by Tanaka et al. [35] should serve as a useful guide. As expected, lubricants gradually failed at elevated temperatures, as indicated by the rising friction at 200°C for the mineral oil and at somewhat higher temperature for the fatty oils and lanolin; a stearate soap, however, was useful even at 400°C. The relative ineffectiveness of the E. P. additives (chlorinated paraffin) was evident, and only aluminum stearate was capable of maintaining relatively low friction over the temperature range investigated.

Graphite is a useful lubricant at higher temperatures, but the method of application is important. Graphite that had been applied to aluminum alloy specimen surfaces before preheating (graphite powder rubbed in) proved completely inefficient, whereas both graphite powder and graphite powder in an E. P. grease performed well when applied directly to the anvils [14].

This is in general agreement with the view according to which graphite is efficient only in the presence of a fluid or vapor but not when it is completely degassed. A similar conclusion can be drawn from the experiments of Shaw et al. [64] (Table 9.7); however, they also found that lubricants that had performed well in the laboratory yielded good or poor results in actual production depending on the shape of the forging. It is thus evident that a single test, such as simple hot upsetting, was not able to provide a dependable rating of lubricants.

In plane-strain compression experiments conducted by Bailey and Singer [69], a mixture consisting of graphite and cadmium oxide was most effective (Figs. 9.15 and 9.16). The beneficial role of cadmium oxide is explained in terms of a parting agent, inhibiting the pressure-welding of aluminum to the dies at elevated temperatures. At this stage it is not easy to explain some of the variations noted with temperature and progressive deformation. It is speculated that the reduction in friction with increasing deformation beyond about 75% could be due to metal or oxide debris acting as rollers.

Simulated forging studies by Shaw et al. [64] utilized the height of filling a rib in a trapped die as a measure of friction (Fig. 5.6a). The results obtained, shown in Table 9.9, indicate that oil-base lubricants produced better die filling than water-base lubricants. Die filling was greatly improved by pretreatment consisting of etching the billets in sodium hydroxide, then dipping them in aqueous colloidal graphite before heating and forging. Polytetrafluoroethylene (PTFE) applied to cold dies prior to heating them produced better die filling than the commercial lubricants; however, the substance generates toxic fumes if heated to 400°C or higher. It is not known whether PTFE has found industrial use.

The force registered on ejecting a simple forging from a cylindrical die cavity (Fig. 5.6e) has also been investigaged [38] as a measure of lubricant effectiveness. Variables included the degree of deformation, depth of die cavity, size of contact area, and draft of the cavity. Ejection force varied considerably with the type of lubricant used; oleic acid gave the lowest ejection force and no lubrication gave the highest, as expected. Die cavity depth and contact friction area between the die and the workpiece have, on the whole, little influence on adhesion force within the range studied. The draft angles ranged from 3 to 9°, and it was observed that the adhesion force

TABLE 9.9

Influence of Various Types of Lubricants on Depth of Fill in a T-Shaped Die with Aluminum [64]

Lubricant[a]	Average Depth of Fill, in.	Surface Condition[b]	Coef. of Friction[c]
	Graphite Suspensions		
Flake graphite in oil:			
260°C dies	0.78	A	—
370°C dies	1.42	A	0.15
Colloidal graphite in oil	1.45	A	0.12
Colloidal graphite in water	1.19	C	0.11
Flake graphite in water	1.25	C	—
Flake graphite + mica in calcium-base grease	1.64	C	0.06
	Molybdenum Disulfide		
MoS_2 in oil	1.28	B	0.10
MoS_2 + mica in calcium-base grease	1.51	B	0.09
	Greases		
Soapless grease	0.94	A	0.17
Silicone grease	1.10	B	0.16
Grease-type, cold-forging compound	0.94	A	0.17
	Billets Etched in Caustic, Dried, and Dipped in Suspensions of Graphite		
As coated	1.20	B	—
Graphite in oil	1.87	AA	—
Graphite in water	1.51	A	—

[a] Lubricants were applied by spraying except where noted.

[b] Surface ratings: AA - no scoring; A - slight scoring on radius; B - slight scoring on surface; C - severe scoring on surface.

[c] Determined by disk-forging method.

Alloy: 2014 aluminum. Forging pressure: 46,000 psi. Die temperature: 370° C unless otherwise noted. Forging temperature: 440°C. Billet size: 1 in. diameter x 1 15/16 in. long.

decreased with increasing draft angle for all lubricants tested, as predictable from elementary considerations.

General Practice

Many proprietary lubricants are used for hot forging aluminum. These usually contain soaps, fatty compounds, and graphite in water or oil base, including compounded medium-viscosity oils [53, 72].

Graphite-base lubricants have serious disadvantages for aluminum and magnesium: Graphite particles imbedded in the surface may cause pitting and corrosion.

In general, graphite suspensions applied by spraying to the die are preferred for press forging [7]. For hammer forging, water-soluble soaps are frequently applied to the die by swabbing. A porous conversion coating on the surface of aluminum can be produced by dipping the blanks in a caustic (10% NaOH) solution. The forgings are then dipped into a colloidal graphite dispersion and left to dry. This technique has been found to eliminate galling and seizing. However, if the forgings are not cleaned, they may begin to corrode.

A great variety of commercially available lubricants for cold and hot forging of aluminum are given in Reference 73. For forgings that are to be heat-treated before machining or use, it is important that residues of the lubricant should evaporate without staining; otherwise, costly cleaning would become necessary. A detailed discussion of staining will be found in Section 6.52.

9.62 Beryllium

In the early stages of development beryllium has been forged by jacketing in 1/2 in. thick steel to reduce tensile stresses and prevent rupture. In addition, steel jackets minimize toxic effects at high temperatures and also protect the workpiece against oxidation [74]. However, because of cost and surface quality considerations, attempts have been made to forge unclad beryllium, and it has been shown that it is feasible to do so. A proprietary solid lubricant has been used in one case [74]. In another study [75], the billet was lubricated with Phosphatherm RN (described in Section 9.34) and the die with MoS_2 dispersed in a graphite-in-oil base, applied by spraying. These lubricants were regarded as being satisfactory. Borax may also be used as a solid lubricant that melts on contact with the hot billet. In another

study [76] the billet was lubricated with proprietary coatings (probably glass) and the dies were coated with an unidentified forging compound, with varying degrees of success.

Beaver [77] has suggested that greases, colloidal graphites, MoS_2, or mixtures thereof can be used in working beryllium below 540°C. Above this temperature, metal lubricants such as silver, nickel, or copper may be used, these being either sprayed or electroplated. Frits, glasses, and salts can be used at still higher temperatures to a maximum of 760°C, according to the toxicity of oxides.

9.63 Magnesium

Experimental Studies

Data on experimental studies with magnesium are rather scarce. Male [63] has used the ring upsetting test to obtain the coefficient of friction in forging magnesium up to 600°C under dry conditions (Fig. 9.18). Friction first increases and then decreases with temperature; as stated earlier (Section 4.28), a number of mechanisms may be responsible for such behavior. The initial rise must be attributed to desorption of gas and water vapors, while friable oxide films formed at higher temperatures reduce friction.

Shaw et al. [64] performed die filling tests with a magnesium alloy at 360°C and studied a number of lubricants. The results (Table 9.10) show

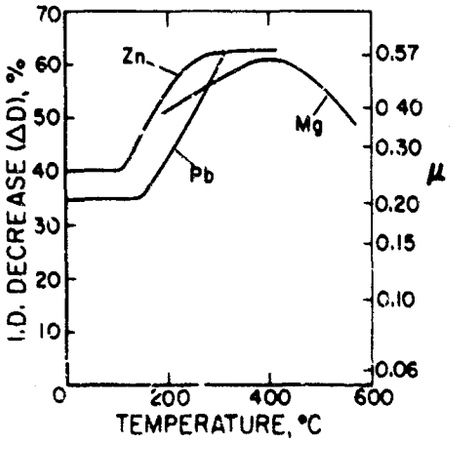

Fig. 9.18. Variation of coefficient of friction with temperature in dry, ring upsetting tests on three materials. Dies are at room temperature. Reduction: 50% [63].

TABLE 9.10

Influence of Various Types of Lubricants on Depth of Fill in a T-Shaped Die with Magnesium [64]

Lubricant[a]	Average Depth of Fill, in.	Surface Condition[b]
Die Lubricants Only		
Flake graphite in oil	1.11	A
Colloidal graphite in oil	0.92	AA
Colloidal graphite in water	1.44	B
Graphite + MoS_2 in water	1.62	AA
Billets Precoated, Dies Sprayed with Oil-Flake Graphite Suspension		
Billets vapor-blasted and dipped in aqueous colloidal graphite	1.87	A
Billets degreased and dipped in aqueous colloidal graphite	1.76	C
Billets etched in acetic acid, rinsed, and dipped in aqueous colloidal graphite	1.86	A

[a] Lubricants applied by spraying, except as otherwise noted.

[b] Surface ratings: AA - no scoring; A - slight scoring at radius; B - slight scoring on surface; C - severe scoring on surface.

Alloy: AZ80 magnesium. Forging pressure: 46,000 psi. Die temperature: 260°C. Forging temperature: 360°C. Billet size: 1 in. diameter x 1 15/16 in. long.

that the best lubricant was a mixture of graphite and molybdenum disulfide in water; pretreatment of the billet surface gave no improvement.

General Practice

The most common lubricants used in forging magnesium are water-base colloidal graphite and lampblack applied directly by an oil or kerosene torch [7]. To reduce friction in critical areas in the die cavity, light oil suspensions of graphite are used. To avoid corrosion, the graphite should

be removed completely after forging. Molybdenum disulfide has also been tried, but was found difficult to apply in a uniform coating [55].

Staining (brown staining) by the lubricant can be a major problem in forging magnesium [57]; thus, care should be exercised in selecting a non-staining oil (typically, a narrow-cut mineral oil of low boiling temperature) as a carrier. Graphite can also prove troublesome to remove. Removal by chemical action can result in pitting and surface deterioration. Because they promote rupturing, lubricants such as greases and oils are seldom used [7]; the reason for and the absolute validity of this observation could not be assessed.

9.7 COPPER AND ITS ALLOYS

9.71 Experimental Studies

Copper and also brass show a remarkably steady and low coefficient of friction even when unlubricated; values of 0.05 to 0.10 were found by Takahashi and Alexander [44] while somewhat higher (up to 0.2) friction values were recorded by Tanaka [35]. In experiments up to 400°C, friction was found to increase but without serious lubricant failure [35].

In unlubricated ring upsetting tests on copper and its alloys Male [63] reported a decreasing friction coefficient for copper above 600°C (Fig. 9.19), attributable to the softening of the copper oxide. In contrast, friction rose with temperature on the brasses, leading to the considerations discussed in Section 4.28.

In another test, Male has shown that lubrication affects the maximum reduction in height obtainable without cracking in compressing cylindrical specimens of brass at 450°C (Table 9.11). A comparison of data in Table 9.11 and Fig. 9.19 for the same temperature of 450°C indicates the marked effect of die surface finish on friction [78]. Similar observations have also been made by Latham et al [9].

9.72 General Practice

Oils containing graphite are used in hot-working copper and its alloys. Water-base graphite dispersions are also used successfully for brasses and bronzes, the lubricant being applied by spraying [57].

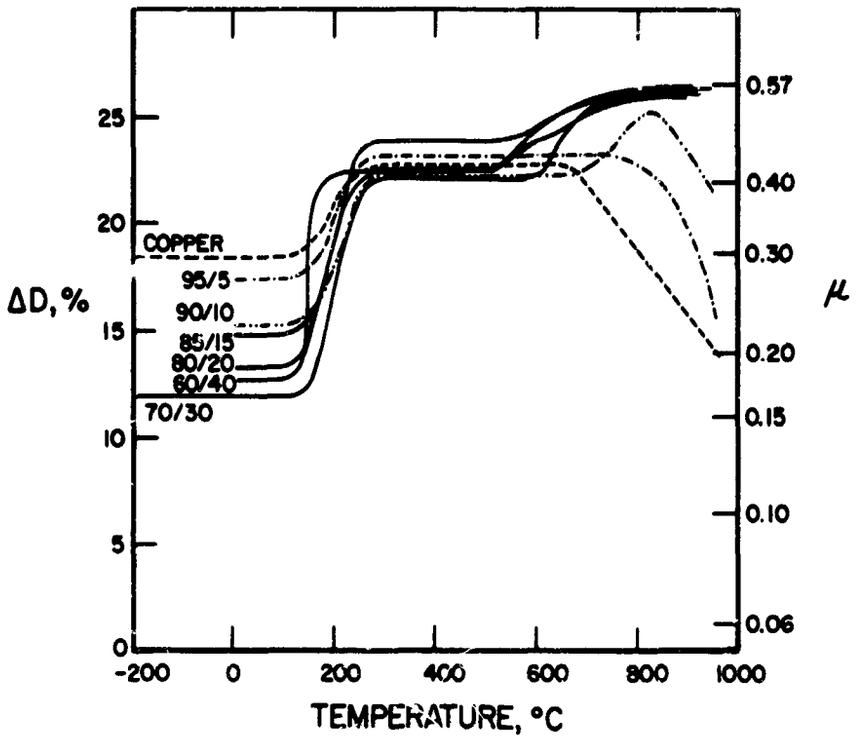

Fig. 9.19. Variation of coefficient of friction with temperature in dry, ring upsetting tests on copper and various brasses. Reduction: 30%. Dies ground to 20 μ in. AA, room temperature [63].

TABLE 9.11

Maximum Deformation of Forged Cylinders before Cracking

Condition	Reduction in Height, %	Approximate Coefficient of Friction
Dry	44	0.25-0.3
Lubricated (graphite dispersion)	67	0.06-0.07

Data by A. T. Male, cited by Rowe [78].

3/4 in. high, 9/16 in. diameter cylinders of 70/30 brass, deformed at 450° C.

9.8 TITANIUM AND ITS ALLOYS

9.81 Experimental Studies

Under dry conditions the coefficient of friction of titanium remains constant around 0.5 (Fig. 9.20) regardless of temperature, indicating sticking in both ring upsetting [63] and plane-strain compression tests [14]. As is well known, titanium has a great tendency to adhere and stick severely to dies. Fig. 9.20 indicates that molybdenum disulfide applied on the dies has reduced friction at elevated temperatures. Low shear strength solids placed between specimen and platen (discussed in Section 3.47) have been found effective in reducing friction [79].

In die-filling experiments with unalloyed titanium [64] a variety of lubricants and glasses were used. Some of the data indicated that a light scale on the billet resulted in better filling. The best results were obtained with billets heated in a salt bath and then forged with a die lubricant containing flake graphite in oil. However, it was observed that the frozen salt in the corners caused underfilling and that the billet seemed to be attacked by the molten salt.

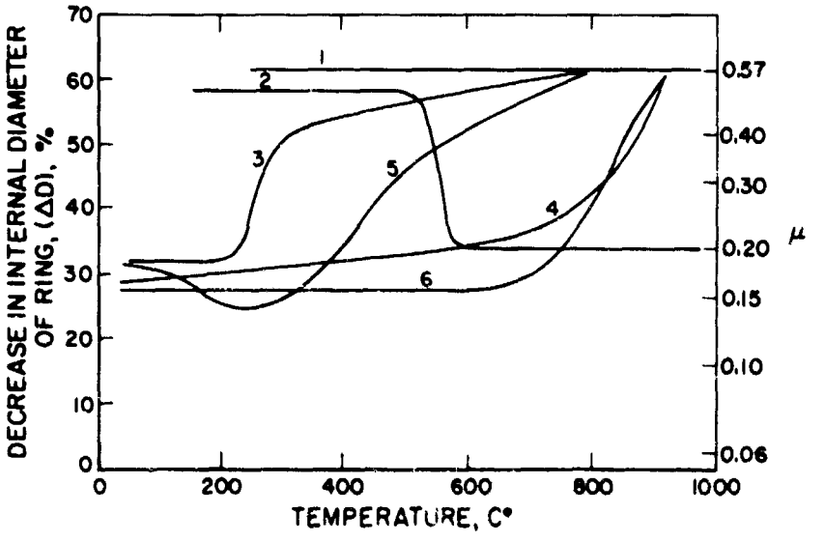

Fig. 9.20. Variation of coefficient of friction with temperature in ring upsetting of titanium with dies at room temperature. Reduction: 50%. Press speed: 2 ips. (1) No lubricant; (2) boric oxide, melting point 577°C; (3) graphite on specimens; (4) graphite on dies; (5) molybdenum disulfide on specimens; (6) molybdenum disulfide on dies [50].

9.82 General Practice

Titanium billets form an adherent scale during heating which is abrasive and causes rapid die wear. Common die lubricants are colloidal graphite in mineral spirits or water and soot from partially burned kerosene [7, 80, 81]. They are often sprayed, particularly for intricate die geometries. For simple shapes the lubricant is applied by swabbing.

Glass-type coatings have also been developed which provide protection of the billet against oxidation as well as lubrication. The glass powder is in a lacquer and is applied by spraying [80]; the lacquer holds on the glass until molten.

9.9 NICKEL- AND COBALT-BASE ALLOYS

The most common lubricants are mixtures of graphite and oil. Sometimes tar is used as a carrier; it sticks to the dies better initially and does not burn quite as fast as oil. Lubricants containing MoS_2 and other compounds of sulfur are harmful because sulfur diffuses into the grain boundaries and causes hot-shortness. In the hot forging of superalloys seizing and galling can be a problem since no oxide layer of lubricating or parting function forms on heating. It has been suggested that the previously mentioned controlled oxidizing of the die (Section 9.43) is beneficial.

Other lubricating materials which also help to minimize the chilling effect of cold dies are glass, mica, sawdust, and asbestos, all of which have been used with varying degrees of success [82]. Because they insulate as well as lubricate, glasses are particularly useful for alloys that have a narrow forging temperature range.

9.10 REFRACTORY METAL ALLOYS

9.101 Molybdenum

The lubricants reported for forging molybdenum include graphite, MoS_2, and glasses. Since the melting point of molybdenum oxide (MoO_3) is 795°C, it is an excellent lubricant [7, 83]. MoS_2 has been found to produce good surface finish but is useful only up to about 400°C, unless contact times are short [84, 85]. Both graphite and MoS_2 have been reported as suitable die lubricants for small forgings. Carbon contamination must be avoided,

however, or carbides will form. To reduce oxidation losses and to insulate the workpiece from the forging dies, glass-type lubricants are also used on large forgings.

9.102 Tantalum and Columbium

Primary working temperatures for most of these alloys are between 1200° and 1750°C. Subsequent working is performed in the range from room temperature to 1250°C. Some of these alloys are not forgeable in the cast condition, hence they are first extruded and then forged [83].

Atmospheric contamination is a problem in heating the blanks prior to forging. Two types of coatings have been successful for billet protection: glass and metallic. Proprietary glass coatings, some with borosilicates, have been used for moderate protection up to 2040°C [7]. Protection has also been obtained by hot-dipping tantalum alloys (Ta-10Hf-5W and Ta-30Cb-5V) in Al-12Si alloy at 900°-930°C for about 10 min. It is reported that 55% reduction in forging has been achieved at temperatures between 1175° and 1350°C [86]. A 50Al-50Sn coating has provided good protection for Ta-10W alloy samples up to 1650°C. Although these coatings provide the best oxidation resistance, they are generally poor lubricants [7]. Thus, glass coatings appear to be preferred as they offer both lubrication and protection.

There are several common protective atmospheres available in furnaces. A disadvantage is that the billets are not protected during forging. If reheating of the forging is required, the oxide layers that were formed during forging will diffuse into the surface unless removed before reheating [83]. Short heating times, the use of a recrystallized billet, and bare forging have been suggested for some tantalum alloys [87].

9.103 Tungsten

A variety of forging lubricants are used for tungsten. An effective lubricant is tungsten oxide (WO_3), with a melting point of 1473°C; this becomes molten and volatilizes at forging temperatures [7]. To lubricate the dies and to act as parting agents, mixtures of graphite and MoS_2 are sprayed on the dies, resulting in good surface finish of the forgings. Carbon contamination must be avoided; otherwise carbides will form.

Some forging companies favor materials which act as insulators rather than as lubricating materials [83, 88]. Those reported are mica, asbestos, glass wool, glass cloth, and sawdust. Sawdust is said to have the advantage of not fouling the die recesses, unlike other lubricating materials. Although glasses reduce oxidation and are good insulators and lubricants, they have the disadvantage of producing rougher surfaces and also collecting in the crevices of dies, thus preventing complete die filling. Hence, glasses are used mostly for simpler forging operations.

Greases and graphite suspensions have also been used; it is suggested, however, that such "slippery" lubricants can sometimes accentuate cracking, particularly in thin sections [83].

9.11 SUMMARY

This review on forging lubrication indicates quite clearly that successful practice requires a careful balance of a great number of variables—among the more important ones, billet and die materials, temperature, speed, surface finish desired, dimensional accuracy, in addition to factors such as economic considerations. In spite of the fact that forging is one of the most ancient technologies, it is evident that the search is still on for a better lubricant than the ones presently available. As we have seen, the performance of any one lubricant will vary depending on test or production conditions; it is little wonder, therefore, that no single lubricant will satisfy all requirements to the fullest extent.

While considerable data are available on the effect of lubricants on compressive-type deformation processes, knowledge of the complex interrelationship between the lubricant and other process and material variables is far from being complete. We find, for instance, that the coefficient of friction—an important factor in determining force requirements and material flow characteristics—is highly dependent on so many variables that it is virtually impossible to make any generalizations. Some of the variability of results is probably due to ill-defined experimental conditions and, in particular, to the presence of adsorbed films and surface contamination. It is both interesting and, at the same time, somewhat disturbing to observe that, despite the great variety of lubricants and new compositions tested, graphite suspensions in water, oil, or grease still seem to be by far the most effective lubricants for most applications in hot forging.

Earnest efforts are no doubt being made to simulate more fully actual forging operations in laboratory tests. However, it appears that this is practicable to a limited extent only; the only fully convincing results would be obtained in full-scale tests under actual conditions. Unfortunately, these are not always easy to perform as they involve considerable expense and occupy equipment for rather lengthy periods; great difficulties are also encountered in making these tests sufficiently versatile as far as the number of variables is concerned. No doubt substantial data of a proprietary nature exist which could not be obtained and included in this chapter. There is reason to believe, however, that much of this information concerns techniques rather than lubricant composition—it is highly unlikely that the nature of such successful lubricants would escape the knowledge, interest, and attention of investigators in lubrication, some of whom would eventually publish their findings in the open literature.

It is hoped that research in forging lubrication will continue with closer approximation to actual conditions and with as many of the important variables as possible included. Interpretation of the results should be made within the framework of the particular experiments conducted with due caution regarding the range and number of variables employed. It appears that those who seek specific answers to specific lubrication problems in forging will still have to make a rather careful and judicious selection of the data available. The purpose of this chapter has thus been to present, as far as possible, a critical review of these data, both to highlight the important findings and to serve as a reference source for further investigation.

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Chapter 10

COLD FORGING AND COLD EXTRUSION LUBRICATION

John A. Newnham

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10.1 INTRODUCTION

A wide variety of operations is encompassed by the terms cold forging and cold extrusion. Usage is somewhat variable from country to country; according to Feldmann [1], the current usage of the term cold forging includes cold shaping, extrusion-forging, cold extrusion, impact extrusion, and tube extrusion, as well as upsetting, piercing, indenting, and coining.

These processes are by no means new; the reverse extrusion of cans is considered to have originated in France in about 1886, while the Hooker process (forward extrusion of tubes) was patented in the U.S.A. in 1999. However, for many years it was possible to work only lead, tin, zinc, aluminum, and their alloys by these methods. The most important advance came in 1934 when Singer [2] developed a phosphate coating as a lubricant carrier, which enabled steels to be cold extruded. Prior to this, attempts at forming steels by cold extrusion resulted in severe damage to the tools and workpiece, making the process uneconomical. During World War II the process was employed extensively in Germany for the manufacture of munitions, and immediately afterwards there was widespread interest in it for production of small components where substantial savings over conventional production techniques were possible.

These conventional practices involved either hot forging and subsequent finish machining or, even more expensive, production of the part entirely by machining, possibly with a heat treatment stage prior to finish machining. There are several advantages which the cold forging process offers over these alternatives. Firstly, substantial material savings may be forthcoming [3] because closer tolerances can be held than in hot forging, and the smooth scale-free surface produced seldom needs further machining. Additionally, there is little or no flash produced in the process. Secondly, a cheaper steel may be employed, since adequate strength is often gained from work hardening. And, finally, even though very high forming stresses (up to 300 kpsi) are involved, tool life often increases since thermal fatigue does not occur.

These advantages must be carefully weighed against other points, the most important of which is economics: tool and development costs will be high, and a substantial capital investment in suitable presses, phosphating lines, and auxiliary equipment will be required. This means that a relatively high number of components must be produced so that these costs can be absorbed. Of course, the exact number at which cold forging becomes attractive varies not only from one part to another, depending upon their geometry and the material employed, but also from company to company, and from one region to another, since both labor costs and overhead will vary too. An assessment due to Clapp [4] is shown in Fig. 10.1 for producing a synchronizing gear unit, both by hot and cold forging techniques. More generally, Wilson [5] has given figures of 3,000 for heavy parts and 10,000 for light ones as representative of economical batches for cold extrusion and based this upon a range of component weights between a few ounces and 20 pounds. Several other economic evaluations [6-8] arrived at similar conclusions.

It is thus apparent that cold forging will become increasingly widespread in an age where so many items are mass produced. Although most of the above assessments have been directed to carbon steels which have far wider application than any other medium- or high-strength material, the arguments

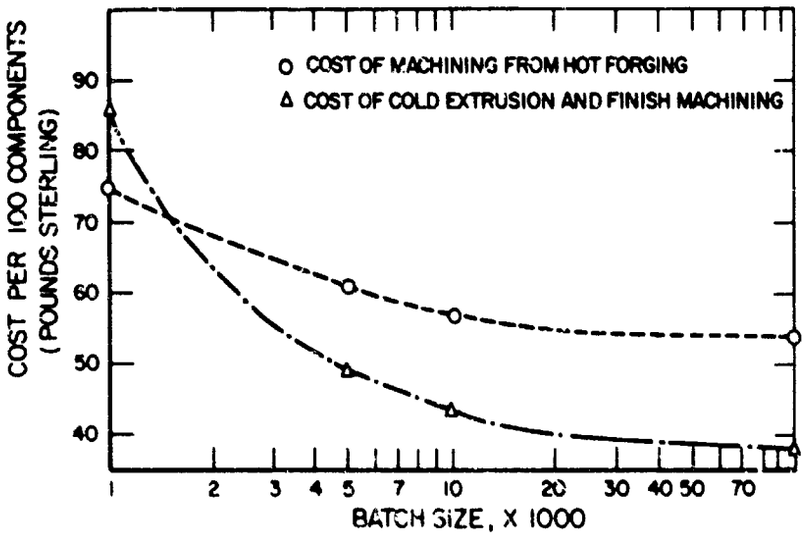

Fig. 10.1. Comparative unit cost curves for fabrication of a synchronizing gear unit [4].

may be extended to other materials. It is also apparent that the field of cold extrusion is closely linked with and, indeed, is at present largely dependent upon the success of chemical conversion coatings.

This chapter will first discuss the friction and lubrication aspects of cold forging and extrusion, including hydrostatic and ultrasonic methods, before considering the lubricants employed in the cold forging of specific materials.

10.2 FRICTION AND LUBRICATION EFFECTS

10.21 Lubrication Mechanisms in Cold Forging

The general area of cold forging presents a wide range of lubrication conditions and requirements. In all instances, however, high production rates cause the dies to heat to 100° -200° C, and the lubricant must function in the environment presented by these temperatures and the high interface pressures. Although there have been no systematic examinations of the mechanisms existing in these specific processes, three operations adequately describe the variety of situations (Fig. 10.2).

In the simplest cold forging operation, that of upsetting, two regimes exist. If a viscous lubricant is employed, this is trapped as relatively thick film covering most of the workpiece/die interface (Fig. 10.2a), while boundary conditions exist at the specimen edge. Therefore, optimum lubrication is achieved by a lubricant having both viscous and boundary properties (for a more detailed account see Section 9.22). This type of lubrication occurs only under certain conditions of geometry, pressing speed, lubricant viscosity, and workpiece yield strength. In practice, such lubrication may be encountered in simple cold heading operations and, to some extent, in coining.

In the forward extrusion of a bar by the more conventional techniques (Fig. 10.2b), the lubricant generally encounters severe conditions since a thick lubricant film cannot easily be maintained. The surface of the slug is greatly extended as it passes through the die and, in order to prevent metal-to-metal contact, it is necessary for the lubricant to follow this surface extension. The lubricant must, therefore, be strongly adherent to the surface, and able to thin out without localized failure under high pressures. However, if a conical die is used and the lubricant is viscous enough, the lubricant itself may be extruded, thereby ensuring good separation of die and workpiece. In this instance, the adherence of the lubricant to the workpiece surface is

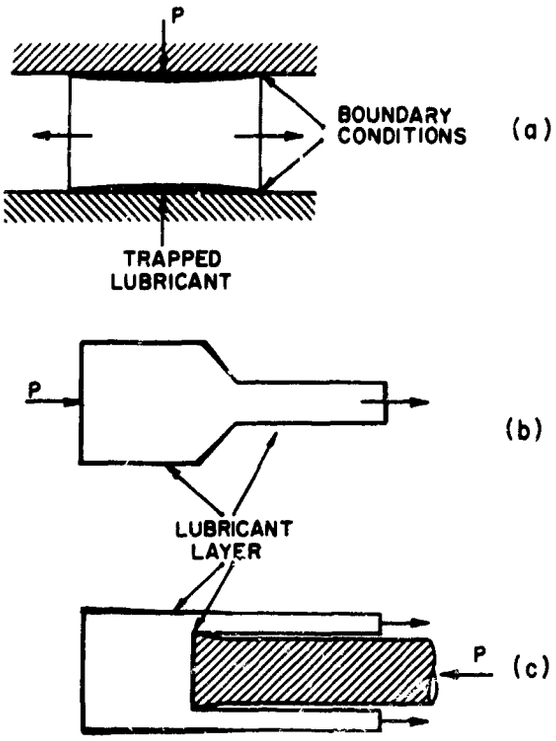

Fig. 10.2. Approximate distribution of lubricant in (a) upsetting, (b) forward extrusion of bar, and (c) backward extrusion of can.

less important, although an adequate amount of lubricant must be provided so that the entire extruded product is protected. Whenever the shape of the extrusion permits, a conical or tapered die is used to take advantage of the less rigorous conditions it creates.

Conditions are far more severe in the backward extrusion of cans (Fig. 10.2c). Whereas in the forward extrusion of bars lubricant trapped at the die and on the cylindrical surface of the billet is available to provide protection for the extruded product, in backward extrusion this protection must come from the lubricant located initially under the punch. This limited lubricant supply is required to follow the development of the new, internal surfaces without rupture.

The requirements of both forward and reverse extrusion are best satisfied by a coating which may be either a soft metallic layer (such as tin or copper) or, most frequently, a chemical conversion coating in conjunction with a lubricant. The conversion coatings have the advantage of lower cost and better bonding to the surface; not only is there a chemical bond between metal and coating, but the possibility of reacting the lubricant with the

coating also exists. In this way, surface extension is followed without wiping off the lubricant and without squeezing it out by the high pressures required for deformation. In a sense, lubrication is similar to that provided by soft films, although hydrodynamic effects are possible when the lubricant is applied in excess, and the conversion coating may perform the function of an effective (but sometimes abrasive) parting agent.

Conversion coatings are most important in the cold extrusion of high-strength materials such as carbon, alloy, and stainless steels and alloys of titanium, zirconium, and nickel. In upsetting or cold heading, such protection is seldom necessary, and E. P. lubricants may be adequate. Finally, extrusion of lower strength materials such as copper and aluminum can be performed satisfactorily with lubricants such as lanolin, tallow, or soap, which provide a relatively thick film for prevention of metal-to-metal contact, or with E. P. lubricants.

It is often feasible—at least under experimental conditions—to arrange for entrapment of lubricant in the more severe processes, thus eliminating the need for conversion coatings. In forward extrusion, for example, Kudo and Takahashi [9] have succeeded in reducing the extrusion pressure by using a cylindrical billet with a flange at the punch end, thereby enabling lubricant to be trapped in the clearance between the billet and the cylinder wall. Lubricant is then fed under pressure to the die/workpiece interface, and the resultant development of thick film conditions reduces friction considerably. The same effect can be obtained by allowing a clearance between the cylinder wall and the billet along its entire length, and trapping the lubricant with a close-fitting follower block. Here, also, there is appreciable reduction in friction both on the die and at the cylinder wall. This method may have some of the benefits of hydrostatic extrusion, without the need for expensive equipment, and may either be termed quasi-hydrostatic extrusion, or billet-augmented extrusion (see, for example, ref. 10).

Kudo et al. [11] have applied the principle also to a piercing process. By using a punch with a conical end face and by premachining a recess at the end of the billet, considerable quantities of lubricant could be trapped between the punch and the billet. Pressures observed in piercing aluminum and steel could be reduced by 20 to 30% in this way.

There are operations in which lubricant entrapment is undesirable. For example, the presence of excess lubricant should be avoided in coining.

Here, die filling is of prime importance, and the accumulation or entrapment of excess lubricant in corners or recesses will lead to incomplete filling of the die in these regions, with the result that the product must be rejected for lack of reproduction of the die impression. It is essential, therefore, that minimum quantities of lubricant be used in this operation and that the lubricant have no tendency to build up on the dies.

10.22 Effects and Properties of Conversion Coatings

Chemical conversion coatings are available for several ferrous and nonferrous metals and alloys, but experimental investigations of coatings have been limited to the phosphate coating applied to carbon steels. Nevertheless, it is reasonably certain that the conclusions derived from these experiments can be extended to the oxalate and fluoride-phosphate coatings used for stainless steels and nickel and titanium alloys, as well as to other phosphated materials. These coatings were previously discussed in Sections 4.4 and 7.31.

Evidence on the desirable phosphate film thickness is somewhat contradictory. Pugh et al. [12] found in the forward extrusion of En2A steel (Similar to SAE 1010 steel) that coating weights between 250 and 3000 mg/sq ft gave only 5% total variation in extrusion load, and the slugs with the lightest coat consistently required the lowest maximum pressures. Similarly, Howard et al. [13] observed very little variation in extrusion pressures with phosphate weights varied between 700 and 8400 mg/sq ft.

In contrast to some plant experience, this would suggest that heavier coatings do not necessarily give improved performance. Confirmation is given by James [14] who also noted that too heavy a coating is not only expensive but could cause buildup of excess lubricant in the tooling. Similar observations were made by Samanta [15]. The Production Engineering Research Association (PERA) of Great Britain have obtained results suggesting that unduly heavy coatings might be associated with increased wear of extrusion dies, whereas lower weights gave a higher incidence of punch cracking, but the tests apparently were not extensive enough to be conclusive [16]. In any case, it must be ensured that the coating is thick enough to provide complete coverage of the extruded part, so that adhesion and pickup are avoided.

Pugh et al. [12] also found that when working with a coating weight of 2000 to 2500 mg/sq ft, but with a finer crystal structure than in previous tests, lower extrusion loads were developed, though the difference was small. Further experiments showed that there was no apparent variation in surface finish attributable to different coating weights. Thus, although small differences in load could arise from varying the phosphate thicknesses, Pugh et al. concluded that tenacity and uniformity of the coating are probably more important, although these properties are not easily measured.

In this respect the condition of the steel surface prior to phosphating might be important. Hot-rolled (black) bar is always a cheaper starting material than bright drawn bar but, apart from the better finish of the cold drawn product, it is also of interest to know if the surface condition has any effect on the phosphating operation. James [14] prepared mild steel slugs of both types in an identical manner and phosphated them by two methods: first in a zinc phosphate solution containing a negligible amount of ferrous ions: secondly, in a zinc phosphate bath containing some ferrous ions. Normally, heavier coatings are produced in the latter type of bath. The average coating weight on black bar was more than 70% greater with the iron-free phosphating solution than that on bright drawn bar and about 80% greater with the iron-containing solution. However, the practical importance of this difference is rather limited, since in most cold forging operations the most severe conditions are imposed upon the end faces of the cylindrical slugs where the lubricant must resist extensive thinning. From Figs. 10.2b and 10.2c it is also apparent that the lubricant on the cylindrical surface of the slugs is exposed to much less severe conditions. Since the slugs or blanks for cold forging are cropped from bar, their end faces are always in the same condition, and the properties of the coating on the end faces will not be dependent upon the surface condition of the original bar stock.

James [14] has also described tests which show the dimensional changes when steel is phosphated. In all cases observed, the dimensional loss due to pickling was almost exactly balanced by the gain due to standard phosphating and sodium stearate lubrication treatment.

Morgan [17] attempted to improve lubrication conditions in cold extrusion by phosphating the wearing surfaces of the tool set. This required a processing sequence entailing degreasing, etching in hot sulfuric acid, and subsequent wiping with white (mineral) spirits prior to phosphating. There was no reduction in backward extrusion load from this technique, but Morgan noted that the greater freedom from metal-to-metal contact provided by coating the tools would be of benefit. The major reason for not recommending such practices was that the tools lost their high polish, and thus it became difficult to slide the finished product off the punch. With polished tools this did not occur, and the component remained in the die. Removal was then simple. Similar results were found when the tools were oxalated.

This technique is, in any case, unnecessary provided that the coating on the extrusion slug does not become so thin as to allow intimate contact of die and workpiece metals. This depends upon the thickness of the phosphate coat and on the surface extension of the most severely worked slug surface. The extrusion configuration is also important since in forward extrusion more of the phosphated surface comes into contact with the tools than in backward extrusion, where local thinning may become severe.

Several techniques have been developed for measuring surface extension and thinning of films. PERA [18] investigated the effect of punch profile and reduction in area in backward extrusion. Surface extension and the thinning of the phosphate coat were measured by scribing circular marks on the flat end face of the slug prior to extrusion, and determining their position at the inner wall of the component after the extrusion operation (Fig. 10.3). The results indicated that there was much greater extension of the surface when a hemispherical or conical, rather than a flat-ended punch was used (Fig. 10.4). Therefore, phosphate thinning would be correspondingly greater. (In this connection, Cockcroft [19] has noted that the phosphate coat can extend to 17 times its original area while remaining intact.)

It was seen in the same work [18] that, for any given punch penetration, flat profile punches retained relatively more phosphate-lubricant coating at lower reductions than at higher reductions, while the reverse was true for hemispherical punches (Fig. 10.5). This indicates that with a flat profile punch, less lubricant is supplied to the walls of the can, so that lubricant breakdown at the punch corner is much more likely. With the hemispherical punch, there is a greater tendency for metal to slide across the punch and,

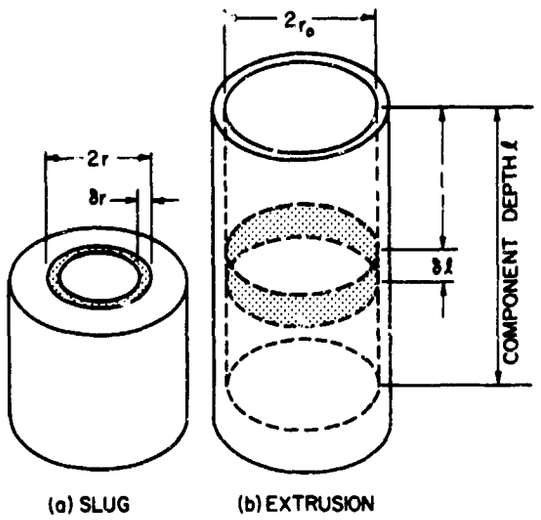

Fig. 10.3. Position of scribed circular mark (a) on slug before extrusion and (b) on the extruded product, to allow measurement of surface extension [18].

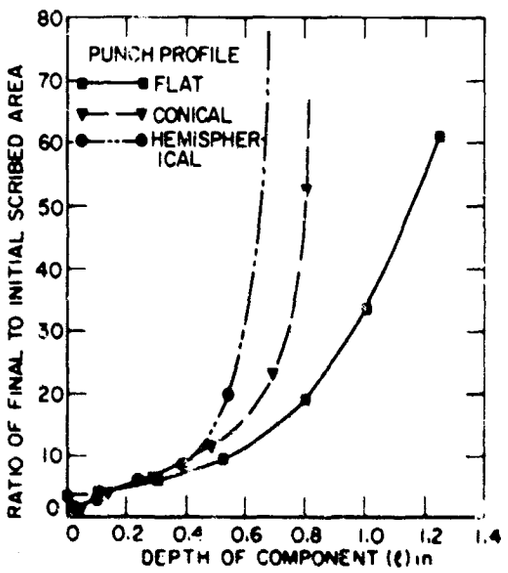

Fig. 10.4. Effect of punch profile on surface extension on the inside wall of an extruded steel can after 76.5% reduction in area [18].

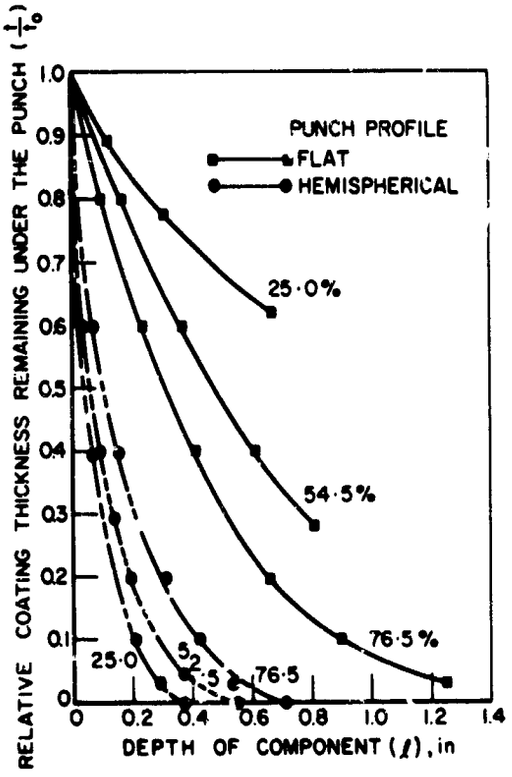

Fig. 10.5. Effect of reduction in area on the relative thickness of phosphate-lubricant coating remaining under the punch face after 76.5% reduction in area of a steel slug of 0.63 in. diameter [18].

while there is greater lubricant thinning, much more lubricant is also supplied to the walls of the can and pickup can be more easily avoided. Unfortunately, the flat-bottomed can is much more frequently required in production than one with a hemispherical bottom, so it is more likely that some design compromise (for example, a shallow conical profile with a generous corner radius) will be made to prevent pickup.

These results compared favorably with the distribution of residual lubricant on an extruded can (Fig. 10.6) as determined by gravimetric methods [14]. Although neither of these methods of determining residual thickness is accurate, they can give a realistic picture of relative thicknesses. Radiographic methods are more accurate; for instance, radioactive phosphorus can be incorporated in the phosphate coating. This system was successful for determining the effect of various lubricants on thinning of the phosphate coat in wire drawing (Section 7.4), and it has been employed to ascertain what percentage of the original phosphate coating was retained over the entire surface of an artillery shell extrusion. This was found to be 89% of that originally deposited [20]. Experiments conducted by the Cold Extrusion

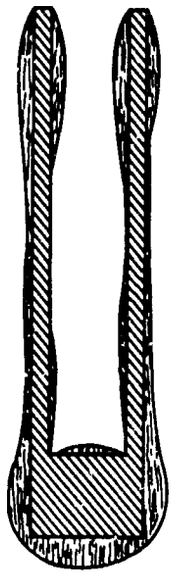

Fig. 10.6. Distribution of residual lubricant film on a backward extruded can [14].

of Steel Group of the Institute of Sheet Metal Engineering (U.K.) have also proved that the radioactive tracer technique of measuring initial and residual surface coatings is far more accurate than alternative methods [21].

Since the nature of the phosphate coating is not unlike that of the oxalate and fluoride-phosphate coatings, it can be expected that these findings will be applicable to most of the commonly used conversion coatings.

10.23 Lubrication in Hydrostatic Extrusion

Hydrostatic extrusion is a relatively new technology, and there is currently considerable interest in it as a means for extruding brittle materials and for achieving large reductions in more ductile ones. The billet or slug is surrounded with a pressurized liquid (Fig. 2.11f) instead of with a container and a punch. Thus, the container wall friction is eliminated and, according to Pugh [22], extrusion pressure is further reduced by efficient lubrication at the die/workpiece interface. For example, it was concluded at NEL [23] that a film of pressure-transmitting liquid was dragged along by the moving metal during extrusion. The efficiency of this lubrication was judged by the fact that there was no difference either in extrusion pressure or in surface appearance of the extruded product in the hydrostatic extrusion of steel billets both with and without prior phosphate coating. A mathematical treatment of hydrodynamic effects in hydrostatic extrusion has been made by Hillier [24].

It is doubtful, however, that a fluid film alone would suffice. As observed by Bobrowsky [25], lubrication other than by the pressurized fluid (unless this happens to have lubricating qualities) is required to overcome the tendency for galling between die and workpiece which occurs in the initial stages of fluid extrusion. Thus, even though the fluid film conditions can be improved at the start of the process by providing a small initial area between die and workpiece (with a workpiece nose angle smaller than the die angle) or by pumping rapidly so that the extrusion pressure is raised quickly to its operating value, deliberate addition of boundary lubricants to the fluid or to the surface of the billet is mandatory.

Fiorentino et al. [26] and Pugh and Low [27] have considered the principles of lubrication in such systems. The pressurized liquid on its own is normally satisfactory as a lubricant only when extruding low-strength materials at low extrusion ratios. A low-viscosity fluid is preferred for transmitting pressure from the pump or plunger and converting it into a hydrostatic pressure, while a high-viscosity fluid is preferred from the point of view of lubrication since full fluid film conditions are more readily promoted, but solidification may effectively terminate hydrostatic conditions. Thus the optimum balance must be determined.

An SAE 30 oil was found to be excellent for low-pressure extrusion, and 10% MoS_2 suspended in this oil improved its lubrication properties when film breakdown threatened. Above about 160 kpsi this oil became solid, and a rather rough surface finish of the extrusion resulted [28]. For higher pressures, lower viscosity media are needed which do not solidify; castor oil with 10% methylated spirits is satisfactory up to about 225 kpsi, glycerine + 25% ethylene glycol to 400 kpsi, and isopentane and white gasoline to 450 kpsi [27]. Unfortunately, these liquids do not possess good lubricating qualities, and a further disadvantage is that E. P. additives could not be found for them; for instance, MoS_2 could not be dispersed in them.

For these reasons, it becomes necessary to apply lubricant to the billet. Fiorentino et al. [26] state that this method is, in any case, more efficient than selecting E. P. agents for the pressurized fluid. Furthermore, Bobrowsky and Stack [28] have reported on Russian literature indicating that a 2/3 transformer oil, 1/3 kerosine mixture was employed there in initial trials, but grease coatings had since been applied to the billets. Bobrowsky used these lubricants in extrusion tests with 1045 steel at 1.43:1 extrusion ratio. The transformer oil-kerosine mixture alone gave a very high pressure (about 200 kpsi) whereas coating the billets with two E. P. greases—one a sodium base, the other a lithium base—gave greatly reduced pressures (140 and 160 kpsi, respectively). However, the greases were prone to solidification at these pressures causing a slight ripple on the surface of the products.

This is, no doubt, the consequence of thick film lubrication, similar to that found in rolling (Fig. 6.4a).

Successful lubricants for hydrostatic extrusion have been indentified, even though no systematic work appears to exist. Fiorentino et al. [26] found that with castor oil as the hydraulic fluid, 20 wt% MoS_2 in castor wax was an excellent billet lubricant for AISI 4340 steel at extrusion ratios between 2.5 and 6:1, but poor for 7075 aluminum alloy at 20:1 extrusion ratio, on which it showed stick-slip behavior. This was eliminated with 20% MoS_2 in stearyl stearate as the billet lubricant, and even better performance was obtained by also changing the fluid to silicate ester. It was noted that billet coatings may sometimes be necessary to prevent galling. These include the zinc phosphate coating for steels, anodized or fluoride-phosphate coatings for titanium alloys, and oxalate coatings for stainless steels. Lubricants should be employed in conjunction with these in hydrostatic extrusion as in the conventional processes. Pugh and Low [22, 27] mention Graphogen (a proprietary graphite-bearing compound) or molybdenum disulfide greases, latex rubber, fused PTFE and, for zirconium, soft metal plating as successful lubricants.

In the lower pressure range, Beresnev and co-workers [29] have examined a number of lubricants for the extrusion of an aluminum alloy through an 80° die at 4.4:1 ratio. The lowest extrusion pressure was given by a hypoid gear extreme pressure oil, but this also gave the worst (presumably, dullest) product surface finish. When a layer of the hypoid gear lubricant was applied to the billet and extrusion was performed with water as the pressurized fluid, an excellent surface finish was obtained without unduly high pressures. It has been repeatedly observed that a thick film of highly viscous lubricant not only indents the extruded surface but also preserves surface defects and machining marks present on the slug surface.

Finally, Pugh and Low [27] observed that in extruding Armco iron at a ratio of 3:1 with a Graphogen lubricant, lower pressures were obtained if the billet was initially sandblasted rather than polished. Reductions in pressure varied from 5% with a 90° angle die to 20% with a 20° die. Sandblasting, of course, creates pockets which trap lubricant on the surface and prevent metal-to-metal contact in bulk deformation, in the same way as in wire drawing (Section 7.23).

10.24 Forging with Superimposed Vibration

The application of ultrasonic energy to metalworking processes was discussed with reference to wire drawing in Section 7.28 and to simple upsetting in Section 9.22. While there was no evidence of a reduction in yield stress, it was also clear that vibrational methods may reduce interface friction, particularly if the process conditions are unfavorable for the generation of hydrodynamic films. This being so, great advantages might be expected in

the working of metals which are difficult to lubricate; unfortunately, experimental work was performed mostly on metals and alloys which present no lubrication problems to industry. Extensive surveys of work conducted in these fields have been made by Jones [30] and by Winsper and Sansome [31]. With very few exceptions, workpiece materials employed were those which are easily lubricated, such as lead, aluminum, and copper. Steel has been used only in upsetting experiments, which again present few problems, as discussed in Section 9.22.

Jones [30] reported that in the direct extrusion of lead (25:1) and aluminum (11:1 extrusion ratio), maximum reduction of static load was obtained if the container was vibrated as well as the punch and ram. Initial extrusion force decreased 15 to 22% for unlubricated aluminum and slightly less than this for lead (which shows less adhesion). It could not be ascertained how much of the reduction in force was due to reduced friction; neither amplitude of the vibrational force nor localized rises in temperature which could have reduced the yield stress of the material were measured. In particular, superposition of the vibrating forces on the nonoscillatory force often brings the total force up to its original "nonultrasonic" value (see Section 7.28) but, in the absence of amplitude measurements, a realistic estimate of frictional reduction cannot be made.

10.3 LUBRICANTS FOR COLD EXTRUSION

10.31 Chemical Conversion Coatings

These coatings, which are formed by reaction with the base metal to form well-bonded layers, were applied to cold extrusion technology before they became of interest in other metalworking areas. Included here are the phosphate coat for carbon and alloy steels, the oxalate coat for stainless steels and nickel alloys, and the fluoride-phosphate coat for titanium and zirconium alloys, previously discussed in Section 4.4.

The coating process is always cheaper if application is continuous, i.e., if wire or bar is coated in a continuous strand. Slugs for extrusion, however, can only be batch coated; this is a much more expensive method but necessary to ensure success of the operation.

These coatings are always used in conjunction with a lubricant.

10.32 Soaps

Frequently, soaps are employed with conversion coatings; in particular, sodium soaps react with phosphate coatings to form a layer of zinc soap which is bonded to the coating [14]. Both phosphate and oxalate coatings

need lubrication, normally by soaps based on stearates of sodium, calcium, or aluminum.

Soaps are also employed alone in impact extrusion of nonferrous materials. Here zinc stearate appears to be the most important commercially, especially for aluminum and copper alloys, although it is also used for tin and lead. Palmitate and arachinate soaps have also been mentioned for aluminum, but the stearates must be regarded as the standard industrial soap base for metalworking. For purposes other than cold extrusion, sodium and calcium stearates are more predominant than the zinc soap (e.g., see Section 7.32).

Soaps were previously discussed in Section 4.22; their ability to provide a thin, continuous separating film on the workpiece is the desirable attribute for cold extrusion.

10.33 Natural Oils and Fats

These have previously been reviewed in Section 4.22, together with waxes and fatty acids. These compounds find wide application in nonferrous extrusion because of their strong boundary qualities. The common fats are tallow and wool fat (lanolin), but sulfonated tallow with its additional E. P. properties is frequently used for all nonferrous materials. When a coating is also employed—for example, the phosphate coating on steel—tallow and lanolin are excellent lubricants.

Rapeseed and cottonseed oil are frequently used natural oils, the former being the more common, while the latter is usually employed only with tin or lead. Rapeseed oil is also a lubricant for the phosphate coat.

Waxes, both natural and synthetic, find application with noncoated, nonferrous metals, and may often be used in combination with a fatty acid.

10.34 Graphite and Molybdenum Disulfide

These materials are not often used for noncoated cold extrusion slugs because they are difficult to remove, though it is known that graphite or MoS_2 in tallow is sometimes employed for copper extrusion. Most frequently they are applied in a suitable carrier to a chemical conversion coating. For example, graphite and MoS_2 in a petroleum oil or in a gum resin binder are recommended for the fluoride-phosphate coat on titanium or zirconium, and graphite in tallow, dry graphite, and MoS_2 have found application as lubricants for the phosphate coat on steels.

10.4 LUBRICATION OF CARBON AND LOW ALLOY STEELS

10.41 Experimental Investigations

Relatively few investigations studied lubrication for the less severe forms of cold forging. Tanaka et al. [32] investigated the coefficient of friction in upsetting 10 mm diameter, 4 mm high specimens of mild steel from room temperature up to 400°C, thus covering the entire temperature range that may be encountered in cold forging. The specimens were upset 60%. The lubricants used represent a series of mineral oils of increasing viscosity, fatty oils and their derivatives, soaps, and some solid lubricants—all used without prior conversion coating (Table 10.1).

At room temperature the friction coefficient decreased with increasing mineral oil viscosity. A slight effect of sulfur content is detectable, higher sulfur content oils giving lower friction than their sulfur-free counterparts of identical viscosity. Of the fatty oils and derivatives, saturated compounds such as tallow and stearic acid and palm oil were considerably better than the unsaturated counterparts, such as oleic acid and rapeseed oil (Table 10.2). In the upsetting of steel at temperatures increasing from room temperature to 400°C, a rather random variation in the performance of selected lubricants was found. The most noticeable exception was chlorinated paraffin which, apparently, became effective at the higher temperatures.

There have been a number of investigations into cold extrusion lubrication for steels. Frequently they have been aimed at finding substitutes for the commercially well established phosphate-soap combination which nevertheless remains as standard practice in industry because of its attributes of relative overall economy and lubricating efficiency. Other investigations have been devoted to optimizing the phosphate coating by finding still better lubricants for use in combination with it.

Metallic Coatings

Pomey and co-workers [33] stated that tin coating was efficient as a substitute for the phosphate coat. This is practical for difficult extrusions when the part would require subsequent corrosion protection anyway. Otherwise, tinning is more expensive than phosphating.

Hauttmann [34] investigated the forward cold extrusion of carbon steel tube from tubular test pieces with the aim of determining the efficiency of various lubricant systems. His initial experiments with a wide range of

TABLE 10.1

Lubricants Used in the Upsetting Experiments of Tanaka et al. [32]

Lubricant No.	Description	Specific Gravity	Flash Point, °C	Viscosity, Redwood 1 sec 30° C	50° C	Sulfur Content, %
Mineral Oils						
1	Solvent oil	0.847	108	35.2	32.1	0.10
2	Spindle oil	0.880	140	52.2	39.5	0.10
3	Spindle oil	0.851	148	66.1	45.4	0.77
4	Machine oil	0.914	198	295.0	112.4	1.02
5	Turbine oil	0.883	196	228.4	94.6	0.18
6	Turbine oil	0.932	206	411.0	144.2	0.75
7	Motor oil	0.945	228	2309.0	532.0	1.41
Fats and Fatty Oils						
8	Palm oil					
9	Castor oil					
10	Rapeseed oil					
11	Spermwhale oil					
12	Lanolin					
13	Tallow					
Fatty Acid or Alcohol						
14	Oleic acid					
15	Stearic acid					
16	Oleyl alcohol					
Soap						
17	Stearate soap					
18	Tallow soap					
19	Palm soap					
Base Lubricant + Additive						
20	No. 17 + 10% PbO					
21	No. 7 + 10% graphite					
22	No. 7 + 10% PbO					
23	No. 7 + 10% Al stearate					
24	No. 7 + 10% Pb					
Other						
25	MoS_2					
26	Chlorinated paraffin					
27	Dry					

TABLE 10.2

Coefficients of Friction Determined in Upsetting Tests, Using the Lubricants Listed in Table 10.1 [32]

Lubricant No.	Coefficient of Friction			
	0.13C Steel 115 kpsi	Stainless Steel 225 kpsi	Aluminum (99.7%) 30 kpsi	Copper (99.98%) 70 kpsi
1	0.350	0.540	0.310	0.170
2	0.375	0.420	0.310	0.145
3	0.295	0.400	0.195	0.115
4	0.240	0.290	0.140	0.090
5	0.275	0.365	0.140	0.075
6	0.240	0.355	0.105	0.060
7	0.215	0.320	0.105	0.060
8	0.105	0.190	0.020	0.020
9	0.240	0.200	0.135	0.060
10	0.170	0.230	0.100	0.085
11	0.200	0.285	0.100	0.060
12	0.125	0.270	0.065	0.060
13	0.075	0.200	0.020	0.020
14	0.200	0.305	0.135	0.085
15	0.075	0.130	0.065	0.020
16	0.170	0.305	0.135	0.060
17	0.190	0.140	0.055	0.050
18	0.120	0.180	0.055	0.050
19	0.095	0.150	0.030	0.050
20	0.165	0.305	0.075	0.070
21	0.165	0.305	0.130	0.070
22	0.165	0.315	0.080	0.060
23	0.110	0.170	0.045	0.050
24	0.140	0.190	0.055	0.070
25	0.085	0.130	0.045	0.070
26	0.140	0.305	0.130	0.070
27	0.410	0.635	0.500	0.185

lubricants (not including phosphates) showed that copper- and zinc-plated steels gave good performance when lubricated with a bearing oil of undisclosed composition. In further tests, these two metallic coatings were compared with the phosphate coat in the forward cold extrusion of carbon steel tubes of various compositions with bearing oil as the lubricant. While differences were not too large (Fig. 10.7), zinc plate served as a better coating than phosphate and copper plate. Undoubtedly, the lubricant employed was not as efficient as the commercial sodium stearates normally recommended and the comparison is not fully valid.

In backward extruding steel cans, Tychowski [35] found that, contrary to Hauttmann's observations, extrusion forces were higher with zinc plate than with a phosphate coat. In any event, differences were small (less than 5% of the extrusion load). The differences were even smaller in the experiments of Saga and Iwasaki [36, 37], who investigated the cold piercing (backward extrusion) of a steel similar to SAE 1015 low-carbon steel, with 6 μ in. thick films of copper, cadmium, or zinc on the steel and stearic acid as the lubricant. At reductions between 20% and 80%, the cadmium plate gave lower pressures than zinc plate and copper plate; however, the differences were only around 1%. The conventional phosphate-Bonderite-stearate system gave some 2% higher pressures.

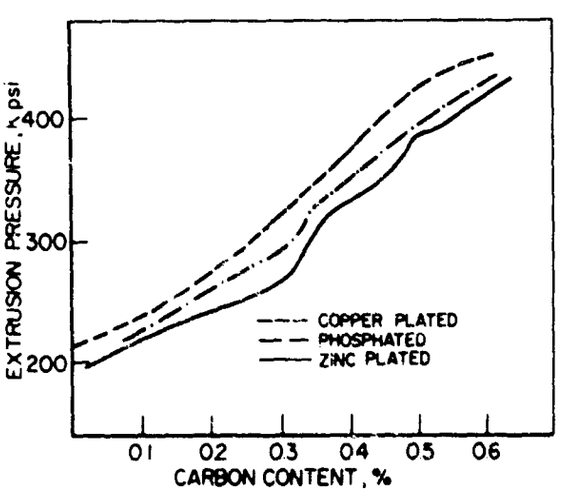

Fig. 10.7. Variation of extrusion pressure with carbon content of steel in forward extrusion of tube, showing the influence of coating composition. The lubricant was bearing oil [34].

Solid Lubricants

Evidence regarding the value of various solid lubricants whether used alone or in a carrier, is rather contradictory. Saga et al. [38] examined a spray PTFE film, a MoS_2 coating applied to the bare steel, and several lubricants used in conjunction with phosphate coatings. In the backward and forward extrusion of cold rolled 0.1% carbon steel, none of these lubricants was better than the commercial phosphate-soap combination as judged by maximum extrusion load. However, phosphate with a spray-on PTFE powder in dispersion in water was only slightly inferior. The PTFE showed almost the same efficiency when used without the phosphate coating. In contrast, the MoS_2 in a plastic resin sprayed on the phosphate coat required a high extrusion pressure. Saga et al. [38] noted that anomalies in the behavior of MoS_2 could have been caused by adverse methods of application, atmosphere, or humidity.

James [14] has reported experiments in which phosphated steel was forward-extruded to 46% reduction in order to test a number of lubricants containing MoS_2. Carriers of water, mineral oil, and other oils were employed and compared with a resin-bonded and a dry MoS_2 powder. There was no correlation between extrusion load and MoS_2 particle size, concentration of MoS_2, or the nature of the carrier in these experiments.

Results presented by Poulsen [39] showed that a commercial MoS_2 lubricant was better than a proprietary wax with a soap, or the soap alone, when tested in the extrusion of phosphated steel slugs. Here a decrease of 10% of the extrusion load was evident, although only single experiments were reported, and therefore the claimed reductions may have been due to scatter.

Tychowski [35] also found solid lubricants to be efficient, especially in the form of 50% rapeseed oil or tallow with 50% graphite. Other successful lubricants were 12% soap + 2% rapeseed oil + 40% graphite with 46% water, and 35% soap + 30% graphite with 35% water. Lubricants containing talc or MoS_2, however, were not as good.

In contrast, Pomey et al. [33] found both MoS_2 and graphite to be worse than other lubricants tested. Carnauba wax was especially good with phosphated steel, as were long-chain saturated fatty acids which were solid at room temperature (e.g., stearic acid).

In the experiments of Pugh et al. [12] slugs lubricated with phosphate and MoS_2 in alcohol required 10% higher forward-extrusion pressures than the standard phosphate-soap system. The maximum pressure required to backward-extrude cans from slugs lubricated with a wet coating of MoS_2 (where alcohol was not given time to evaporate) was about 20% lower than for slugs lubricated with a dry MoS_2 layer.

Experiments on Improved Lubricant Systems

Several attempts have been reported aimed at improving the performance of phosphate/lubricant systems.

Pugh et al. [12] compared a number of coatings— including zinc phosphate, rust, a sulfurized coat, and a methacrylic resin (Trilac)—and a range of lubricants (listed in Table 10.3) in the forward extrusion of a 1010-type steel at extrusion ratios of 2.78 and 4, and also in backward extrusion at an extrusion ratio of 2.58. There was only 10% difference in extrusion pressure over the whole range of lubricants tested (Fig. 10.8). All lubricants used with the phosphate coating were effective, with lard oil (2.7% free fatty acid)

TABLE 10.3

Lubricants Used in Extrusion Experiments of Pugh et al. [12]

Coating	No.	Lubricant
Sulfurized	1	Sulfonated tallow
	2	Lard oil (2% aluminum stearate)
	3	MoS_2 in alcohol
Trilac (resin)	4	MoS_2
	5	Aluminum stearate
	6	Chlorinated paraffin
Rust	7	MoS_2 in lanolin
None	8	MoS_2 in lanolin
Zinc phosphate	9	Lard oil (2.7% free fatty acid)
	10	MoS_2 in lanolin
	11	Bonderlube A
	12	Bonderlube 235
	13	Lard oil (2% aluminum stearate)
	14	Chlorinated paraffin
	15	MoS_2 in alcohol
	16	Colloidal graphite
	17	Sulfonated tallow

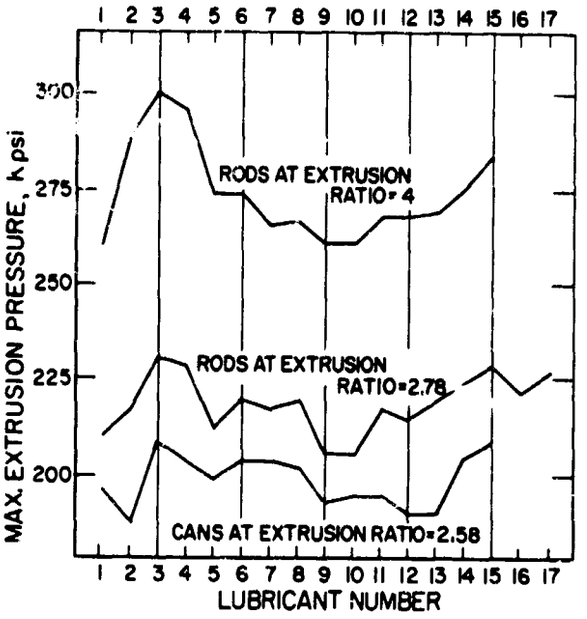

Fig. 10.8. Effect of lubricant on maximum extrusion pressure in extruding a low carbon steel. Lubricant numbers refer to the compositions given in Table 10.3 [12].

and MoS_2 in lanolin giving the lowest pressures. Uncoated slugs lubricated with MoS_2 in lanolin always registered lower pressures than phosphated slugs lubricated with MoS_2 in alcohol. Sulfurized slugs lubricated with sulfonated tallow appeared to be as effective as the best phosphate combinations; the system comprising a Trilac coating with aluminum stearate as the lubricant was most effective in terms of extrusion pressure but gave a poor surface finish.

Kunogi [40] used a novel method of backward extrusion in which a substantial amount of container wall friction was eliminated by suitable design of tooling (Fig. 10.9). A steel similar to SAE 1010 was used, and the dimensions of the slugs and the tooling were varied. It was quickly ascertained that a phosphate coating was necessary to avoid galling and to reduce extrusion pressure. Kunogi next tested various phosphate coats against each other, using "Bonderlube" (based upon sodium stearate) and a palm oil emulsion as lubricants. The coatings examined included a proprietary mixture of manganese and iron phosphates ("Parkerizing E"); a zinc phosphate formed in a bath containing some iron salt ("Bonderite 181X"); zinc and iron phosphates ("Bonderite 160X"); a calcium phosphate ("Bonderite 165X); and

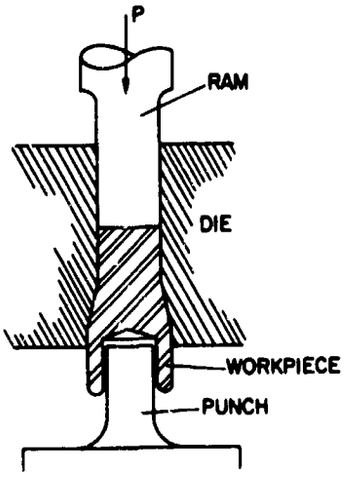

Fig. 10.9. Sketch of extrusion method proposed by Kunogi [40].

aluminum phosphate. Of these, the commercial zinc phosphate ("Bonderite 181X") was the best both with the reactive sodium stearate soap and the palm oil emulsion, although the differences were not great.

In combination with this zinc phosphate coating, several lubricants were tested, including a colloidal graphite. A "fatty acid potassium soap" was outstanding initially, but when the load was measured after 80% of the punch stroke, aluminum stearate was superior. Both of these performed better than the commercial sodium soap which is the current standard lubricant with the phosphate coating on steel.

Ishiguro and Takase [41] investigated cold forward-extrusion of steel, and confirmed that phosphate alone was not effective in reducing the extrusion load. Metal soaps were found to be fair to excellent lubricants, MoS_2 was effective only in repeated extrusion, and E. P. oils gave outstanding results at high reduction ratios (~60%) when trapping of the lubricant occurred.

Two aspects of lubrication which have more practical importance have been studied by Joseph Lucas Research Centre in England and reported by James [14]. These experiments concerned the effect of three lubricants on surface finish and punch wear in the 50% backward extrusion of a steel similar to SAE 1010 (British Specification En2E). The lubricants examined were the standard phosphate/soap combination, a chlorinated paraffin (kerosine) hydrocarbon, and a mineral oil base cold-heading lubricant containing an undisclosed E. P. agent. The results of testing in long runs are shown in Figs. 10.10 and 10.11. Surface finish was measured in

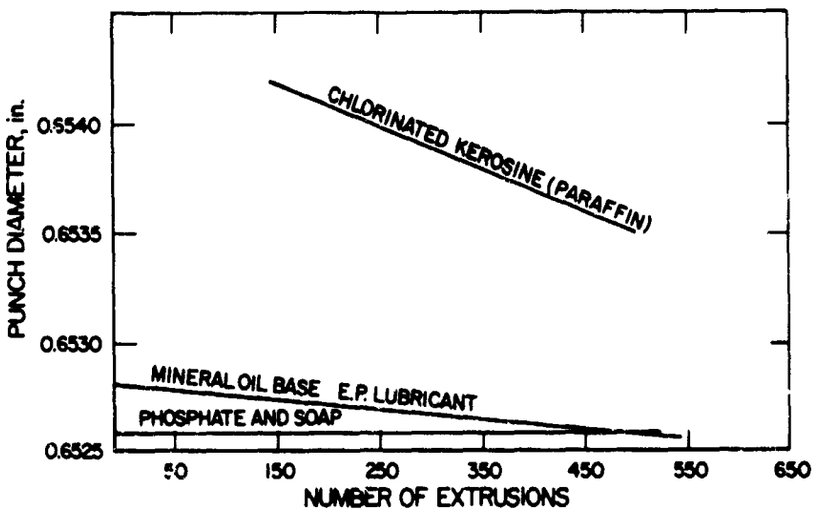

Fig. 10.10. Effect of lubricant and number of components produced on punch wear in backward extrusion of can [14].

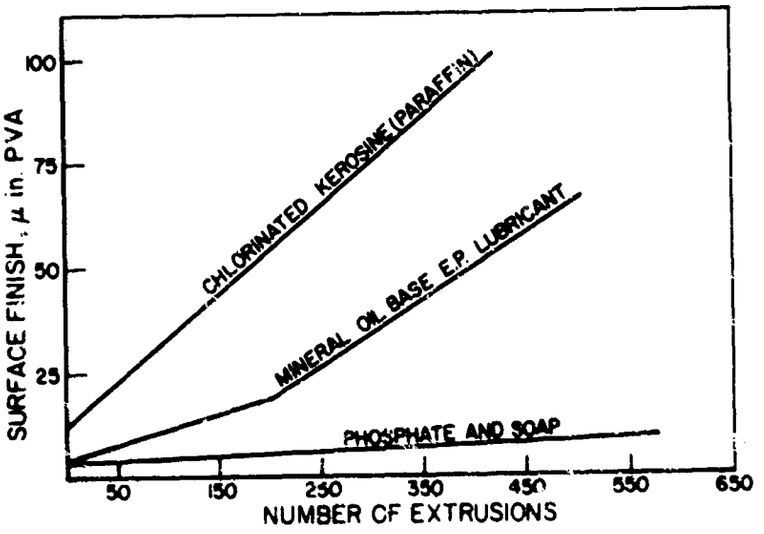

Fig. 10.11. Effect of lubricant and number of components produced on the surface finish on the inside curved surface of a backward extruded can [14].

peak-to-valley average units (PVA) in the bore of the extruded can, 0.1 in. from the base. Wear rate was lowest and surface finish best with the phosphate/soap system and by far the worst with the chlorinated paraffin. Such comparative results illustrate plainly why the zinc phosphate/sodium

stearate combination is still the most widely used lubricant system in the cold extrusion of carbon and low alloy steels.

10.42 Industrial Practices

Cold Heading

Cold heading is a relatively mild form of cold forging whose popularity has not depended upon development of the phosphate coating. The cold heading of wire has long been successfully applied to the forming of nails, bolts, and other flanged articles, but the advances made in cold forging technology—in particular, phosphating—are gradually influencing practices in this area.

Townend and Wilson [42] have discussed cold heading of steel wire. They note that frequently it is necessary to limit the wire drawing reduction of hot-rolled rod to one draft so that adequate ductility remains for heading. The wire is usually drawn dry, and substantial amounts of lubricant remain on the wire so that—for mild operations—no further lubrication may be needed. Most frequently, this lubricant will be a lime coating with aluminum or calcium stearate soaps [42-45]. In some instances, the only additional lubricant necessary is a mineral or emulsifiable oil; but as deformation becomes more severe, pastes or oils containing sulfur or other E. P. additives need to be employed [45]. Cooper [46] has listed a range of additional lubricants for the cold heading and extrusion of wire—among others, stearate and palmitate soaps, molybdenum disulfide, graphite, and oils or waxes containing E. P. agents.

For more severely worked components, annealed wire must be used. The final heat treatment is often introduced between a preliminary drawing draft and a very light finishing draft; in this way, a bright-drawn and lubricated, yet soft steel is obtained by the simplest means [42]. In this instance lime and soap could be used. Alternatively, the light draft is eliminated and the wire is phosphated, soaped, then cold headed without prior cold work [42, 47]. The disadvantage is that the sheared end faces remain without a coating. The choice is usually dictated by economics. It may be cheaper to use a nonphosphated wire, and to work conventionally lubricated slugs in a series of dies rather than taking the full deformation in one die, which would warrant a phosphate coat.

In those instances where phosphating is recommended for cold heading or other simple operations, supplementary lubrication of the end face is

mandatory. Freshly sheared slug faces may be lubricated at the press with graphitic pastes or oils [48], while Faust [49] has observed that it is common U.S. practice to use E.P. oils on the bare faces and to keep individual deformation low, so that to achieve a total deformation of 65% reduction in area, as many as 4 to 6 individual stages may be required.

Cold Extrusion

For more severe operations which involve slugs sheared from bar (rod) rather than wire, batch phosphating is needed so that the entire surface of the slug is adequately lubricated. The phosphate coating weight is important in determining the success of the operation, and although there is a wide acceptable range of weights, difficulties will be experienced if the coating is too thin [50] or too thick, as discussed in Section 10.22.

The phosphate layers should be thicker than those provided for rust protection or for drawing of thin tubes; an ideal thickness of between 10 and 15 μin. has been quoted by Fischer [51]. The coating thickness is more frequently controlled by weight. Acceptable ranges have been summarized by Morgan [17]; apparently, European practice favors between 750 and 1250 mg/sq ft, in agreement with figures of 800 to 1300 quoted by James [14]. Morgan [17] stated that over 3000 mg/sq ft is employed in the United States and 2000 mg/sq ft in operations with which he was associated in Britain.

There are numerous examples of the use of phosphate coatings in industry, not only at conventional speeds [52-61] but also for impact extrusion [62-65]. Most frequently, a soap based on sodium stearate is the lubricant for heavy deformations, since this reacts with the zinc phosphate coating to form an insoluble zinc stearate soap that is also well bonded to the surface. This combination has great resistance to rupture.

Other lubricants, however, are also used in industry, but evidence is not entirely clear. For example, Fischer [51] noted that rapeseed oil and tallow were fairly widespread and that additional improvements in lubrication were secured by the addition of sulfur-containing compounds. Palm oil and soap solutions were also considered to be suitable, as were dry soap films, but these are usually intended only for relatively light operations. Mineral oil, tallow, and graphite mixtures have also been mentioned.

Writing on German practice, Faust [49] considered that molybdenum disulfide and graphite were far more suitable for heavy reductions (greater than 40% deformation in backward extrusion) than commercial sodium

stearates ("Bonderlube"), which he considered adequate for reductions below this. For less than 20% reduction in area, fat or tallow may be applied by dipping in a suitable solvent-lubricant solution. Faust also noted that H/D (final extruded height/internal diameter) is a better parameter for judging severity in backward extrusion, but did not qualify these lubricants accordingly.

Bastian [64] noted that rapeseed oil, wool fat (lanolin), and tallow were employed in Europe, whereas U.S. practice included warm (65°C) aqueous solutions and emulsions. They contained small concentrations (about 2%) of sulfonated tallow, lard oil, chlorinated waxes, and free fatty acids in dilute sodium stearate solutions. Presumably these solutions were the forerunners of the current sodium stearate based soaps, and are similarly allowed to dry on the phosphated surface of the workpiece after warm dipping, giving a solid soap film.

10.5 LUBRICANTS FOR STAINLESS STEELS

10.51 Experimental Investigations

In compressing stainless steel, Tanaka et al. [32] found that the high adhesion of this material to the die surface was reflected in a very high and constant friction in unlubricated conditions. With mineral oils as lubricants, viscosity was a dominant factor, although the unexpectedly good performance of oil No. 4 (Table 10.1 and 10.2) might be attributed to the sulfur content. However, sulfur compounds cannot be recommended for stainless steels because the chemical reaction produces deterioration in surface properties. Best results were obtained with stearic acid and molybdenum disulfide. The good performance of tallow and palm oil probably reflected their high effective viscosity, while the unsaturated fluid products were, as expected, rather poor. Lubricants which were in solid or paste form at room temperature yielded the lowest friction coefficient, the load being supported mostly through the lubricant film (Table 10.2). At temperatures up to 400°C, lubricant behavior showed somewhat random variations, but the consistently good performance of molybdenum disulfide is worth noting.

Kunogi [40] has tested a range of lubricants, each in conjunction with a commercial oxalate coating on an 18-8 stainless steel, by the novel backward extrusion method described in Section 10.41 (Fig. 10.9). Slugs of 12.5 mm

diameter and 12.5 mm height were deformed into cans of 14.6 mm OD and 2.9 mm wall thickness. A range of soaps and other lubricants were rated by observation of maximum and minimum loads and of the load when the stroke was 80% complete. All of the metallic soaps (the Al, Ca, Zn, Cd, and Ba stearates) exhibited adequate performance, but the aluminum and zinc stearates were the best. Both palm oil emulsion and an E. P. oil based on a mineral oil were poor lubricants; little oxalate coating remained on these slugs after extrusion, as evidenced by the lack of characteristic green coloring that the oxalate imparts to the slug. Excellent performance was obtained with a colloidal graphite applied to the oxalate coat.

No other relevant experimental data could be found in the open literature. It is likely though that—as in wire drawing—highly chlorinated oils, waxes, or varnishes and organic resins can be used successfully both with or without oxalate coatings [66], at least for more moderate duties.

10.52 Industrial Practices

For cold heading and cold extrusion of stainless steels, the phosphate coat is inadequate, and for many years these operations could only be performed by copper coating the stainless steel slug [44, 46]. Then the characteristic lubricants for copper (see Section 10.7) could be applied. Sciullo [44] notes that the thickness of the copper coat on stainless steel is important, since too little will not prevent galling and too thick a coat might flake off during extrusion. A coating thickness of 0.0097 in. was quoted for cold heading. Lead was also applied, which gave low friction and efficient parting of die and slug surfaces.

More recently, however, the oxalate coating was developed, and this has largely replaced copper and lead for prevention of metal-to-metal contact in the cold extrusion of stainless steels [44, 67], so that it is now accepted as a standard treatment [15, 19]. The oxalate coat is generally used in conjunction with a soap such as calcium stearate.

10.6 LUBRICANTS FOR ALUMINUM AND ITS ALLOYS

10.61 Experimental Investigations

Aluminum is almost inevitably extruded by an impact or other high-speed technique. The tendency of aluminum to pick up on tool surfaces is

somewhat heightened by high deformation speeds so that correct lubrication is essential. However, by correct design of dies and workpiece, fluid lubricants can be made more efficient at high velocities, owing to the tendency to form a hydrodynamic film. Such improvement has been confirmed in the work of Parsons et al. [68, 69].

Pugh [70] has examined lubrication in the cold drop forging of simple cylindrical specimens of aluminum at various height-to-diameter (H/D) ratios. Sulfonated tallow, lanolin, graphite in acetone, MoS_2 in alcohol, and MoS_2 in lanolin were tested as lubricants, and these results were compared with unlubricated specimens. For a constant nominal deformation energy per unit volume, considerably increased reduction was obtainable with lubricants and the height of ram rebound also decreased as lubrication became more efficient. However, there were no consistent variations between individual lubricants, indicating that all the highly viscous or solid materials tested were adequate. This must have been due partly to trapping of the lubricant and partly to the light duties involved.

In contrast, Tanaka et al. [32] found considerable variation of friction in their upsetting tests which extended to lighter lubricants. Mineral oils showed improved effectiveness with increasing viscosity, irrespective of their sulfur content. Boundary additives such as fatty oils and their derivatives were found effective both neat and as additives (Table 10.2). These results are in agreement with other investigations discussed in Section 9.61.

For more severe extrusion duties, the lubricant is of high viscosity or even solid, and often also possesses boundary lubrication properties. In many ways, the lubricants performing best in simple upsetting (Section 9.61) have also proven useful in cold extrusion.

In Belvedere's work [71], aluminum-magnesium alloys, SAP, and aluminum ingots were impact extruded, using a variety of lubricants. From an evaluation of the surface finish of the extruded product, sulfonated tallow was the most effective lubricant while performance was progressively poorer with colloidal graphite suspensions in oil or water, grease containing MoS_2, and wax or zinc stearate base lubricants.

Sulfonated tallow was the standard lubricant in the experiments of Dower [72], who impact extruded commercial (99.5%) purity aluminum and an aluminum-zinc-magnesium alloy to form bars. Watkins and co-workers [73] also used sulfonated tallow, but in conventional cold extrusion in a

hydraulic press. The performance of sulfonated tallow was not as good under these slow-speed conditions, and when results of their prior NEL experiments were summarized, it was apparent that lanolin, tallow, various soaps, and graphite in tallow gave better performance in terms of maximum extrusion pressure. In fact, Galloway [74] employed lanolin, applied by tumbling commercial purity aluminum and Al-Mn alloy slugs in a 20% solution of lanolin in white (mineral) spirits, for the impact extrusion of cans; thus, this old established lubricant is not necessarily restricted to slow-speed conditions.

The utility of graphite is somewhat restricted by the need of removing it to avoid corrosion. The other solid lubricant, MoS_2, was found to perform adequately by Kitchen [75], who sought a suitable material for the back extrusion of aluminum capacitor cans. Several lubricants were tested but when surface finish was adequate, die life was poor and vice versa. Finally, a lubricant of 5 g MoS_2 powder (0.7 μin. particle size) in 60 cc comercial floor wax was applied by barrel tumbling and gave substantial improvements in both die life and surface finish. It was claimed that this mixture could be removed either by hot water or by conventional degreasing fluids, leaving no residue. Another lamellar solid lubricant has been found suitable for the explosive forming of 7075 aluminum alloy cans. In this case, a mixture containing 50% (by volume) mineral oil and 50% forging compound, defined as a colloidal graphite, was found to be adequate in preventing surface imperfections on the cans.

10.62 Industrial Practices

Although a wide variety of lubricants have been tried for the lubrication of aluminum and its alloys, there are a number of materials whose use is more prevalent. For example, Gmöhling [76], Faust [49], and Elliott [77] have all noted that zinc stearate is common. Gmöhling considers that although this, along with zinc arachinate, is the most frequently used lubricant for aluminum, an even distribution on the slug surface is difficult. Faust states that zinc stearate is not used where sharp corners have to be filled—for example, on hexagon head screws or nuts—since it settles in corners and prevents complete filling. Elliott [77] has given zinc stearate along with ethyl palmitate and, to a lesser extent, lanolin as standard lubricants for the extrusion of collapsible tubes.

Lanolin is in common usage in the production of engineering impact extrusions. If applied unevenly or allowed to accumulate, it causes underfill as any other semisolid lubricant would. According to Faust [49], it tends to oxidize with the trapped air at explosive speeds. Bastian [64] notes that both lanolin and tallow have varied appraisal, being alternatively considered to be superior or inferior to specially developed lubricants such as wax or petrolatum blended with tallow, fatty acids, or stearates. Sulfonated tallow might be included in this category.

Kemppinen [78] found MoS_2 or flake graphite applied on top of a soap film suitable for impact extrusion of hard aluminum alloys, while for soft alloys carnauba wax was applied in a thin coating by dipping in a solution of wax in trichlorethylene.

Among other lubricants recommended are mineral oils, stearyl alcohol, lard, and various waxes [77], especially medium hardness waxes (i.e., with melting points in the range 33° to 43°C) combined with 25 to 35% animal fats such as lanolin, tallow, or fatty acids [64].

Judging from the general properties of aluminum, it is likely that highly viscous or semisolid substances with sufficient boundary activity should be successful lubricants.

Correct application of these lubricants is important, since optimum results are obtained only when there is a thin uniform film of lubricant on the slug. Such films may be deposited from a solution in a volatile carrier by spraying or dipping slugs in the warmed-up lubricant, or by tumbling. The quantity of lubricant normally used was given as 1 lb per 100 to 125 lb of metal by Bastian [64]. Thicknesses of the order of 0.001 in. of lubricant may be required, and can be controlled well within acceptable limits of consistency by controlling the amount of lubricant dissolved in an organic solvent such as carbon tetrachloride or trichlorethylene. An advantage of tumbling is the matte finish produced, which traps the lubricant and helps to avoid pickup to a greater extent than a smooth surface [77].

Phosphate coatings have also been mentioned in connection with aluminum [15], but there are no examples in the open literature of their use either experimentally or industrially. In cold extrusion the phosphate coating would be used for aluminum only under the most severe deformation conditions, but it might be found necessary in the extrusion of the high-strength alloys.

10.7 LUBRICANTS FOR COPPER AND ITS ALLOYS

10.71 Experimental Investigations

Copper, like aluminum, is most frequently cold extruded by an impact technique and, again like aluminum, it does not require a conversion coating to prevent severe galling. In fact, the ability of copper to maintain a low friction and smooth surface finish even when the dies become coated with copper makes extrusion relatively easy. Problems do, however, arise with brass and even more with bronzes of higher strength.

Pugh [70] deformed copper cylinders with the same lubricants and techniques as described in Section 10.61 for aluminum. It was evident that sulfonated tallow was outstanding as measured by the percentage reduction in height and the height of the ram rebound for all initial specimen geometries. There were only minor differences in the behavior of the other lubricants.

Tanaka et al. [32] have used a variety of lubricants in compression tests with copper up to 400°C. Friction increased with increasing temperature, and the dry condition gave the highest values. However, copper still shows a remarkably steady and relatively low friction even when unlubricated, as found by Takahashi and Alexander (Table 9.2) and Tanaka (Table 10.2). The latter also found the effectiveness of lubricants to be a function of viscosity; it is noteworthy that the unsaturated fatty acids reduced friction no more, or sometimes even less, than a corresponding mineral oil of similar viscosity. On the other hand, saturated fatty oils were again effective (Table 10.2).

These experiments also showed that fatty oils and derivatives became gradually less effective with increasing temperatures, but without catastrophic failure. It is remarkable that solid lubricants and extreme pressure additives maintained low friction up to 300°C, but performance deteriorated at 400°C.

In recent work, Cook and Spretnak [79] obtained the flow stress of annealed OFHC copper by compression testing cylindrical specimens with four different lubricants. A graphited grease and, particularly, Teflon (PTFE) and lead were effective lubricants, reducing interface pressures to half the value measured without a lubricant.

Dower [72] used sulfonated tallow for both copper and 70/30 brass in high-speed bar extrusion experiments, while Watkins et al. [73] employed it in conventional extrusion using a hydraulic press.

10.72 Industrial Practices

A range of lubricants appears to be suitable industrially for the cold extrusion of copper and its alloys. Zinc stearate, lanolin [49], waxes, tallow, sulfonated tallow [19], fats, and various combinations of these, as well as mixtures with graphite and molybdenum disulfide, have all been used. Bastian [64] recommends dry soap coatings or solid layers of a soap-fat drawing compound or tallow which are applied by dipping in a hot solution and then air-dried. Evidently, almost any substance that is viscous enough and can be made to coat the surfaces uniformly is adequate.

10.8 LUBRICANTS FOR TITANIUM AND ITS ALLOYS

The basic problem with titanium is its tendency to adhere to the die surface. In ring upsetting experiments, Male [80] found that sticking friction prevailed with a dry specimen, but low shear strength solids were effective in reducing friction (Fig. 10.12).

There is only a small volume of cold extruded titanium parts currently produced, although with increased interest in supersonic air transport this process has taken on greater importance, at least as far as rivet forming is concerned. So far, only one sizable effort to find suitable lubricants for

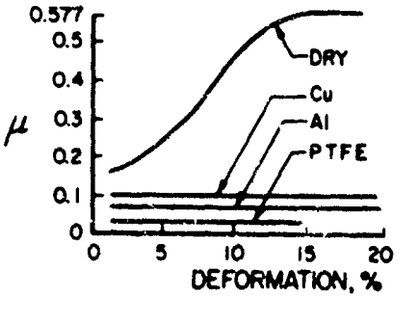

Figure 10.12 Effect of lubricating titanium with low shear strength solids on the coefficient of friction measured in a ring compression test [80].

cold extrusion has been reported, and it has produced a usable industrial lubricant for the process.

In this effort, undertaken at Battelle Memorial Institute, a fluoride-phosphate coat was initially developed in a research program to prevent galling of titanium as tested in wear tests and wire and tube drawing [81]. Sabroff et al. [81-83] then applied this and other coatings, as well as a number of lubricants, for the cold extrusion of titanium. The fluoride-phosphate coat was compared with an oxidized fluoride-phosphate coating, which was produced by heating the conventionally coated titanium in air at 425°C for 2 hr to form a layer of TiO_2 at the metal/coating interface. An experimental anodic coating produced by immersing the billet as the anode in a 5% NaOH bath at 99° C for 20 min with a current density of 50 A/sq ft was also tested. Solid wax and soap-type lubricants were employed with these coatings, either alone or with a carrier of semihydrogenated gum resin (both self-drying and nondrying), a thermoplastic resin, an alkyd resin, or an epoxy resin. Billets of 2 in. length and about 1 1/2 in. diameter were forward-extruded to 60% reduction at 80 ipm, and the lubricants were evaluated by comparison of extrusion pressures and of surface finish.

Only with the two fluoride-phosphate coats were acceptable finishes (30-60 μ in.) recorded, and this was always given by gum resin lubricant containing 5% MoS_2 and 5% graphite. However, forces were rather high. On the other hand, the self-drying wax gave the lowest pressures but the poorest surface finish. The fluoride-phosphate coating was not the outstanding choice as the best coating on the basis of these tests, but it performed as well as the other coats and was cheaper and easier to apply. An extensive investigation of lubricants of varying composition indicated that 10% graphite in gum resin was superior from both surface finish and load considerations.

A very cheap method for providing protection to the titanium surface has frequently been used in tube drawing, and has had limited application in the more moderate cold forming operations. Titanium and its alloys must be annealed in an inert atmosphere prior to cold working; if a little air is admitted into the annealing furnace during the cooling period, a thick oxide coat is formed which provides adequate protection when used in conjunction with a lubricant at moderate reductions. Under more severe conditions, however, much better performance can be obtained by means of the fluoride-phosphate coating.

Other potential coatings (for example, copper) also exist for use with titanium metal and alloys, but these are generally far more expensive than the fluoride-phosphate coat or other chemical conversion coatings (which are essentially its commercial modifications). These must now be regarded as mandatory for titanium extrusion; lubricants containing graphite and/or MoS_2 are most common, especially the 10% graphite in a gum resin carrier recommended by Battelle.

10.9 LUBRICANTS FOR OTHER METALS

Few other materials are commercially shaped by means of cold extrusion, and often very little information is available. One source is Bastian [64], who has suggested lubricants for tin, lead, magnesium, and zinc alloys.

10.91 Tin, Lead, and Their Alloys

Soft metals, such as tin and lead, were the first materials to be impact extruded [1], and subsequently the process was applied to zinc and aluminum. Bastian states that hydrogenated cottonseed oil is the most commonly used lubricant for tin and lead, but cottonseed oil, zinc stearate soap, and commercial combinations of wax and fatty acid have all been employed. In the experiments of Watkins et al. [73] sulfonated tallow was used for lead and plain tallow for tin. However, because of the inherently low dry friction of these materials, often no lubricant will be required.

10.92 Magnesium and Zinc Alloys

Magesium and its alloys are extruded at elevated temperatures (above 220°C) since they are brittle at room temperature. In the experiments of Watkins et al. [73] sulfonated tallow was the lubricant for the cold extrusion of zinc, while Parsons et al. [68] successfully used lanolin for impact extrusion.

10.93 Nickel-Base Alloys

Nickel and the nickel-base superalloys are seldom cold extruded. Because of the high strengths of these alloys a coating would normally be required to prevent metal-to-metal contact. The oxalate coating combines chemically with the surface of such materials, and would be employed in conjunction with a soap, in the same way as for stainless steels.

10.94 Zirconium Alloys

The fluoride-phosphate coating is mandatory in the extrusion of zirconium alloys [15, 19]. Graphite or MoS_2 in a suitable carrier has been found to be most suitable for this coating when used with titanium, and presumably may also be employed for zirconium.

10.10 SUMMARY

Cold forging and, in particular, the more severe operations of cold extrusion represent a continuing challenge to lubricant technology. The importance of these processes can hardly be overestimated; they are likely to be employed increasingly in the future, especially for the production of parts previously machined from bar stock or hot forgings. Lubrication is of great importance because pressures are high and often approach the limits of strength of available die materials.

There is little doubt that the system comprised of a conversion coating and lubricant will remain predominant for higher strength materials. Further development is likely to come from consideration of the cold extrusion process as a whole. Thus, workpiece composition, die design, choice of die materials, conversion coating, and lubricants will have to be considered together, since minor changes in die design, for example, can lead to a substantial change in the duties imposed on the lubricant, particularly in operations such as back extrusion.

For some materials, the possibility of providing improved lubrication with some of the newer lubricants, such as the synthetic polymers, cannot be overlooked. It remains to be seen whether surface treatments can be omitted with these materials or whether alternative, lower cost surface treatments can be found. Difficult-to-form materials are currently cold forged and extruded to a limited extent only, but their increased application will call for more effective lubricant systems. In particular, titanium is likely to present a challenge within the rather near future because of its incorporation in high-speed aircraft.

Cold extrusion benefited from its late introduction to the industrial scene, and some of the currently available lubricants have been developed as a result of systematic studies. Future improvements will have to be based on even more concentrated and fundamental investigations.

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Chapter 11

SHEET METAL WORKING LUBRICATION

John A. Newnham

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11.1 INTRODUCTION

The major requirements of lubricants in various press forming operations are essentially no different from those in other metalworking processes, but the wide range of sheet working operations (Section 2.61) and materials used commercially results in an equally broad variety of frictional conditions and acceptable lubricants. For some light operations, no deliberate lubrication may be necessary. When deformation is a little more severe, relatively poor lubricants may be employed, such as simple emulsions or straight mineral oils. Under even more severe conditions, or when the material is likely to adhere to the tool surface, some of the most heavily compounded lubricants available will be called upon to ensure consistent quality of the product, and to minimize pickup and die wear.

Most of the research into lubrication in sheet forming has been conducted to determine the order of merit of various lubricant systems under severe conditions of deformation and to clarify the effect of various parameters on the efficiency of lubrication, and hence on drawability. Very little experimental effort has been expended to find the cheapest and most effective lubricants for less rigorous duties, such as shallow presswork, and industry has generally had to find solutions by trial and error. In consequence, widely variable practices are found and conflicting opinions are held, as reflected in published industrial recommendations.

Agreement is lacking to some extent also regarding the more severe sheet forming processes. Here, however, the number of lubricants which can be used effectively is greatly reduced, and so presswork practices are more uniform. Moreover, considerable research has been conducted using tests which correlate with or simulate severe conditions of sheet deformation and, as a result, more experimental evidence is available in the open literature.

This chapter will first survey research aimed at evaluating the response of lubricants to different process variables and at determining the effect of lubricants on sheet drawability under conditions more typical of the severe

forming operations. Deep drawing, stretch forming, and ironing are the processes that have received most attention; of these, deep drawing tests to form cylindrical cups have been most frequently used since the process can be adapted to incorporate the other two modes of deformation. The conclusions derived from this experimental work are, to some extent, applicable to the less severe processes, provided that correct interpretation of lubricant action is made. Subsequently, experimental evaluations of different lubricant systems and industrial recommendations will be reviewed for both conventional and aerospace alloys. Proper understanding of the terminology used in sheet metalworking is important for following this discussion; a review of Section 2.6 is therefore advisable.

11.2 FRICTION AND LUBRICATION EFFECTS

11.21 Lubricating Mechanisms

The basic mechanisms of lubrication have been discussed in Chapter 3. From a consideration of process conditions, the mechanism of lubrication and the resulting surface finish can largely be predetermined for most sheet metalworking processes. If conditions of boundary lubrication prevail and breakdown does not occur, generally a good (smooth and bright) surface finish results. If mixed boundary and fluid film conditions prevail, loads decrease since friction decreases, and a higher degree of deformation is attainable, but often poorer (less bright) surface quality results. Under conditions of hydrodynamic lubrication most or all of the sheet metal is separated from the die by a thick film of lubricant; as a result, the sheet surface is not smoothed in any way and, in fact, could even become rougher during processing. The load may or may not be reduced, depending upon how hydrodynamic lubrication is achieved, but the maximum deformation generally increases, especially with materials susceptible to pickup on the die surfaces.

The cost of providing complete separation of sheet and tools by means of a thick film of lubricant is usually greater than that involved in using a boundary lubricant. Since the choice of lubricants in industry is largely governed by economic factors, substances that assure complete separation of tools and sheet metal (for example, polyethylene sheet) are used only to a very limited degree. They provide, however, a valuable standard of

comparison for test purposes. Such less conventional thick-film lubricants are considered for production only when the sheet material is not efficiently protected by boundary or E. P. additives and is likely to cause die damage (for instance, titanium or refractory alloys).

Separation of tools and sheet can be arranged in two ways: first, a tenacious film of lubricant can be interposed so that the die is always in contact with the lubricant, never the metal; these films are provided by chemical conversion coatings such as the phosphate/soap combination on carbon steels, or by dry-film and plastic sheet lubricants. All of these lubricants and/or techniques are relatively expensive, and thus would not be used for shallow pressings. The second method is the creation of a hydrodynamic or hydrostatic film of liquid lubricant in the region where deformation is most severe.

Consideration of the cupping process indicates that there are two regions where hydrodynamic conditions are possible (Fig. 11.1): around the draw radius and along the punch [1]. It will be noted that cupping is a fairly severe process which typifies many industrial deep drawing operations. In many pressings there will be regions where sheet metal is pushed downward by the punch surface and other regions where metal is drawn over a flat region of a die or around a die corner. In this latter instance especially, a hydrodynamic wedge can form provided that pressing speed and lubricant viscosity are high enough. Such a lubrication mechanism would be welcome, since the die corner is the area where metal pickup and lubricant breakdown most frequently occur. Pure hydrodynamic lubrication would guarantee that this is prevented, but in practice speeds and viscosities are high enough only to give partial fluid-film conditions.

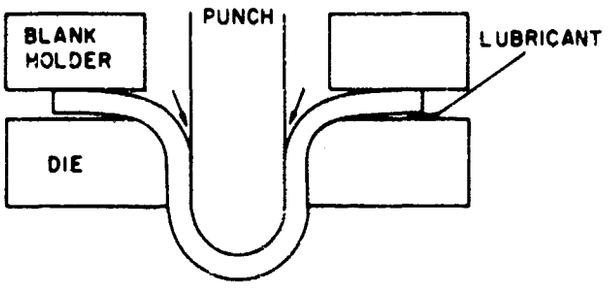

Fig. 11.1. Sketch of a deep drawing operation, indicating the regions where a hydrodynamic wedge may be formed.

Fully hydrodynamic conditions can be assured only with techniques such as that utilized by Kasuga et al. [2, 3], and subsequently by Kazachenok and Chauzov [4]. The die is set into a blind orifice which is filled with oil prior to drawing (Fig. 11.2). As the punch penetrates this orifice, lubricant is forced out between the sheet and die so that metal-to-metal contact cannot occur. This technique has been recommended for the working of refractory metals to eliminate galling, often very severe with these metals. The tool-workpiece lubrication is far better on the die side than on the punch side of the blank and, as discussed in Section 11.27, this will lead to increased formability. However, it should be noted that small variations of blank thickness will lead to preferential flow of lubricant over the thinner material. Similar unstable conditions could result if the punch were not precisely centered. Furthermore, the forces required for the operation would be higher than if a plastic sheet were used as a lubricant, and the time involved between operations would probably be greater. Therefore, the process has limitations as an industrial technique, but in theory it offers a relatively simple means of separating sheet and die without resorting to expensive lubrication techniques.

11.22 Coefficient of Friction

It is apparent from the above discussion that sophisticated or costly means of lubrication may be necessary to ensure that a severe drawing operation can be effected without failure. Load reduction is of minor consideration and higher loads may even be tolerated, as long as metal-to-metal contact is avoided. Similarly, coefficient of friction per se can also be disregarded. Indeed, an average friction coefficient in an operation with such

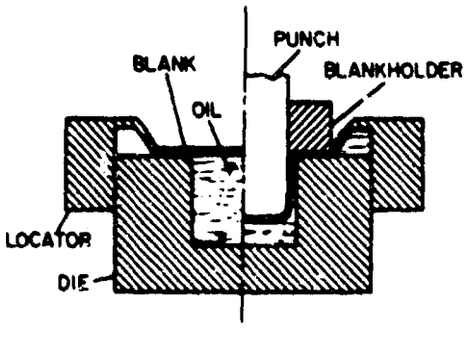

Fig. 11.2. Deep drawing with fluid-film conditions between the die and the blank [2, 3].

widely varying conditions as those encountered in cup drawing ceases to be meaningful (Section 2.63). Nevertheless, Chung and Swift [5] estimated a coefficient of friction of 0.06 in calculating the loads required for drawing a low carbon rimming steel cup, and obtained good correlation with loads observed in experiments using graphite and tallow as lubricant. A summary of the work of Swift has been given by Willis [6]. Fukui [7] has also derived average friction coefficients for cupping of Armco iron and aluminum, and obtained higher values (0.16 for Al, 0.19-0.26 for iron), but with a refined rapeseed oil as the lubricant. Most of the other examinations of lubricant behavior in cup drawing do not include estimations of friction coefficient, mainly because conditions are nowhere consistent. Much greater use is made of the limiting drawing ratio (LDR) or the load to draw a given blank diameter, as a method of lubricant comparison (Section 5.26).

In stretch forming the blank is clamped (Fig. 2.24a); therefore, deformation is more uniform and an average friction coefficient has more meaning. The magnitude of friction can be assessed from the position of fracture. Fig. 11.3a shows a 2 in. diameter, 0.035 in. thick copper blank deformed by hydraulic bulging, in which the friction coefficient is effectively zero [1, 8]. Maximum sheet thinning and, ence, failure have occurred at the pole of the pressing. A finite value of friction was acting when the blank in Fig. 11.3b was formed over a punch, and the friction has displaced the point of plastic instability away from the pole. The distance between the pole and the fracture site can be taken as a measure of the friction coefficient, so that lubricant comparison may be made on this basis. Good lubrication ensures that the thickness strain is more evenly distributed over the punch surface. Poor lubrication or none causes localized thinning, which eventually leads to fracture relatively early in the test. Thus, even though there is no reason for assuming a constant coefficient of friction in stretch forming, an average value does have significance since there is only one mode of deformation.

Recent Russian work [9-14] has concentrated to a large degree on the surface action of lubricants in metalworking, and the significance of a coefficient of friction is also questioned, but for different reasons. Here, the metal surface is regarded as being "plasticized," and a layer of low shear strength material is assumed to be present on the surface (see also Section 3.45). As a direct consequence of this view, the shear strength of

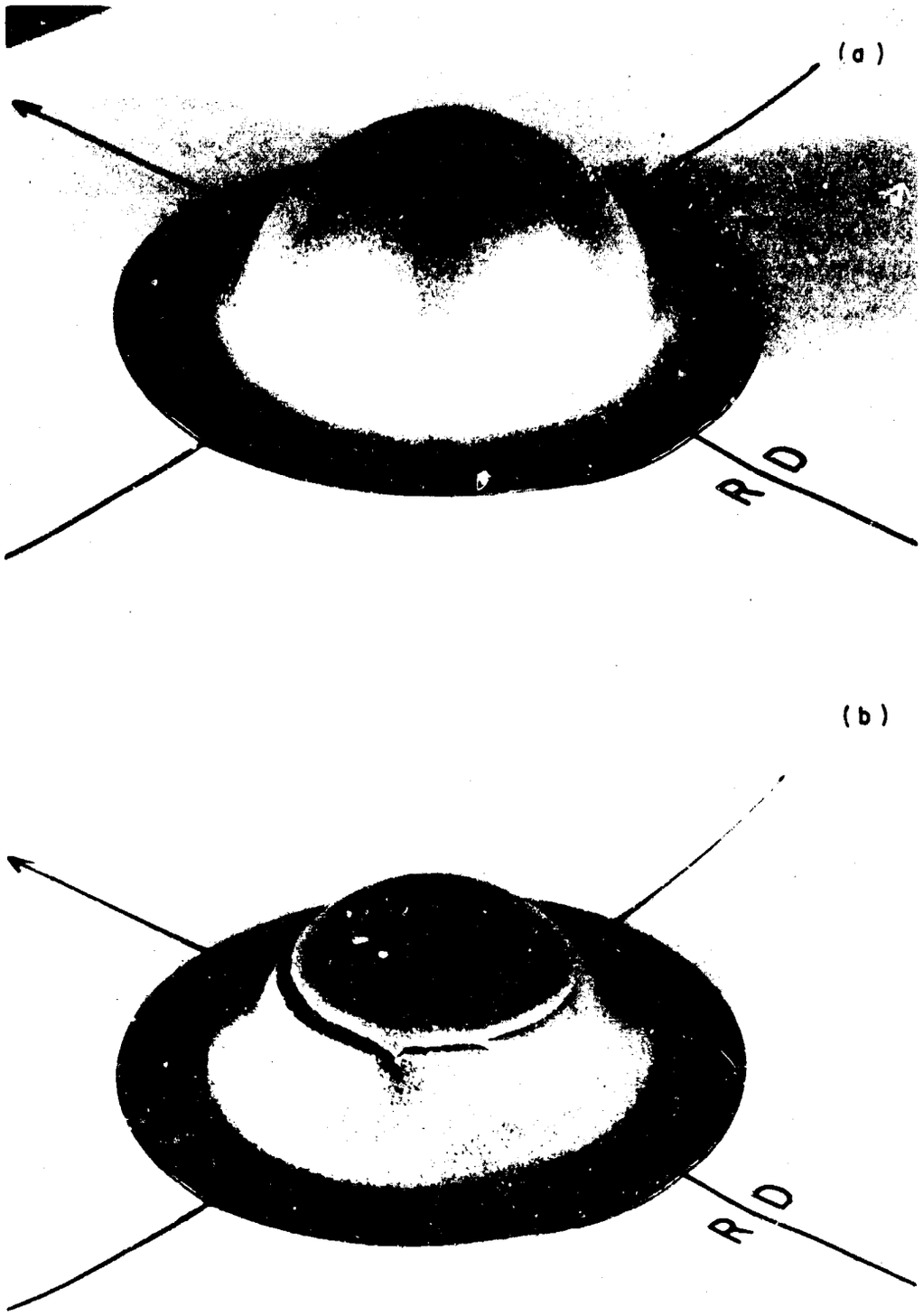

Fig. 11.3. Stretch-formed 2 in. diameter cups made from 0.035 in. annealed copper, using (a) hydraulic bulging, (b) a hemispherically nosed steel punch lubricated with polyethylene sheet.

this layer is taken as a measure of lubricant efficiency instead of the coefficient of friction. The relative merits of each viewpoint have been discussed in Section 2.1.

A novel approach to frictional phenomena in deep drawing was taken by Kasuga et al. [15-18]. Besides measuring the frictional force by means of a split blankholder (Fig. 5.7b), both halves of this blankholder were lapped to give an optically flat surface. Conformance of the sheet workpiece to the blankholder surface could then be determined from the optical reflectivity of the workpiece surface, and was correlated with the frictional force and with the conditions of lubrication. The percentage of light reflected increased with increasing blankholder pressure and with decreasing lubricant viscosity, indicating that more lubricant was squeezed out. Further, the percentage of workpiece surface area in intimate contact with the blankholder was related to the pressure generated in hydrodynamic pockets, which in turn was found to be dependent upon lubricant viscosity, in good agreement with observations noted earlier for rolling (Section 6.28). Kawai et al. [19] also employed a split blankholder, but this method does not separate friction in other regimes of the deep drawing operation.

Many workers prefer to investigate friction in simulative tests such as those presented in Fig. 5.8 and Fig. 5.10b. The relative utility of these tests has been discussed in Sections 5.26-5.28 and will not be further dealt with here.

11.23 Effect of Lubricant Viscosity

An increase in lubricant viscosity shifts lubrication towards the hydrodynamic regime and thus leads to a decrease in surface friction in both deep drawing [1, 20-22] and stretch forming [23]. This has been repeatedly confirmed by various workers. In the simulative test used by Littlewood and Wallace [24], a 0.040 in. thick steel strip was drawn over the curved surface of a quadrant die while under a back tension (Fig. 5.10c). They found viscosity to be the primary factor to the extent that E. P. additives which did not affect viscosity caused little reduction in the friction coefficient. These additives were, however, beneficial in that surface finish improved due to reduction in pickup and scoring. In the experiments of Wojtowicz [25] with the elastically loaded strip drawing test (Fig. 5.10b) the coefficient of friction steadily decreased as the viscosity of petroleum oils increased from 63 to 4400 cs at 22°C.

Researchers at PERA [21, 26] drew 70/30 brass and mild steel blanks into cylindrical cups with a flat-nosed punch at conventional and elevated blankholder loads. Their results confirmed that improved lubrication and increased LDR resulted with higher viscosity oils at all blankholder loads. An optimum blankholder load existed for each oil, the optimum increasing with increasing lubricant viscosity (Fig. 11.4). They also noted that straight mineral oils gave inferior performance to blended and E.P. oils of similar viscosity in that they were ineffective in preventing pickup and scoring with both brass and steel.

Isachenkov [27] varied sugar content in water to get different viscosities in drawing operations with stainless steel and Duralumin. Here, however, load decreased and reached a minimum as viscosity increased; at very high sugar concentrations, the drawing force started to increase. It is conceivable that at high concentration the consistency of the lubricant changed.

The experiments of Coupland and Wilson [1.20] employed both flat- and round-nosed punches in the Swift Cupping Test, a deep-drawing test of standardized geometry. Steel and 70/30 brass blanks were drawn with four mineral oils of viscosities from 162 to 2522 Redwood 1 sec at 70°F (34 to 56

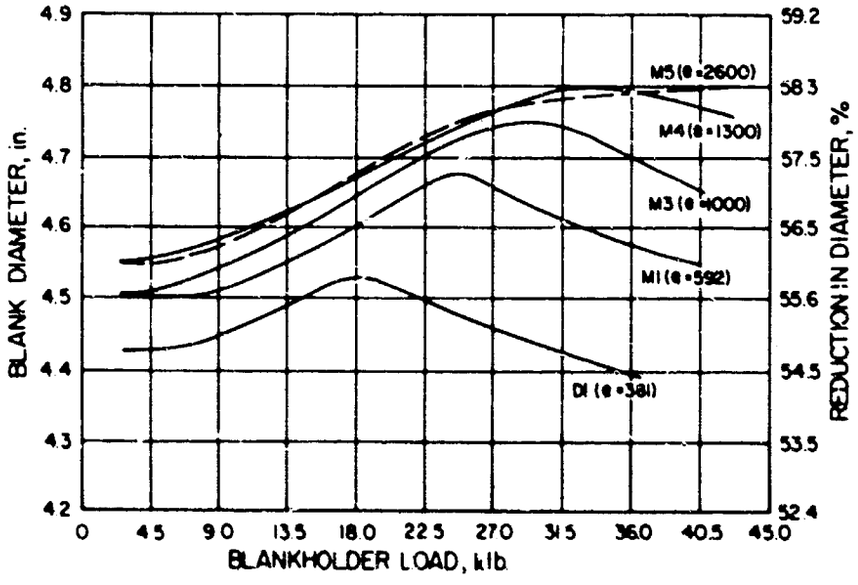

Fig. 11.4. Effects of lubricant viscosity, e, measured in Redwood 1 seconds and blankholder load on the maximum blank diameter of 0.036 in. thick mild steel which can be drawn into a 2 in. diameter cup [26].

sec at 210°F). Increased viscosity increased the separation of sheet and tool, independent of tool configuration. However, the tool configuration determined where and how this improved lubrication had most influence. With a flat-nosed punch, an increase in critical blank diameter was observed (Fig. 11.5) while the critical blank diameter decreased with the hemispherical punch. This apparent contradiction will be discussed more fully in Sections 11.24 and 11.25.

11.24 Effect of Speed

Speed has been investigated in deep drawing and stretch forming tests, and also in a simulating test designed to correlate with conditions around the die profile radius [24] where partial fluid film conditions (Fig. 11.1) may be generated at high drawing speeds.

In both cupping and stretch forming, the effect is the same as that of increased viscosity: increased speed causes a decrease in friction coefficient when a liquid (or viscous) lubricant is used. In cupping, the blank is drawn through the die and improved lubrication gives improved drawability (limiting draw ratio) when the punch has a flat end (Fig. 11.5). In contrast, lower friction on the punch side decreases the load which can be supported by the material over a hemispherical punch head and, therefore, the critical blank diameter or limiting draw ratio also decreases.

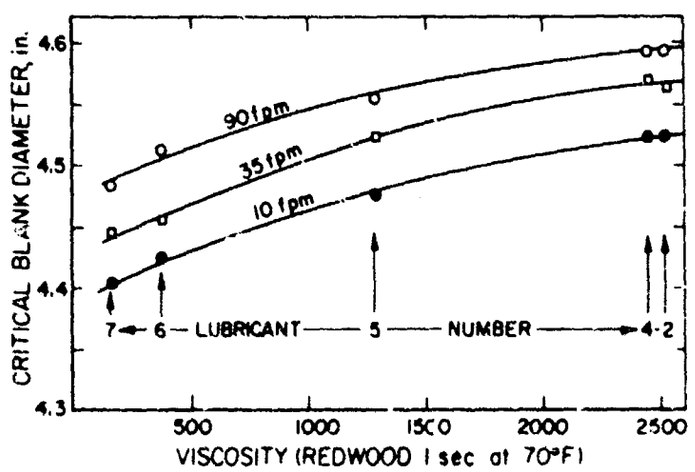

Fig. 11.5. Effects of lubricant viscosity and drawing speed in drawing 2 in. diameter cups from 0.040 in. thick rimming steel [1].

Increased speed gives increased depth of stretch-formed cups because of improved lubrication, since the position of the fracture site moves closer to the pole of the cup (Fig. 11.6) as discussed in Section 11.22. This was also found by Wilson et al. [28] who conducted stretch forming tests using a modified Swift cupping apparatus, with Esso TSD 996 (an E. P. oil containing 90% mineral oil and 10% chlorinated wax, and having Redwood 1 viscosity of 86 sec at 200°F) as lubricant.

No matter how speed affects the limiting drawing ratio, the lubricating properties of liquid lubricants are enhanced by increasing the speed of punch travel. This enhanced lubrication is attributed to an increase in average lubricant film thickness between tool and workpiece, similar to that seen in wire drawing (Section 7.24) and rolling (Section 6.23).

The behavior of solid lubricants should be unaffected by speed variations, and for this reason, Coupland and Wilson tested both brass and steel at varying speeds using graphite in acetone, a volatile carrier, as a lubricant. While speed now had no influence on the behavior of brass with either punch configuration (Fig. 11.7), steel exhibited a much reduced speed effect. However, this was readily explained on the basis of the strain-rate sensitivity of

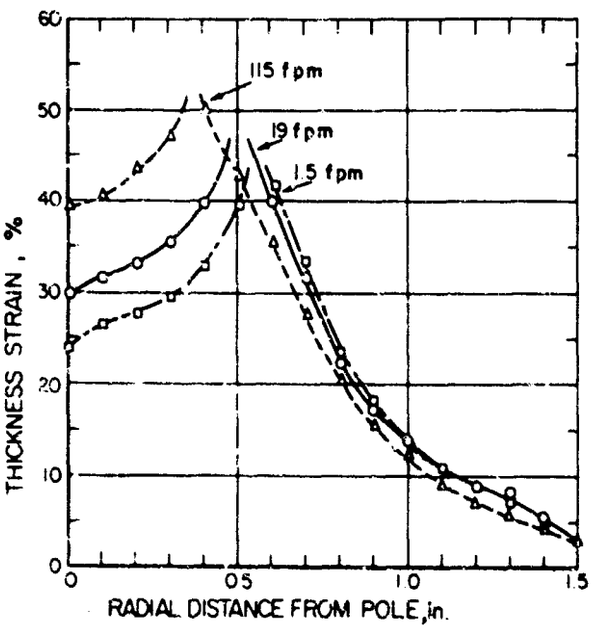

Fig. 11.6. Effect of punch speed on thickness strain distribution in stretch-forming 0.036 in. thick steel until fracture occurred. Chlorinated oil was the lubricant, with a 2 in. diameter hemispherically nosed punch [1].

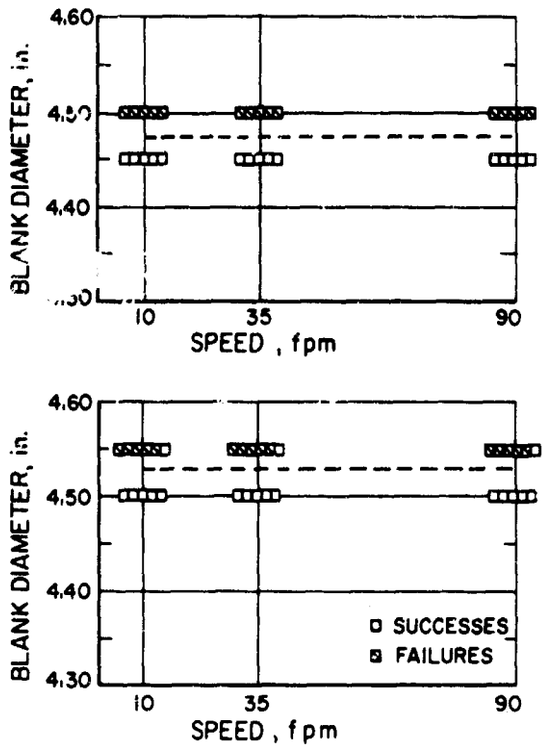

Fig. 11.7. Effect of punch speed in deep drawing 2 in. diameter cups from annealed 70/30 brass lubricated with graphite: (a) flat-nosed punch, (b) round-nosed punch [20].

the steel, and it was considered likely that the effectiveness of the solid lubricant was not influenced by speed. Fukui and co-workers [29] found that graphite, applied in aqueous solution to a metal strip, as well as a dry wax film, gave a constant coefficient of friction in a simulated ironing test, in which mild and stainless steels, copper, and aluminum were drawn through a double die at various speeds.

11.25 Effect of Tool Profiles in Deep Drawing

It is evident from Sections 11.23 and 11.24 that the punch profile influences the consequences of frictional variation in deep drawing.

With a flat-nosed punch, lubrication between punch and sheet is relatively insensitive to variations in speed and lubricant viscosity, and the improvement in interface conditions between the die and sheet causes an increase in LDR. Indeed, higher friction on the punch side is beneficial because it helps transmit the drawing force (Section 2.64).

With a hemispherical punch profile, punch surface conditions have overriding effects on the limits of formability. As friction between the punch and sheet decreases, the sheet strain is distributed more evenly over the punch surface. Thus, stretch forming with the blank clamped not only allows deeper punch penetration but also causes the load at which fracture occurs to decrease, because less of the load is transmitted to the punch. In deep drawing, this decrease in fracture load leads to a decreasing LDR as lubricant efficiency increases.

The hemispherical punch represents one extreme of conditions in cup drawing, and the other extreme would correspond to a flat-nosed punch with sharp 90° corners. The latter would cause the bottom to be punched out, and it is common practice to have a radius on the corner of the flat punch, usually of around 10 times the sheet thickness.

In order to eliminate the effects of lubrication over the punch nose from cup drawing tests, Wallace [30] suggested that the ratio of punch profile radius to punch diameter should be less than or equal to $\pi/4$ times the coefficient of friction; the fracture site will then usually be located in the wall of the cup (at the secondary neck) rather than at the punch profile radius (the primary neck which is caused by bending under tension).

11.26 Effect of Tool and Sheet Surface Roughness

Several investigators have shown that the surface roughness of both tool and workpiece is of great importance in sheet metalworking operations. These parameters affect not only the value of the coefficient of friction and the mode of lubrication, but also the surface finish of the product.

A rough punch surface increases friction, which in turn helps to support the drawing load and thus increases the limiting drawing ratio in deep drawing and cupping. This effect has been repeatedly confirmed experimentally and is exploited in practice. Thus, Keeler [31] found that localized strain at the punch profile radius was responsible for failure in drawing steel with a 4 in. diameter punch. A piece of emery tape, affixed to the punch in the region of high sheet strain, redistributed strain, retarded failure, and therefore allowed greater limiting draw ratios to be obtained. Keeler notes that in the automobile industry similar effects are obtained by roughening the punch. Wallace [32] has shown that punch surface roughness may override the importance of selective lubrication (Section 11.27) in increasing the

limiting drawing ratio. In cup drawing tests on rimming steel, better results were obtained with a lubricated knurled punch than with a polished punch which was not lubricated (the die was lubricated in both cases).

Since surface roughness increases friction, a smoother draw die finish is generally desirable. For example, Fukui and co-workers [33] used a cupping test to determine the best conditions for drawing mild steel sheet and recommended that die and blankholder surfaces should have roughnesses of the order of 3-4 μin. maximum peak-to-valley height. This value was confirmed [29] by a strip drawing test having similarities to ironing. They also found that, in the presence of a lubricant, die material has no effect on friction coefficient—only its surface roughness is important. Without a lubricant, composition is of major importance in determining friction and adhesion in metalworking processes (Section 3.25).

The effect of sheet surface roughness is more complex, and is much more dependent upon lubricating conditions. Whitton and Mear [34] showed that increasing the surface roughness of steel sheets from 40 to 65 μin. CLA by abrasive methods resulted in a slight increase of limiting draw ratio when smooth tools and a lubricant equivalent to TSD 996 was used. Butler and Wallace [35] found that if smooth sheets were drawn with a lubricant, the sheet metal was prone to wrinkling and puckering, caused by lack of control between blankholder and dies. This control was attained by the use of rougher sheets, and the occurrence of wrinkling decreased; at the same time, tooling suffered less damage through metal pickup [36]. Presumably these effects are due to the increased number of hydrodynamic or hydrostatic pockets on the sheet surface, which not only serve as lubricant reservoirs to decrease the average friction coefficient throughout the draw, as in the experiments of Whitton and Mear [34], but also provide enough high spots on the surface to establish intimate contact with the blankholder at the edge of the specimen, where interface speed and deformation are low. This gives the control required to prevent wrinkling of those regions of the specimen nearer the die orifice.

Any advantages of increasing the roughness of the sheet must also be be related to the lubricant viscosity, as shown by Fukui and co-workers [33]. They found that bright or dull finished sheets, produced by rolling to the same thickness reduction with rolls of different surface roughness, showed little variation in deep drawing behavior unless a very viscous lubricant was

used. With a lubricant of 1600 Redwood 1 sec viscosity at 50°C, better performance was obtained in cupping tests with dull finished sheets. Using a strip drawing test, Fukui et al. [29] confirmed that an increase of surface roughness caused a decrease of friction coefficient when a liquid lubricant was used.

Fogg [23] has summarized the effect of sheet surface roughness on friction when a liquid lubricant is used. In stretching and drawing tests, it was indicated that friction increases with increase in surface roughness when the tool contact pressures are a small fraction of the bulk yield stress of the sheet material. If contact pressure and yield stress are of the same order, however, small reductions in friction can occur but this depends on the lubrication. This latter statement is in accordance with the observations of Fukui et al. [33], who found frictional reductions only with a very viscous lubricant. With a solid lubricant, sheet surface finish did not affect the forming characteristics of the sheet [33].

Littlewood and Wallace [24] have suggested optimum sheet surface roughness values. They estimate that 40 μin. CLA should be representative of many types of industrial pressings, but in auto body presswork where greater control through blankholder beads is required, 55-80 μin. is considered a more applicable standard. Butler and Pope [36] have confirmed these values.

The initial surface roughness of the sheet will, together with the lubricating conditions, determine the final surface characteristics of the formed product. If no lubricant is used, intimate sliding contact promotes burnishing of the surface and great reductions in surface roughness result. In some instances, especially when the sheet material is steel which will subsequently be painted, a burnished surface is a disadvantage [37], since burnishing reduces the activity in phosphate pretreatment solutions. In this case, fluid film lubrication would be much more beneficial, with regard both to the reduction of friction which leads to lower loads and increased formability, and to the suitability of the resultant surface.

With liquid lubricants, there is the same relationship as in rolling (Section 6.22) between the degree of smoothing and the lubricant viscosity: the lower the oil viscosity, the greater the smoothing of the sheet. In other words, with increasing viscosity, higher blankholder loads must be applied to produce a similar area of burnished surface, and lubricants of high

viscosity can actually cause a roughening through the generation of hydrodynamic or hydrostatic lubricant pockets. An interesting effect was observed by Kasuga et al. [17], who found not only that a sheet material having a larger initial grain size gave higher blankholder friction (because lubricant could become entrapped at fewer sites) but also that the larger grained material was rougher after deformation. To explain this phenomenon it was theorized that hydrodynamic pockets were deeper but less widespread for large-grained material. Some supporting evidence for this was shown in micrographs of the original grain structure and of the processed surface.

It should also be remembered that the extent of smoothing varies from point to point on the blank surface. Lange and Dalheimer [38] noted that surface roughness is greater at the inside of a drawn cup because of lubricant entrapment, and there is also a gradual increase in roughness from the cup radius to the lip of the cup, because of the greater amount of deformation at the lip. Conditions are reversed at the outside wall because of contact and sliding over the die radius. At the base, smoothing may occur inside the cup, where metal has been in contact with the punch, whereas the outside surface roughness is unchanged from the original value, since here there has been no contact with the die; free bending in this area may even increase surface roughness if the grain size is large (orange peel).

In industrial pressworking, surface roughness of tools and sheet must be considered from several viewpoints so that optimum conditions may be determined. Usually, intentional roughening of the tools is not practicable, since subsequent use will cause gradual smoothing of asperities. The solution of any forming problems by this means is mostly a temporary one and can give rise to constantly varying pressing conditions and a high rate of tool wear.

The surface roughness of the sheet metal, however, is a very important consideration in press shop practice. For a given operation, using a liquid lubricant, the combination of lubricant and surface roughness will determine the surface quality of the pressing and the effective frictional conditions between tool and workpiece. Since all process conditions are standardized for most pressworking operations, it is obviously important that the surface conditions of the sheet metal conform to strictly governed specifications.

11.27 Selective Lubrication

According to Lloyd [37], the practice of hand-applying lubricants persists in the sheet metal industry mainly because of the great benefits that are obtained by lubricating only selected areas of a sheet metal blank prior to pressing. However, these benefits are gradually being forfeited because of the difficulty of fitting the hand application operation into continuous press lines. Wilson [1] suggests, in view of the progress in roller-coating of dry-film lubricants, that blanks may someday be coated in selected areas by this technique. This would obviously overcome the objections to the manual method, since the roller-coater could conveniently be installed in a production line.

The benefits of lubricating selected areas of a blank and leaving other areas without lubricant are significant. The most easily observable effect correlates with that of roughening the punch, as in the preceding section. Obviously, lubricating the die, while leaving the punch unlubricated, will produce a similar increase in limiting draw ratio [1, 22, 39-41], because high friction between punch and sheet allows the load–that would be borne only by the sheet under well-lubricated conditions–to be transmitted to some extent to the punch. Because of this reduced load on the sheet metal, greater total loads can be accommodated, and hence deeper draws can be obtained before failure. Conversely, with punch side lubrication only, conditions are worse than with full lubrication and, consequently, the LDR drops. This is true for both round- and flat-nosed punches.

Deeper drawing, however, is not the only advantage of selective lubrication. Timoshchenko [42] investigated thinning and observed that full lubrication reduced localized thinning with a flat punch (5 1/2 in. diameter) having a large profile radius (1.2 in.). With a small radius (0.3 to 0.35 in.), lubrication on the die side only was recommended.

Despite advantages, one difficulty with the use of selective lubrication in industry is that lubricant may very quickly be transferred from die to punch, or from wet areas to dry areas when conventional liquid lubricants are used. For this reason, the alternative approach of roughening the punch was suggested by Wallace [32] and others [21, 33] although this method of improving drawability also has its problems, as discussed in Section 11.26.

The necessary reproducibility and control in selective lubrication techniques may well come from dry film lubrication of selected areas of blanks [1]. An even more promising technique may be that of selective phosphating. Wilson [1] has shown that improvements in limiting draw ratio can be obtained with steel blanks phosphated and subsequently lubricated with soap, on the die side only, while using E. P. oil on the punch side (Fig. 11.8). With

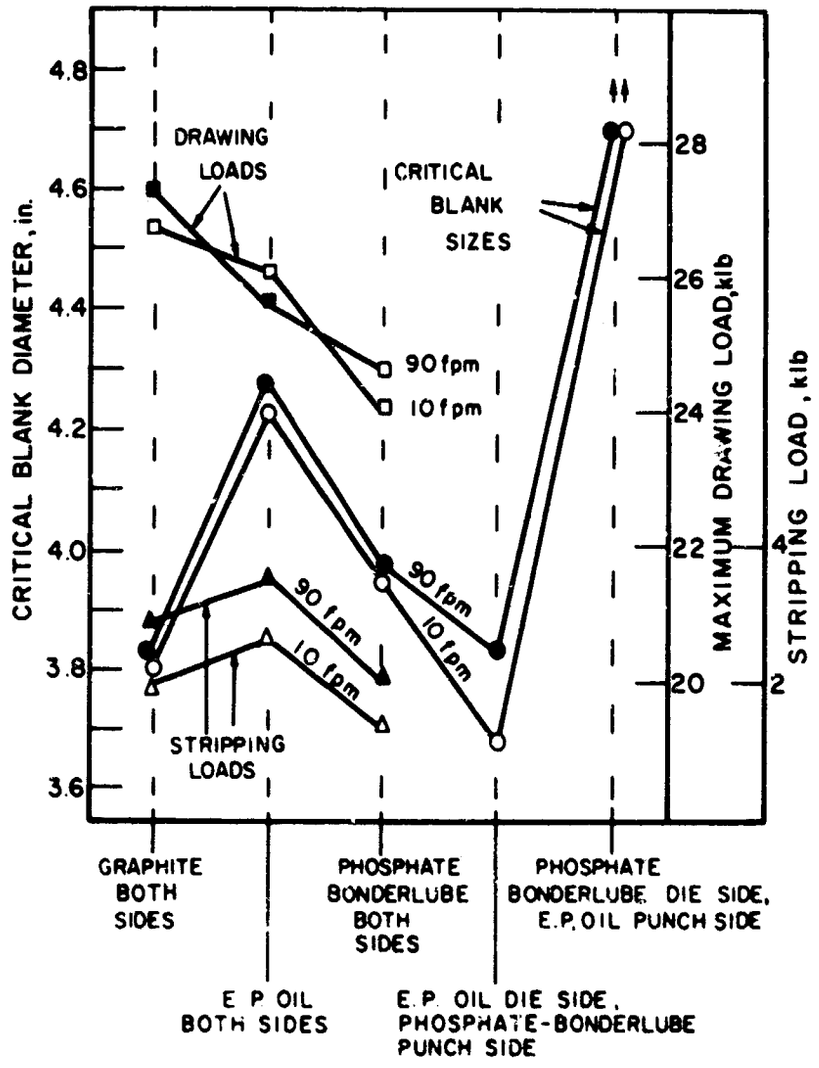

Fig. 11.8. Effects of selective lubrication on critical blank sizes, maximum drawing loads, and stripping loads in deep drawing 0.065 in. thick annealed low carbon steel into 2 in. diameter cups, with simultaneous wall ironing [1].

the development of high-speed spray phosphating [43], such a method could have application as a means of achieving reproducible selective lubrication.

In the experiments of Wilson [1] blanks were phosphated and then drawn into cups with heavy ironing of the walls—to the extent of about 50% reduction in wall thickness. In ironing the tool pressures are more severe and surface extension is much greater than in a free draw; therefore, lubrication is more critical. It has been shown in pure ironing experiments [40] that optimum conditions of lubrication occur when a good drawing lubricant is provided between the die and cup surfaces and good lubrication between cup and punch is avoided. Fortunately, these requirements are identical to the optimum conditions for deep drawing without ironing. Under these conditions the ironing load is reduced, and the high friction acting over the punch not only helps to support the drawing load but also relieves the tensile stresses in the cup wall, so that larger ironing reductions are possible for a given load. Ironing is, of course, very similar to tube drawing over a bar, and many of the lubrication techniques used in tube drawing (Section 7.29) are applied to wall ironing.

11.28 Lubrication Standards in Simulating Tests

Perhaps the greatest interest in the most common deep drawing and stretch-forming simulations (such as the Swift, Ericksen, and Olsen tests) arises not from a desire to evaluate the relative performance of various lubricants, but from investigations into the effect of process variables on the quality and physical properties of sheet metal. In these investigations the "drawability" and "stretch-formability" of the sheet are evaluated and related to the processing history of the sheet metal—lubrication is preferably kept a constant.

From the foregoing discussion it is apparent that both Swift (deep drawing of a cup) and Ericksen (stretch-forming of a clamped sheet over a hemispherical punch) test results are influenced by many variables other than the properties of the sheet metal under investigation. For this reason Kemmis [44] drew attention to the need for a set of standards for the Swift test, and proposed specifications which not only fixed the dimensions of the apparatus, but also standardized the lubricant to be used. The suggested lubricant was to be a mineral oil of 70-80 sec Redwood 1 viscosity at 200°F, and with a specified viscosity index, pour point, and flash point. When used

with ferrous materials, the oil should be blended with 10% chlorinated paraffin wax (an E. P. additive) of about 35% chlorine content. A standard method of application was also suggested.

The use of a standard Swift cupping test lubricant is now quite widespread. A proprietary oil, Esso TSD 996, has properties similar to those specified by Kemmis [44] and is very frequently used in Europe not only in Swift tests but also in the Ericksen stretch-forming simulation, so that results of many investigators may, to some extent, be correlated. However, there are obviously many drawbacks in using a liquid lubricant, because the surface finish of both the die and strip material play a large part in determining the efficiency of the lubricant, as does the drawing speed. Moreover, Wilson and Butler [22] point out that it is primarily the lack of standardization of frictional effects which necessitates a lengthy experimental determination of a limiting draw ratio as a measure of sheet metal drawability. If the tool-workpiece interface condition were accurately specified, a comparison of fracture loads and drawing loads measured on blanks of standard size would provide a criterion of drawability of equal significance to that of the limiting draw ratio. Such evaluations would be far less time consuming and more convenient.

For these reasons, Wilson and Butler [22] suggested polyethylene sheet as a standard lubricant since the frictional force would then be a function only of the shear strength of the polyethylene sheet. Indeed, polyethylene sheet has been found very effective as a lubricant in deep drawing tests. In experiments on low carbon steel sheets, Atkinson and MacLean [45] obtained a high (90% confidence limit) correlation between limiting draw ratios and $\bar{R}$, the average width strain to thickness strain ratio, which demonstrated that there had been negligible variations in lubricating conditions. Wilson and co-workers [46] examined similar parameters with equal success using steel, zinc, aluminum, and titanium sheet metals.

Kaftanoglu and Alexander [47] pointed out that, while friction over the punch head in the Ericksen test (a stretch-forming test) may seem desirable from the point of view of simulating practical conditions, it may obscure the response of the material to the imposed biaxial stress system. Since polyethylene and PTFE sheet were known to have good lubrication properties in stretch forming, these were suggested as standard lubricants for the Ericksen test. Yokai and Alexander [48] confirmed that this test was

improved with PTFE as a lubricant and with a grooved blankholder that prevented any drawing-in of sheet metal during the tests, since only the stretch-forming properties of the metal were then evaluated. Lloyd [37], however, does not recommend PTFE in sheet forming because of its low ductility, which sets an obvious limitation in systems where shearing of the intermediate plastic film occurs. In Ericksen tests conducted in Lloyd's laboratory, polyethylene was found most suitable [49]. Difficulties were encountered only when the tests were scaled up; with an 8 in. diameter punch Lloyd [37] found that fracture of the stretch-formed sheet occurred not near the pole of the dome, but close to the die ring, presumably because polyethylene had too high a shear strength. This is a serious limitation for plastics for use in industry, but not in materials testing, since the stretch-forming properties of a metal sheet would not normally be tested on such large scale. For laboratory stretch-forming tests, polyethylene sheet seems to be the most suitable lubricant since it provides a simple and effective means of standardizing conditions at the punch-metal interface.

Therefore, it seems that when only the properties of the sheet material are under investigation, polyethylene should be the standard lubricant for both stretch forming and deep drawing, thereby eliminating many factors which could obscure material property variations or mislead the investigator if a liquid lubricant were employed.

11.29 Lubrication in Other Methods of Forming

So far, discussion of lubricants has concentrated on only three operations—namely, deep drawing, stretch-forming, and ironing. These processes are extensively used in industry. Stretch-forming and wall ironing were seen to be the simplest of the operations, in that only one mode of deformation occurred. Of these, the severest interface conditions prevail in ironing, where high surface strains occur and very good lubricants are required. In stretch-forming, much smaller deformations are involved, so that high-viscosity fluids could be used without breakdown. The cupping operation, however, useful as it is, was seen to be more complex, so that a number of functions must be fulfilled by the lubricant. Since cupping may include wall ironing, once again a more powerful lubricant would be required.

These three operations are, of course, but a few of the vast number of sheet metalworking processes, and while it would be impossible to review

them all, some deserve mention because of the special lubrication situations they create.

Drawing of Irregular Shapes

Industry is frequently concerned with deep drawing of irregular shapes. With these shapes it often becomes desirable to restrict the flow of metal into the die, in order, for example, to avoid flange wrinkling. This is done by raising the force necessary to draw the metal through that particular region on the blankholder. Raising the friction force by leaving this region unlubricated is one method which could be used, but a far simpler and more reliable technique utilizes draw beads or spleens incorporated into the blankholder surface (Fig. 11.9).

Some basic work on the effect of draw bead geometry on the induced additional tension in two-dimensional bending tests was presented by Fukui and Yoshida [50]. They found that a rectangular draw bead with an appropriate corner radius had a greater effectiveness in controlling tension than a draw bead of circular section. Butler and Pope [51] have discussed draw beads with respect to materials and surface finish. They noted that, in general, aluminum requires larger radii on the draw beads than steel, in order to achieve direct bearing on the flat areas between the beads. They also noted that smooth sheet is not able to draw lubricant into areas of high pressure and could suffer severe damage when passing through draw beads, whereas rougher sheet retains lubricant in the asperity troughs.

Some friction difficulties may arise with draw beads; for example, roller-coated material causes some problems because the lubricant may build up on the beads. Nevertheless, they allow a great degree of flexibility

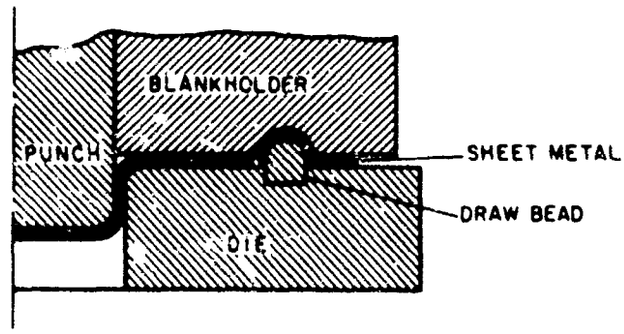

Fig. 11.9. Sketch of a typical draw bead configuration.

in deep drawing, not only with regard to complexity of pressing, but also with respect to the process. Lloyd [52] gives an example where draw beads have been utilized to give a draw-stretch forming process, thereby avoiding the use of hydraulic radial blank tension. In any event, the technique is still preferred to selective lubrication because of its simplicity.

Rubber (Hydraulic) Forming

The cost of tools for sheet forming may be very high. In the automotive and household appliance industries this cost is usually distributed over many hundred thousands of parts produced with one set of tools; therefore, even though die costs are of great concern, rigid dies are mandatory. In the aerospace industry, however, where relatively few parts are produced per set of tools, any method of forming which involves cheap tooling is of interest. The rubber die and "Hydroform" processes (Fig. 11.10) only require a rigid punch, whereas the die is of rubber and therefore very cheap. If a

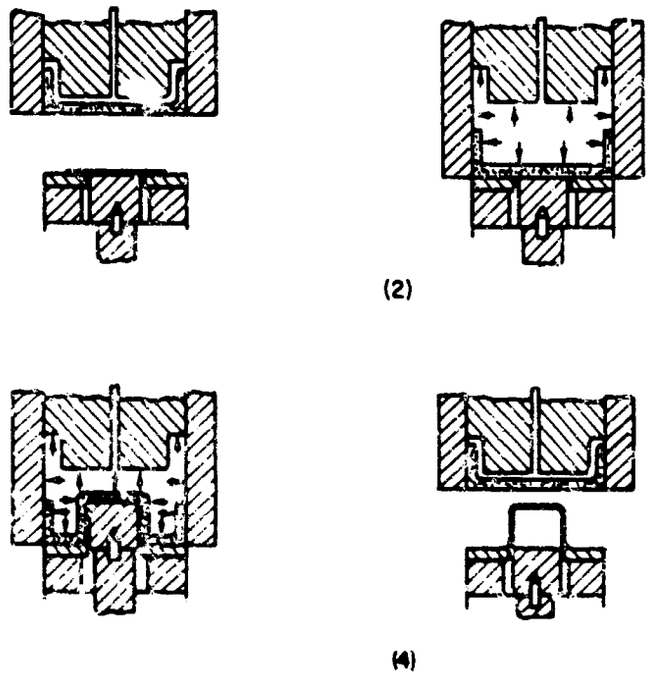

Fig. 11.10. Operational sequence for the Cincinnati Hydroform process. (1) Blank is placed on blankholder; (2) forming chamber is lowered and initial pressure applied; (3) punch moves upward into flexible die member; (4) pressure is released, forming chamber is raised, and the finished part is stripped from the punch.

lubricant is necessary for rubber pad forming, it should be neither too acid or too alkaline [53], so that there will be no detrimental effects on the rubber pad.

Panknin [54] has compared the various techniques utilizing a rubber die with conventional forming and noted that, frequently, large improvements are possible in depth of draw. This is attributable to the fact that the stress in the sheet to be drawn is redistributed, so that the effective peak stress is made less tensile [55]. This results in a greater LDR for a given sheet. A method used by Maslennikov [56] goes further by eliminating the punch which causes the high tensile stresses, replacing it with a rubber ring placed on what would be the punch side of the blank (Fig. 11.11). As load is applied, the rubber flows toward and into the die orifice, drawing the metal sheet with it. The operation now is largely accompanied by compressive stresses. Under such conditions, it is claimed that the LDR for aluminum alloy sheet can be increased from between 2.0 and 2.5 to 6.6 and at the same time the number of draws for a given shape can be reduced from 8 to 1. A lubricant is of great importance to reduce friction between the rubber and the die body

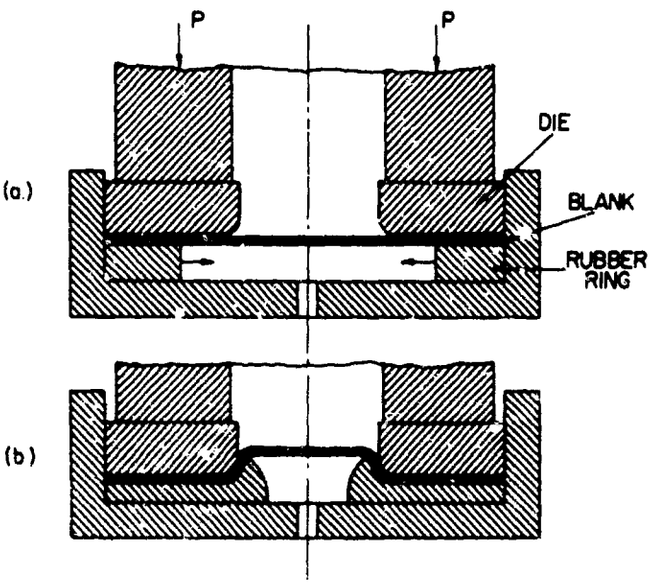

Fig. 11.11. Sketch of a deep drawing method in which a rubber ring replaces the punch. (a) Die assembly showing blank in position; (b) with pressure applied, rubber ring is forced in towards the die orifice [56].

which supplies the forming force, and also to ensure a low strain gradient across the thickness of the rubber ring.

Yet another process has involved hydrostatic pressure. Fuchs [57, 58] has described an operation in which the cooling was basically similar to that used in conventional cupping, but a pressurized liquid was made to act on the blank. By this means better lubrication was achieved, giving a good surface finish on the drawn product and decreasing the die wear. A small increase in LDR was credited to the fluid pressure acting on the edge of the blank, which gave rise to a combined extrusion-drawing mechanism. Since thinning (and necking) of the sheet metal in drawing is not affected by hydrostatic pressure, it is not surprising that very little increase in LDR was observed.

Other Operations

Many of the other industrial processes may not require lubricants. Thus, in bending and manual spinning, lubricants are used only when the metal is difficult to form and might stick against the working tool, giving high wear rates and poor product surface finishes. In power spinning (shear spinning) the high localized temperatures generated necessitate a lubricant that also performs the function of a coolant.

Currently, there is much interest in processes such as explosive forming where no punch is required since the metal is propelled toward the die by the explosive force. The die is also cheap to construct, often consisting of Kirksite (a zinc-base casting alloy), epoxy-lined concrete, or fiberglass [59]. Stretch-forming dies can also be made of these inexpensive materials, accounting for the wide use of this process in the aerospace industry where parts are produced in relatively small quantities. Explosive forming and other single-die forming operations may be frequently performed without lubrication, offering a double advantage over conventional techniques.

Lubricants are applied primarily for the reduction of tool wear and also for prevention of pickup in blanking and slitting operations. In experiments aimed at developing a process for blanking materials with minimum edge damage, Meyer and Kienzle [60] found that a lubricant promoted material flow around the punch edge and increased the proportion of the smoothly deformed edge surface by some 10% for aluminum and 20% for a medium carbon steel. In this respect, lubrication had the same effect as a slight rounding of the punch radius. In these and other less severe operations lubricants of

low or intermediate efficiency may adequately serve the purpose, and the final choice of lubricant always depends more on the workpiece material than upon the operation concerned, at least if rigid tools are used.

Vibrational Energy

Among the latest modifications in metalworking methods is the application of ultrasonic energy to the deforming tools; a general review has been given in Sections 7.28 and 7.29. The technique has been used in sheet forming for dimpling [61], ironing, and cupping [62, 63]. Dimpling of a titanium alloy and 7075 aluminum alloy was reported by Peacock [61], and the apparatus on which tests were made is schematically represented in Fig. 11.12. Sheets of copper were deformed during the ironing and cupping experiments of Langenecker et al. [62]. In both sets of experiments, low static loads were observed. There was evidence that the friction coefficient between tool and workpiece was lower than in a conventional operation, since the product structures were more homogeneous. Kristoffy et al. [63] has shown that the total amounts of energy in both oscillatory and conventional operations were equal, indicating that the real benefit was essentially that of lower friction. However, lubrication in these sheet forming processes was not discussed.

11.3 LUBRICANT TYPES FOR SHEET FORMING

The whole range of metalworking lubricants has been considered from the standpoint of their chemical and physical properties and functions in

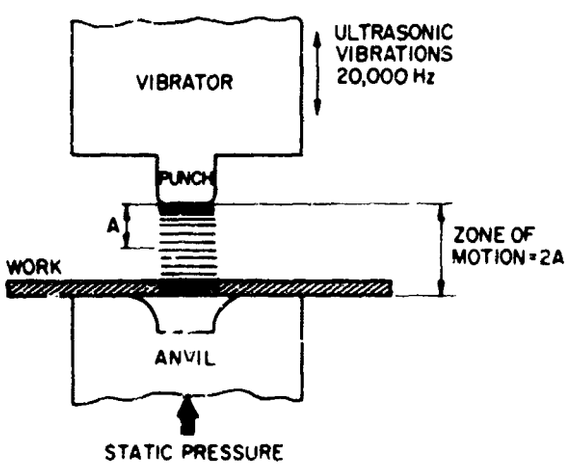

Fig. 11.12. Schematic diagram of arrangement for dimpling of sheet, using ultrasonic energy [61].

Chapter 4. However, not all of these lubricants find use in sheet metalworking, and it will be pertinent to review the lubricant types having application in this field prior to considering the lubricants used and recommended for specific materials and processes. The common lubricants used in sheet forming have been discussed by Bastian [64-67], Salz [68-72], White [73], Lloyd [37, 49], ASTME [53], and others [74-82].

Salz [70] suggests that the most suitable lubricants for sheet forming can be selected by considering first the severity of the operation (which will then indicate the efficiency required of the lubricant, and also the cost to be expected) and then the secondary properties of the lubricant to see that they agree with other industrial requirements which will have varying degrees of importance in different operations. By this means, the number of candidate materials can be reduced considerably.

Determination of the best lubricant involves many factors discussed in Section 5.1. The severity of the forming operation can be determined by reference to the type of sheet metal to be drawn, its condition, the change in shape required, and the design of the tools. The sheet metal involved has great influence on the difficulties to be expected in providing an efficient lubricant. Copper, of course, is very ductile and has little tendency to gall against the tools, so that it poses few problems. Stainless steel, on the other hand, presents many difficulties. As is implied by its name, it is not a reactive material, so that conventional boundary and extreme pressure additives are not efficient when used as lubricants. Similar difficulties are encountered in working titanium alloys, the superalloys, and the refractory metal alloys. The condition of the metal relates both to its strength, as determined by prior cold work and/or heat treatment, and to its surface condition. Increase in yield stress of the sheet before forming will lead to increased pressure requirements and reduced ductility in the forming operation. Scale on the surface of the metal, though sometimes acting as a lubricant for hot work, is detrimental in cold working. Obviously, the change in shape required and the means of doing this have great influence: a part produced by explosive forming might need no lubrication, whereas if it is made by deep drawing, it almost certainly will. The design of dies must also be considered; for example, small radii might increase the severity of the draw.

The secondary considerations are not always as obvious. Satisfactory lubricating performance must be considered along with several other factors.

The lubricant should be physiologically safe, so that materials containing toxic substances or skin irritants should be avoided. Corrosion of the sheet metal should be avoided and many lubricants do, in fact, contain corrosion inhibitors. In addition, compositional limits may have to be set. Thus, the free fatty acid content of a lubricant is often kept below 1% if staining is to be avoided with copper and its alloys. Similarly, water-dispersible lubricants should have a pH value below 9, to avoid white stains with zinc and stainless steel. Other properties required of the lubricant are stability and, if the drawn part is to be welded before cleaning, residual traces of lubricants should not affect weldability. Ease of removal, rust prevention during storage, or subsequent painting requirements may also be very important.

The economics must also be considered; this is not solely represented by the bulk cost of lubricant material, but factors like frequency of tool reconditioning, tool life, number of components, and ease of application and removal will have to be taken into account to give a realistic estimate.

From a survey of the open literature, and from information obtained by contacts with industry, it appears that the range of lubricants in current use for sheet forming can be classified into eleven basic groups. These will now be discussed with reference to their composition and to application and removal methods.

(1) Soap Solutions. These are predominantly potassium or sodium oleates or stearates diluted with water. Soap concentration is tailored to the difficulty of the operation. The solution is frequently brushed onto the sheet metal, but may also be supplied by a drip system. Continuous circulation of soap solutions is not practicable because of their foaming characteristics. The lubricant is easily rinsed off with water after forming.

(2) Soap-Fat Compound Emulsions. These are fairly thick pastes, containing some 35-60% fat, and are usually diluted with water before use. The amount of water used will depend upon the severity of the operation; a 1:1 ratio is often favored for the heaviest work, while 6 parts of water may be added for light work. These compounds are applied to the workpiece by brushing, dipping, or roller coating. Their removal is difficult by either vapor degreasing or aqueous cleaning.

By adding between 10 and 50% of solid filler, such as talc, chalk, mica, or others to soap-fat compounds, they will withstand very severe operations.

These compounds are either used as supplied or diluted with water, but the removal of pigment from the part after forming is very difficult, and represents a serious drawback to the performance of this lubricant.

(3) Soluble Oils (Emulsions). The so-called soluble oils are oil-in-water emulsions of mineral oil (Section 4.3). They can be used in a recirculating system or can be applied by hand or drip feed. The straight soluble oil emulsions are not capable of withstanding very high pressures and are used for mild operations only.

Boundary additives incorporated into the emulsion allow it to be used for more severe operations. E. P. additives are sometimes beneficial in that greater pressures can be tolerated, mainly in the drawing of steel; but more care must be taken in removing the residue, or corrosion might occur.

(4) Mineral Oils. Mineral oils are relatively inexpensive but often fail to provide adequate scoring protection at even moderate loads. They are, therefore, only suitable for use in very light working operations. They are applied by various methods and removed by aqueous or vapor degreasing. Their performance is often improved by the addition of 5-50% boundary lubricating agents.

Addition of about 5 to 50% of either sulfurized oil, chlorinated oil, or phosphorus compounds such as tricresyl phosphate gives mineral oils the capacity to withstand severe sheet deformations, provided that these active molecules react with the metal concerned. Oils containing chlorine additives are effectively removed by vapor degreasing.

(5) Straight Fatty Oils. These are more efficient as lubricants than the mineral-fatty oil blends, but are also usually more expensive and far more difficult to remove. Lard oil is one of the cheaper of these oils, and has found wide use. Palm oil is frequently used in rolling steel strip, and may often be a residual lubricant in pressing.

(6) Undiluted E. P. Oils. When metal deformation is severe, straight chlorinated or sulfurized oils may be used. Chlorinated oils prolong die life and are favored in deep drawing, but can cause corrosion of the product unless removed completely either by vapor degreasing or, if the oil contains an emulsifier, by aqueous methods. Sulfurized oils are more widespread for blanking than for drawing. These offer better rust protection than chlorinated oils but may not give as good die life.

(7) Phosphate Coatings. Phosphate coatings assure separation of tools and workpiece in the most severe operations, usually in conjunction with a soap as a lubricant. Application may be by dipping, roller coating, or spraying. The main drawback is removal, which is quite difficult since these are chemical conversion coatings. If the part is to be subsequently painted, the phosphate coating may serve as a paint base. Usually, however, the part will have to be rephosphated anyway, since most of the original phosphate coat is removed during working and in the operations prior to painting [77]. Therefore, this coating finds only limited use in sheet forming, mostly when it is absolutely necessary to have score-free surfaces. An oxalate coating replaces the phosphate coating for stainless steels, but is seldom used in sheet forming because the special techniques required for oxalate removal might spoil the surface finish of the sheet.

(8) Dry Film Coatings. There are essentially two types of dry film lubricant: the solid soap coating [83], and the plastic polymer [84, 85]. Of these, the former is by far the most widely used. Soaps are applied by either immersion or roller coating techniques, and are subsequently dried in an oven. Aqueous methods are generally adequate for removal of soap coatings, whereas the plastic polymer type needs organic solvents. Both give excellent lubrication properties, and are used mainly for drawing of large sheets. Dry soap coatings are also used in conjunction with a phosphate undercoat.

There are advantages to be found with both types of dry film lubricant. The dry soaps are only a quarter the price of acrylic resins and are water-soluble, but the plastic polymers give much greater corrosion protection in humid conditions, which soaps would not withstand. This is also a disadvantage when sheets are precoated with soap and stored, since a damp soap film offers much less mechanical protection during handling than the plastic film. Some plastic film lubricants may be applied at room temperature and, in particular, do not involve oven drying, which is a drawback with some soap films.

However, the water-soluble dry film lubricants possess more of the industrially important advantages such as low cost, generally lower friction, and greater versatility in performance [83]; therefore, they are more widely used.

Waxes may also be regarded as dry-film lubricants. However, they are not water-soluble, and this is the main drawback from an industrial point of

view. Otherwise they have properties which are not unlike those of a dry film soap; they can withstand high pressures, and natural waxes have a polarity which will ensure at least boundary lubrication if the film is severely thinned [86]. The chief attribute of some waxes is their moderate temperature resistance up to about 300°C, which other dry film lubricants do not possess. Other waxes volatilize leaving no carbonaceous residue on heating at around 250°C and are thus removed during annealing [86]; more often, however, satisfactory removal is achieved only by means of solvent degreasing.

(9) Solid Lubricants. Graphite and molybdenum disulfide are the common solid lubricants. They are often dispersed in a volatile vehicle (for instance, alcohol, kerosene, or naphtha,) and are applied by spraying, brushing, or dipping. The solvent flashes off and leaves only the solid film which can withstand high working pressures and moderately high temperatures. The chief drawback with these lubricants is that removal is very difficult. Frequently, mechanical surface cleaning is required in addition to vapor degreasing or solvent cleaning.

(10) Sheet Lubricants. Polyethylene and PTFE sheets find very limited application in the sheet forming industry because of economical considerations, but it has been shown that they are very efficient under severe conditions of deformation, since metal-to-metal contact is prohibited as long as rupture of the sheet is avoided. They are the cleanest and easiest to handle of the lubricants so far discussed, and can also be used in conjunction with a liquid lubricant [87] so that the plastic sheet no longer shears during deformation but slides over the metal surface. By this means, very low friction can be obtained under very severe conditions of deformation. PTFE is sometimes sprayed on the surface in a solvent vehicle. Polyethylene may be applied as a plastic dry film lubricant, or in sheet form which might be self-adhesive. Methods of application and performance characteristics of polyethylene have been discussed by Rao [88]. Paper is also available as a sheet lubricant, but withstands only mild deformation.

(11) Glasses. There is only a limited use for glass lubricants in sheet forming. Temperatures should be high, from about 550°C upwards. Most ductile materials as well as magnesium are worked at much lower temperatures than this, so that more conventional lubricants suffice, but glasses may be preferred when titanium alloys are worked at elevated temperatures, thereby avoiding the rapid work hardening that would occur otherwise. They are

applied usually by pasting or painting a glass slurry on the cold part to be formed or by spraying a glass dispersion, so that a coherent glass coating is formed on preheating the metal. Removal is frequently very difficult, unless the glass is water-soluble.

The properties of most lubricant types discussed in this section have been compared and tabulated by Salz [69, 72] in terms of die life, ease of removal, rust protection, and staining (Table 11.1). It will be noted that "Vanishing Oil" has not been considered here; this is a proprietary synthetic product, which has lubricating properties similar to mineral oils but does not require removal by the normal methods.

These, then, are the basic lubricant types that find application in sheet forming. Other lubricants have been explored experimentally but are not employed on a commercial basis as far as is known, and so will be considered in the later sections relating to specific metals. The lubricants for different metals and alloys will now be discussed separately, and the special techniques and recommendations noted.

11.4 LUBRICANTS FOR STEEL FORMING

In this section carbon and alloy steel will be examined. Since the automobile industry is by far the greatest consumer of sheet steel, much of the information on industrial lubrication practices has come from that source. There have also been many experimental investigations in which lubricants have been compared by means of a simulating test or by small-scale cupping tests aimed at finding the most efficient lubricants.

11.41 Experimental Studies

All lubricant evaluation involves, by necessity, a number of lubricants; for convenience, the following discussion is subdivided according to major classes of lubricants.

Lamellar Solids

One of the earliest investigations based on the cupping test was reported by Evans, Silman, and Swift [89]. They drew 2 in. diameter cylindrical cups from 4 in. diameter mild steel blanks, both with and without ironing, and compared lubricant efficiency in cupping with the effects observed in a wedge drawing test, a pure ironing operation, and a tube sinking operation. Since all of these operations present rather severe conditions, it is not surprising

TABLE 11.1

Press Lubricant Compositions for Stamping and Deep Drawing—Comparison of Properties [72]

Composition	Capability of Prolonging Die Life	Cleanability by Vapor Degreasing	Cleanability by Aqueous Methods	Rust Protection	Nonferrous Metal Staining	Remarks
Chlorinated oils:						
Concentrate (non-emulsifiable)	1	3	5	5	Usually none.	Light color; almost no odor.
Concentrate (emulsifiable)	1	3	2	5		
Mineral oil blend (high Cl content, emulsifiable)	1	2	1	5		
Mineral oil blend (low Cl content, emulsifiable)	2	1	1	5		
Sulfurized oils:						
Concentrate	2*	3	4	3	Nonstaining to Al, Zn, and Sn. Active S causes black stain on Cu, brass, and bronze.	Brown color, typical sulfur odor.
Mineral oil blend (high S content)	4*	2	3	3		
Mineral oil blend (low S content)	5*	1	2	3		

TABLE 11.1 (Continued)

Press Lubricant Compositions for Stamping and Deep Drawing—Comparison of Properties [72]

Composition	Capability of Prolonging Die Life	Cleanability by Vapor Degreasing	Cleanability by Aqueous Methods	Rust Protection	Nonferrous Metal Staining	Remarks
Fatty oils and fats:						
Concentrate	2*	3	3	3	Usually none. Cu alloys develop green stain with compounds having high free fatty acid content.	Typical fatty odor. Burns off at 1000°F, leaving no residue.
Mineral oil blend	4*	1	2	3		
Soap-fat compounds:						
Nonpigmented	3	4	3	3	Usually tarnishes brass, bronze, Zn, and Sn.	
Pigmented	2	5	4	2		
Soap solutions	3	5	1	3	Usually tarnishes brass, bronze, Zn, and Sn.	Foams
Dry film soaps	1	5	2	2	Usually tarnishes brass, bronze, Zn, and Sn.	Requires special equipment. Best suited for production work on larger parts.

TABLE 11.1 (Continued)

Press Lubricant Compositions for Stamping and Deep drawing—Comparison of Properties [72]

Composition	Capability of Prolonging Die Life	Cleanability by		Rust Protection	Nonferrous Metal Staining	Remarks
		Vapor Degreasing	Aqueous Methods			
Mineral oil	5	1	2	3	None	Wide range of viscosities.
Soluble oils:						
General purpose	5	2	1	3	—	
Heavy duty	3	2	1	3	May tarnish brass, bronze, Zn, and Sn.	
Vanishing oil	5	—	—	—	None	Evaporates from metal within 1 hr exposure to air, leaves no residue.

Ratings: 1 - best, 2 - good, 3 - average, 4 - poor, 5 - worst.

*Rating indicated is for ferrous metals. Rating would be upgraded for nonferrous metals.

that liquid lubricants failed while tallow was better, and the oleate soaps (calcium, sodium, and chromium) were found to be the superior lubricants, surpassed only by lubricants containing finely divided graphite (for example, graphite in tallow). Lange and Dalheimer [38] measured the punch load in a cupping operation; a soap solution gave the highest load, zinc stearate the lowest, and an MoS_2 paste occupied an intermediate position.

Similarly, in the experiments of Fukui et al. [29] graphite exhibited relatively high friction coefficients in a double strip drawing operation (this can be visualized as a plane-strain ironing process as shown in Fig. 5.8c). The measured values were of the order of 0.068-0.120, compared with 0.032-0.060 for a proprietary solid wax lubricant.

Eary [90] used a statistical approach to obtain an order of merit for the twelve lubricants used in his experiments, in which the evaluation was based upon the force required, the percentage of failures, and the variation in wall thickness in cups drawn from standard sized mild steel blanks. Once again, a wax—this time a chlorinated wax—gave the best performance, and a pigmented medium was the next most effective. Graphite followed this, but MoS_2 was found to be the poorest of all lubricants tested, including the straight oils. Reasons for the differences in performance of the two solid lubricants were not given, but on this evidence there is very little to be gained from graphite as a sheet steel lubricant unless, of course, elevated temperatures are involved. Under severe conditions, however, graphite as a dispersed phase in other materials would certainly be beneficial; for example, graphite in tallow has been found to be a good drawing and extrusion lubricant [89].

Apparently, lamellar solids are unable to compete with viscous materials such as waxes or soaps in drawing, whether it is sheet or wire drawing, unless elevated temperatures, unfavorable geometries, or high-strength workpiece materials increase the severity of the operation. Under such conditions the ability of these solids to withstand high temperatures and interface pressures can be effectively utilized.

Chemical Conversion Coatings

Even for severe sheet deformation processes, there are often more preferable alternatives to graphite or MoS_2, since they are very difficult to remove. If the sheet steel part requires a scratch-free surface after forming, phosphate coatings may be used. Bonderlube 350, a proprietary

stearate-base soap designed specifically to react with phosphate coatings, has been shown to be a good dry-film lubricant when used alone [91], but for heavy drawing operations, it should be used in conjunction with a phosphate coating. These heavy drawing operations often combine deep drawing with wall ironing.

Dry Film Lubricants

Dry film lubricants are gaining favor in the sheet forming industry, and have been frequently cited for steel sheet (for example, References 49, 86, 88, 92-96). Of the two basic types of dry film lubricants, the soap-based film has been discussed by Lloyd [37] and Clarke [83], and has found widespread industrial use. The organic polymer dry films have been described and tested by Mear et al. [84, 85]. In this category can be included the plastic sheet lubricants.

Coupland and Hollyman [97] conducted a laboratory and press shop evaluation of various lubricants of both types, based on the loads required to draw cylindrical cups from blanks of standard size. The lubricants included three dry-film soaps, a methacrylate resin described in more detail by Mear et al. [84, 85], and a spray-on PTFE film. Another lubricant was composed of water-soluble fatty acids and resins, while a drawing oil based on the volatile mineral spirits was more representative of the dry film type than of the liquid lubricants even though it did not become fully dry. Polyethylene sheet, a Latex-backed paper film, and spray-type molybdenum disulfide and silicone wax lubricants completed the range of dry films. Comparisons were made with conventional lubricants tested in an earlier paper by Coupland [98].

Tests were made on 0.036 in. thick rimming steel sheet, and the same sheet but with tin (terne) and electrozinc coatings. In the laboratory cupping tests, a nonadhesive polyethylene sheet lubricant was very successful, as were the dry soaps, the water-soluble fatty acid and resin compound, and the methacrylate resin. Of the conventional lubricants, a pigmented tube drawing compound was almost as efficient as the best dry film products, but this was virtually impossible to remove from the sheets after drawing, whereas removal of the dry film types was relatively easy. Only a few of the lubricants were tested in the press shop. Dry soaps gave significant load reduction over a medium drawing oil, showing better surface finish and requiring no further lubrication for a redrawing operation. The paper film was useful only with shallow pressings; the polyethylene sheet ruptured at the high

pressing speeds while the methacrylate resin gave good but not outstanding results. Molybdenum disulfide aerosol lubricants found application in the press shop where a film was sprayed onto the tools as a temporary measure for preventing excess pickup and adhesion.

Thus, the soap-based dry film lubricants gave the most satisfactory results from a number of viewpoints: they were economical and efficient in a wide variety of pressing operations, but were still relatively easy to apply and, more important, to remove. It must be noted, however, that while good lubricant performance is required in deep drawing, a poorer material may be more suitable for operations involving a high degree of stretch forming. For such processes straight mineral or E. P. oils have been recommended [98].

For these reasons, the dry soap coating—usually of the soap (sodium stearate) and alkali (borax) type—is gaining importance as a lubricant for the deep drawing of steel sheet. However, Clarke [83] has noted that etching of the more reactive metals might occur because of the alkali content of these compounds, so that their use will in general be confined to steels. Moreover, he also suggests that the heat generated in forming some nonferrous materials may not be sufficient to induce fluidity of the film and that inadequate lubrication may result.

Conventional Lubricants

The more conventional lubricants have been tested by a number of workers. Coupland's [98] results have already been mentioned, and these are of particular interest since press shop trials were compared with laboratory cupping tests. In general, correlation was very good; the greatest difficulty, however, was the interpretation of the severity of the operation. With shallow pressings, straight mineral oil was found to be adequate. With a difficult rectangular pressing, where optimum lubrication was required to reduce the failure rate, only the best lubricants—as judged from the laboratory tests—were able to improve pressing conditions. In contrast, too good a lubricant gave rise to buckling when stretch forming contributed greatly to the pressing operation. The surface composition of the steel also influenced the performance of certain lubricants. For instance, the sulfonated oil performed better than an oil containing finely divided sulfur with both plain and terneplated steel, but the order was reversed with electrozinc-coated

sheet. Similarly, the oil containing free sulfur stained the tin terneplate but did not affect the other two materials.

Other more conventional lubricants have been found effective in a number of investigations. In the experiments of Eary [90], a chlorinated wax was the most successful lubricant overall. A heavy oil developed similarly low drawing forces, but was rated lower because of wall thickness variations in the draw cup; a dry wax coating and a plastic film lubricant showed the same shortcoming. The good performance of oleate soaps in the investigation of Evans et al. [89] has already been mentioned.

Since one of the prime functions of any lubricant is separation of the surfaces, fillers (pigments) are rightly expected to be beneficial. Thus, PERA [26] evaluated the most suitable lubricants for deep drawing mild steel sheet with both conventional and high blankholder loads, as referred to already in conjunction with Fig. 11.4. Under conventional conditions, undiluted water-soluble drawing pastes that contained a high proportion of talc as solid filler were the best of the lubricants examined, with sulfur-chlorine E. P. oils next in preference. At high blankholder pressures, the order of lubricant efficiency was the same, but mineral oils were found completely unsuitable. Korolev and Podluzhnaya [99] used a strip drawing test with elastic loading to evaluate the efficiency of various solid fillers in an oil base. Talc was shown to be the most satisfactory filler, not only from the standpoint of efficiency but also for economic reasons. The value of pigments was evident also from the low drawing forces registered in the tests of Eary [90]. Talc is, in fact, widely used as a filler for industrial lubricants, along with chalk, borax, mica, zinc oxide, and other materials. In general, however, these solid additives present removal problems.

11.42 Lubrication Practices

There is a wide range of ideas on the best lubricants for a given pressing operation. Obviously, there is more agreement in the choice of lubricating materials for severe forming processes, since there are fewer lubricants that can withstand these conditions. Listed below are the lubricants commonly considered for light operations (stamping, blanking, shallow pressing) and for deep drawing operations.

Light Presswork

Lubricants of many varieties have been recommended for stamping. When duties are light, preference is inevitably for liquids which are most

easily applied and removed, and which are relatively cheap. These materials will frequently be water-soluble (emulsions and soap solutions).

In the blanking and shallow drawing of very thin sheet, difficulties are mostly unrelated to friction, and the lubricant is applied for reduced die wear. Light mineral oils or mineral oil emulsions usually suffice. For heavier gages, the mineral oil or emulsion might be lightly compounded with a polar additive, such as a fatty oil, for increased boundary lubrication properties. Otherwise, dilute soap solutions or, in more severe cases, dilute soap-fat compound emulsions might be used. Cold-rolled steel strip often has residual films of palm oil or other lubricant used in the rolling operation. Frequently, in light operations these residual films may perform adequately without further lubrication.

As the severity of the operation increases—for example, if alloy steels are used or if more difficult geometries are involved—the mineral oils or emulsions are fortified with greater quantities of boundary or E. P. additives. Thus, fatty oil emulsions (pigmented for use with alloy steels), and possibly straight chlorinated oils are representative of lubricants for shallow press-work.

PERA [100] investigated the effect of lubrication in the finish blanking of 7/16 in. thick 0.1% carbon steel plate by a 5/8 in. diameter punch. This operation is more severe than is normally encountered with sheet, and serves to illustrate the selection of more powerful lubricants for such conditions. The materials considered included a range of oils with various E. P. additives—chlorinated, sulfurized, sulfochlorinated, and phosphorized compounds—and solid lubricants such as graphite, MoS_2, and PTFE. The most efficient lubricants were found to be E. P. lubricants with around 40% chlorine content, molybdenum disulfide powder, PTFE powder, or a combination of these two solids. All other lubricants were unsuitable, as judged by the surface finish of the blanked slug and the condition of the die and punch after blanking up to 1000 parts. The most highly recommended lubricant for this severe blanking operation was the chlorinated oil containing between 20 and 40% chlorine, this content depending upon the thickness of the steel plate. The solid lubricants were more costly and more difficult to apply and remove from the stock. The chlorinated oils were most effective when the tools were fairly rough (about 30 μin. CLA). It was also found that for equal amounts of chlorine, the viscosities of oils did not influence the performance of the lubricant.

Deep Drawing

Dry film lubricants are widely employed in the deep drawing of carbon and alloy steels. Most frequently these are soap-base lubricants, but waxes may also be used in the same way. Soaps are relatively inexpensive and are very easily removed; their chief disadvantage is the large initial capital expenditure and special equipment needed to ensure even distribution of the soap film onto the sheet. In addition, drying ovens may be required for some of these lubricant types. There is little evidence to suggest that plastic polymer dry films have found practical application with either carbon or alloy steels.

In special cases—for example, in heavy ironing operations [37] or in severe drawing operations [78, 79] where no scoring or roughening of the surface is permissible—the surface of the sheet may be phosphated. This gives excellent protection from metal-to-metal contact, and also allows considerable smoothing of the surface irregularities. These coatings are generally used in conjunction with a reactive or nonreactive soap lubricant, and usually find application only when a dry film lubricant would break down or give inadequate protection. Either dry film soaps or phosphate/soap combinations may be used for alloy steels as well as carbon steels.

The more traditional lubricants for deep drawing are pigmented soap-fat compounds which, although difficult to remove, are efficient and of relatively low cost. In some lighter operations, emulsions containing E. P. additives might be adequate; the water content of the emulsion is usually reduced as the severity of the draw increases. Similarly, mineral oils with E. P. additives may be used, the proportion of active constituent (usually chlorine) increasing for more difficult operations. Straight chlorinated oils or, alternatively, sulfochlorinated oils are the most efficient nonpigmented liquid lubricants when used with steels. These observations are tabulated in Table 11.2.

11.5 LUBRICANTS FOR STAINLESS STEEL

Stainless steel adheres readily to steel dies and, because it is a relatively inert alloy, there are few extreme pressure additives which are really successful as lubricants. For this reason, a solution to lubrication problems is often sought through a complete separation of the workpiece from the pressing tools.

TABLE 11.2

Lubricants Recommended for Sheet Forming of Carbon and Low Alloy Steels

Operation	Lubricants
Blanking	Residual fatty oil from rolling.
	Light mineral oils.
	Mineral or fatty oil emulsions.
Light presswork	Residual fatty oil from rolling.
	Soap-fat emulsions.
	Mineral oils containing boundary or E.P. agents.
	Chlorinated oils.
Deep drawing and heavy pressing	Undiluted chlorinated oils.
	Pigmented soap-fat compounds.
	Sulfochlorinated oils.
	Dry soap films.
	Phosphate/soap (special applications only)

11.51 Experimental Studies

Even though stainless steel prevents serious lubrication problems, few systematic studies have been reported, probably because the total production volume is much smaller than that of other steels.

Stainless steel was apparently the first metal to be lubricated with plastic polymer films [37]. However, at that time a sprayed vinyl copolymer was used, which required an expensive solvent and which was also difficult to apply in a controlled film thickness. Currently, plastic films are available [75, 85] which present relatively few problems. The methacrylate resins can be applied by dipping; control of bath temperature, concentration, and withdrawal speed results in reproducible film thickness. The film dries in air and, after pressing, is removed completely by solvent degreasing (trichloroethylene). A small amount of oil applied to the tools prevents any buildup of the polymer on their surfaces, and also eases stripping of the drawn products from the punch.

It has been shown that if some stainless steels are deformed at near-zero temperatures, greater strengths are developed [101]. In this respect, the

novel method of lubrication suggested by Wallace [102, 103] may have application. Wallace used ice as a phase-change lubricant in stretch forming, with melting induced by the heat content of the strip, which is held at a temperature slightly above zero. The stretch-forming die was made of concrete, and the ice film was built up by spraying water onto the forming surface with the concrete at a temperature of not greater than -6.7°C(20°F). The optimum thickness of the ice layer was found to be between 1.5 and 2.0 mm, and its optimum temperature was -3.3°C (26°F) in an ambient temperature of about 11.5°C (60°F). Under these conditions, very low (0.01 to 0.02) coefficients of friction were observed. Alternative lubricants which could be considered in a similar system, but operating at lower temperatures, are carbon dioxide [104] and solid krypton [105].

11.52 Industrial Practices

A general discussion of the forming of stainless steel plate has been given by Pohlman and Koontz [106], and of a sheet and strip by Parker [107]. Based on a survey of the recommendations given by Bastian [64-67], Salz [68-72], White [73], and others [53, 74, 75, 108], a summary is given here of the lubricants most widely used in and recommended for industry.

Light Presswork

Because of the great tendency of stainless steel to adhere to the surface of working tools, the lubricants recommended for operations that normally require minimal lubrication, such as blanking, are notably more powerful than for equivalent operations with mild steel.

Emulsifiable mineral oils are fortified with fatty oils or E.P. additives, depending upon the severity of the operation. Similarly, a plain soap-fat compound emulsion may be used for light work, but for heavier work this will inevitably be pigmented.

Mineral oil blended with chlorinated oil is frequently used, but in processes involving higher pressures a straight chlorinated oil would be more suitable. Soap-based dry film lubricants have also been recommended [67, 73, 83] either for operations involving slightly higher local pressures or where metal-to-metal contact must be avoided at all costs. Although the equipment that must be purchased initially for controlled application is expensive, the subsequent bulk cost of materials is fairly low [97].

Teterin and Luk'yanov [109] considered lubricants for the rather special application of hot punching a 2.36 in. hole in a 1.57 in. thick stainless steel blank. The tests included both solid and hollow punches, with the blank at 1000°C; optimum results were obtained with a hollow punch and with glass cloth as a lubricant. This reduced the power requirements by 20-25%, and ensured a good surface finish of the sheared hole. Dry powdered graphite was also found to be an effective lubricant. Obviously, these conditions are extremely severe and would not often be found in industrial practice.

Deep Drawing

Rather infrequently, a mineral oil with chlorinated additives gives adequate results in the deep drawing of stainless steel, but a straight chlorinated oil is more likely to be preferred. Even this might not withstand the severe conditions involved, and the most widely used lubricants for this type of operation have been the heavily pigmented soap-fat compounds, generally in paste form. The major drawback of solid fillers, including graphite or molybdenum disulfide, is that they are difficult to remove. This is a particularly important consideration with graphite because traces left on the surface of a stainless steel pressing cause subsequent carburization on annealing. Even if annealing is not necessary, the surface discoloration caused by graphite or other solid fillers is undesirable since stainless steel pressings must usually have a high surface quality.

The dry film lubricant types are gaining importance since most of the familiar problems with stainless steel forming are easily overcome by their use. Of these, the soap-based dry films are probably the most efficient, and there is evidence [37, 95] to show that they have wide applications for forming stainless steel in the sheet pressing industry.

Lead coatings are excellent as lubricants on stainless steel, but they are also very difficult to remove and expensive. They must now be regarded as obsolete. Oxalate coatings are also good, since the lubricant is absorbed into the porous coating, thus creating a reservoir. This coating is widespread in cold extrusion and heavy tube drawing of stainless steel [110], but there is very little evidence to show its use for deep drawing. Stainless steel is frequently put into service in the as-formed condition, and the burnishing that occurs during the operation is desirable. Since oxalate coatings and any pickling impair the appearance of the metal surface, heavily chlorinated oils are usually preferred in stainless steel finishing operations.

Two lubricants which are currently suggested for industrial application [111] are a mineral oil of high viscosity containing a chlorinated paraffin and applied in a chlorinated solvent, and a chlorinated polymer which sets to give a hard nontacky film. These were developed specially for nickel-base superalloys, and are described in more detail in Section 11.10.

The recommendations for stainless steels are summarized in Table 11.3.

11.6 LUBRICANTS FOR COPPER AND ITS ALLOYS

Copper frequently presents fewer lubrication problems than most other materials. Although adhesion of copper to deforming dies occurs in both dry and lubricated operations, there is often no significant increase in recorded load or friction values, nor is there appreciable scoring. With brass the lubricant must withstand greater pressures, and scoring could become troublesome if lubricant breaks down. Bronzes usually call for better lubricants than either copper or brass.

11.61 Experimental Studies

There is very little reported experimental work in which lubricants have been evaluated for copper. Grainger [112, 113] used cupping tests to determine the effectiveness of oil-base lubricants, some of which contained molybdenum disulfide, and MoS_2 in a volatile vehicle. Of these lubricants an E. P. oil containing dispersed molybdenum disulfide was the most effective. However, graphite or MoS_2 is usually only recommended for elevated temperature deep drawing, when other materials break down. Once again, this is because their removal is very difficult.

Evans et al. [89] found that graphite dispersed in tallow gave only marginally better results than when kaolin was used as a solid filler for the lubrication of 70/30 brass during cupping and other drawing operations. Kaolin is a good alternative to graphite, but the problem of removal is still a large one. Soap lubricants based on calcium, sodium, and chromium oleates were found to be the best of the nonpigmented lubricants.

PERA [21] investigated the effect of lubricant viscosity, composition, and blankholder load in the deep drawing of 70/30 brass. E. P. oils containing sulfur and chlorine were superior to undilated soap-fat compounds, both with and without solid filler, to compounded oils and to straight mineral oils. The familiar improvement in lubricating ability as viscosity increased was

TABLE 11.3

Lubricants Recommended for Sheet Forming of Stainless Steels and Copper Alloys

Operation	Lubricants
	Stainless Steels
Blanking and light presswork	Fatty oil emulsions (very light work).
	Chlorinated mineral oils.
	Soap-fat emulsions (pigmented for heavier work).
	Dry soap films (for special applications).
Deep drawing and heavy pressing	Chlorinated oil (possibly undiluted).
	Pigmented soap-fat compounds.
	Dry soap films.
	Dry polymer coatings (usually chlorinated and often with a chlorinated oil above it).
	Copper and Alloys
Blanking and light presswork	Soap solutions.
	Straight emulsions.
	Mineral oils (blended with fatty oil or noncorrosive E. P. agent for heavier work).
	Soap-fat emulsions.
Deep drawing and heavy pressing	Soap-fat emulsions (pigmented for very heavy work).
	Undiluted fatty oils.
	Noncorrosive E. P. oils.

also seen, and increase in blankholder load beyond about 18,000 lb enabled larger blanks to be drawn (Fig. 11.13). This minimum was not observed with lubricants of very high viscosity.

Large and Dalheimer [38] evaluated four lubricants—namely, a soap solution, a grease of unspecified composition, a zinc stearate, and a molybdenum disulfide paste—on the basis of the drawing force at a drawing ratio of 2:1. Zinc stearate, an insoluble soap, was applied in a trichloroethylene carrier, and the residual dry film was found to be the most efficient lubricant, with the grease better than the molybdenum disulfide paste and the soap solution worst of all.

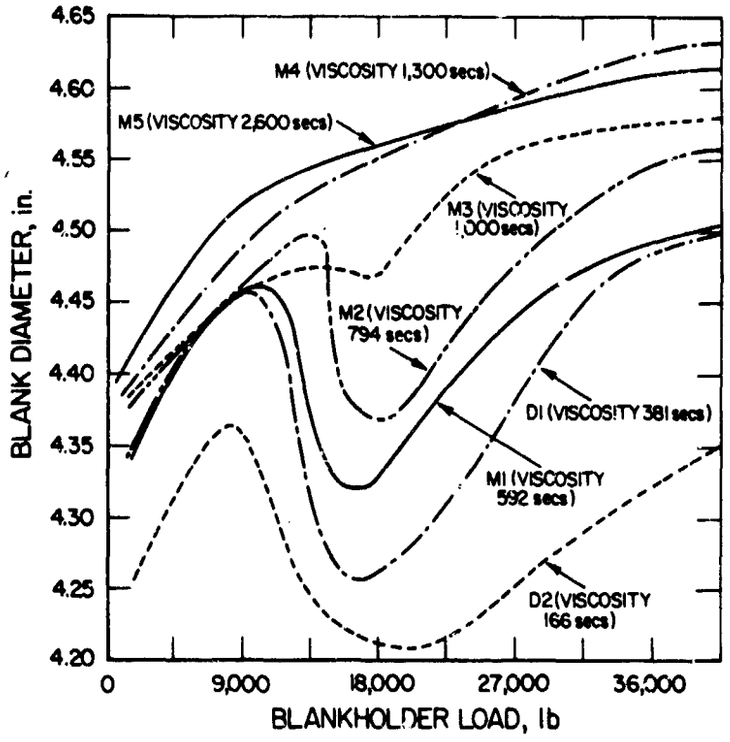

Fig. 11.13. Effects of lubricant viscosity, measured in Redwood 1 seconds, and blankholder load on the maximum blank diameter of 0.039 in. thick annealed 70/30 brass which can be drawn into a 2 in. diameter cup [21].

The effectiveness of dry film lubricants was also demonstrated by Mear, Topper, and Ford [84], who compared dry films based upon methacrylate resins against Esso TSD 99¢ in the cupping of 70/30 brass and found large increases in LDR when the dry film lubricants were used.

11.62 Lubrication Practices

Light Presswork

Soap solutions, straight emulsions, and straight medium viscosity mineral oils are generally adequate for stamping and shallow pressing. Bronzes might require a fatty oil addition to the mineral oil, or a dilute soap-fat emulsion pigmented for heavier work. This pigmented emulsion might also be used for copper and brass for the more severe operations.

Mineral-fatty oil blends, with 25 to 50% of fatty oil compounds, are also recommended. Alternatively, E. P. constituents may be added to mineral oil, this usually being a noncorrosive sulfurized oil. However, care should be taken to avoid staining with E. P. oils.

Most frequently, however, soap-fat compounds (which can be diluted according to the severity of the operation) are employed for pressing. These do not generally present a problem of staining with copper alloys, and are efficient lubricants.

Deep Drawing

Soap-fat compounds are often used for deep drawing or other heavy operations, and may sometimes be pigmented. Mineral base E. P. oils containing relatively high amounts of chlorinated or sulfochlorinated additives, straight sulfurized oil, or a straight fatty oil such as lard oil may also be used. However, difficulties in avoiding staining are generally experienced with E. P. agents. Soap-based dry film lubricants may find application here, but their use with copper alloys is by no means widespread.

Sometimes these alloys may be deep drawn at elevated temperatures. In these infrequent instances, graphite is applied, either by dipping or spraying a collodial dispersion of the solid in a volatile vehicle. Molybdenum disulfide may be used in the same way, of course, but graphite withstands higher temperatures before oxidation occurs, so that it is used more often for warm or hot work.

Recommendations are listed in Table 11.3.

11.7 LUBRICANTS FOR ALUMINUM AND ITS ALLOYS

Aluminum is a difficult metal to lubricate, especially in the annealed condition. Adhesion of aluminum to the working tools can often be avoided only with thick film lubrication. The most commonly used lubricants for aluminum contain boundary additives such as the fatty acids, which usually give low friction but do not entirely avoid metal transfer to the tools.

11.71 Experimental Studies

Evans, Silman, and Swift [89] investigated the effect of lubrication on the cupping of aluminum, on the basis of the reduction in drawing force. Rather surprisingly, the best lubricant was found to be dry graphite; mineral oils were useful only under moderate conditions.

Barnes and Cafcas [114] used a wide variety of lubricants, including straight oils, blended oils, emulsions, and dry film lubricants; 0.514 in. diameter aluminum cups were redrawn to 0.462 in., and the wall thickness was reduced by about 10%. Lubricants were graded on the basis of the

drawing work and the resulting surface finish of the cups. Dry film lubricants were found to be efficient only if the films were soft and pliable. The two most successful lubricants were a fluid emulsion based upon approximately equal parts of mineral oil (viscosity 95 SUS at 210°F) and a synthetic hydrocarbon polymer (viscosity 1000 SUS at 210°F), and the synthetic polymer used alone.

Boccaccio [87] was interested in a more severe operation in which 3/8 in. thick, 11 1/2 in. diameter 7075 aluminum alloy plate blanks, rather than sheet, were to be drawn into hemispherical-ended cups, at 50% reduction, to be used as preforms for subsequent spinning operations. It was found that liquid lubricants did not allow the required preform to be drawn. Polyethylene sheet lubricated the blanks adequately, however, and embossed polyethylene in conjunction with a base oil caused a substantial reduction in drawing load. A further load reduction occurred with graphite on polyethylene. Ultimately this lubrication technique was employed for obtaining a 50% deep drawing reduction with blanks of 32 in. diameter and 7/8 in. thickness.

Another unusual lubrication technique was used by Petronio [115] in the redrawing of clad 2024 aluminum alloy samples. Various surface treatments were investigated, including pickling in various acids and alkalis, oxidizing by electrochemical means, and by chemical immersion and phosphating. A sulfurized fatty oil and a soda-tallow soap solution were the lubricants. The oxidizing pretreatments were successful in preventing pickup of aluminum onto the dies, especially when used in conjunction with the sulfurized fatty oil. All other surface treatments were inferior. This was confirmed in shop trials involving deep drawing, cold forging, and extrusion, with 7075, 2024, and 5052 aluminum alloys as workpiece materials. Stearic acid was the lubricant in forging and extrusion.

11.72 Lubrication Practices

Light Presswork

For mild operations, relatively simple lubricants may be used. Evans, Silman, and Swift [89] found straight mineral oil a useful lubricant for relatively light working; in fact, it is widely recommended for the blanking of aluminum. In shallow pressing operations, boundary additives such as free fatty acids are required to improve the lubricating efficiency of the mineral oil. These compounded oils are the most common lubricants for aluminum

alloys. Alternatively, straight mineral oil emulsions (soluble oils) often give good efficiency and have the advantage of being water-soluble. Other water-soluble lubricants for this work are soap solutions or, for heavier operations, a fairly dilute soap-fat emulsion.

For more severe operations, a straight fatty oil is often preferred as a lubricant. Of the water-dispersible compounds, generally only the soap-fat compound emulsion is used, in less dilute emulsions than for lighter press-work (frequently four parts water to one part compound.)

Deep Drawing

There is a wide variety of lubricants commonly recommended for deep drawing aluminum and its alloys, and only in the very severe operations is there much agreement of opinion. For very heavy gage operations, Boccaccio [87] has suggested embossed polyethylene film in conjunction with oil or graphite. Graphite is also known to withstand high working pressures, and has performed well [89] in deep drawing sheet aluminum, but the cleaning problem would normally prevent its use. Dry film lubricants have been suggested in one case [53] and, in fact, dry wax coatings are frequently used in industry, but the greatest concurrence of opinion is in the recommendation of pigmented soap-fat compound emulsions, straight chlorinated oil or, for slightly less severe operations, straight fatty oils.

Other Operations

Sheet aluminum is also formed in a variety of other ways which require different lubricant properties. Several rubber forming methods are currently used, especially in the aerospace industry where the cost of steel dies would increase the cost of each component produced by a significant amount. A lubricant is frequently required to ensure evenly distributed strain in the rubber, but the acid or alkali content of lubricants should be as low as possible to prevent reaction with the rubber pad. ASTME [53] has suggested a soft neutral potassium soap, applied to the blank by spraying or brushing in a soap solution, or by hot dipping to give a dry film. Alternatively, a light mineral oil blended with an unspecified amount of neutral lard oil has also been proposed [53].

For stretch forming of aluminum alloys, emulsions containing solid fillers are frequently used, as are heavy compounded oils. For elevated temperatures around or in excess of 200°C, graphite is normally employed as a lubricant, either alone or as a dispersion in other compounds.

In explosive forming, a lubricant is not generally required [116], since appreciable metal sliding does not occur. However, with aluminum there is a slight tendency to adhere to the forming die, especially with heavier gages. In order to prevent this, conventional deep drawing compounds, usually in the form of pastes or viscous liquids, are adequate.

Recommended lubricants for aluminum alloys are given in Table 11.4.

11.8 LUBRICANTS FOR TITANIUM AND ITS ALLOYS

The forming of titanium sheet is frequently limited by its tendency to adhere to most tool materials and its high rate of work-hardening. In order to overcome difficulties caused by work-hardening, a large proportion of secondary working of titanium is carried out at elevated temperatures—possibly between 500°C and 800°C. However, at these temperatures, the tendency of the metal to seize to the dies is increased; furthermore, the metal is susceptible to embrittlement by absorption of excessive oxygen from the atmosphere. This latter problem may be overcome by inert gas preheating. If this is not practicable, a surface coating is required which preferably would ensure both protection from the atmosphere and a low value of friction in subsequent forming operations.

Among the more conventional lubricants usually considered for temperatures between 425° and 540°C are bentone greases with graphite, powdered mica-graphite mixtures, graphite or MoS_2 in volatile carriers, and metallic coatings. Apart from the usually expensive metallic coatings, very little surface protection during preheating is afforded by these materials.

Since the forming of titanium sheet may require temperatures much higher than this, low melting point glasses were considered by Boeing Airplane Company [117, 118]. The chemical composition of the workpiece material was found to be important since some oxides dissolve in the glass, changing its composition and possibly causing removal problems. However, several glasses were found suitable up to about 900°C. These were based upon porcelain enamel glasses of suitably low softening temperature. The glasses were applied by brushing or spraying a slurry obtained by addition of butyl acetate (9.2 wt%), butyl alcohol (17.0%), ethylene glycol (2.2%), acrylic resin (6.3%), and a suspending agent (1.9%) to glass (63.4%). They had to be removed by immersion either in hot sodium hydroxide or in cold nitric acid. These lubricants prevented galling during hammer- and draw-

TABLE 11.4

Lubricants Recommended for Sheet Forming of Aluminum, Titanium, and Magnesium Alloys

Operation	Lubricants
	Aluminum and Alloys
Blanking and light presswork	Light mineral oils.
	Soap-fat or mineral oil emulsions.
	Mineral-fatty oil blends.
Deep drawing and heavy pressing	Mineral-fatty oil blends.
	Undiluted fatty oils.
	Dry soap or wax films.
	Undiluted chlorinated oils.
	Pigmented soap-fat compounds.
Stretch forming	Emulsions (often pigmented).
	Heavy mineral-fatty oil blends.
	Titanium and Alloys
Cold working	Oxide film with soap.
	Fluoride-phosphate with soap or MoS_2.
	Dry polymer films.
Warm working	Graphitic or MoS_2-containing lubricants.
Hot working	Glasses.
	Magnesium and Alloys
Cold working	E. P. oils, waxes, lanolin.
Warm working	Graphite in tallow.
	Hard wax.
	Colloidal graphite in naphtha.

forming operations. However, the most successful of the materials tested were not commercially available.

Beryllium copper dies were used in another investigation [116] of the forming of titanium at 375°C, in conjunction with a graphitic lubricant. Apparently, a low rate of wear was observed with these dies, and the problem of galling was eliminated. The dies could also withstand short periods

of use at 540°C. Aluminum bronze dies also resist galling with titanium and its alloys.

The deep drawing of the 6Al-4V titanium alloy was investigated by PERA [119] at temperatures up to 380°C. Much larger blanks could be drawn at elevated temperatures than room temperature, but most lubricants decomposed. This was overcome with a fluoride-phosphate chemical conversion coating on the titanium sheet, which was then sprayed with resin-bonded molybdenum disulfide. Both of these materials were unstable at the forming temperature; therefore, it was necessary to draw the cups as soon as the blanks attained the temperature of the heated dies. The dies were also coated with graphite, applied as an aqueous dispersion. This provided a satisfactory means of lubrication.

Lorant [120] also reported some work on the hot hammer-forming of sheet titanium. Blanks of dimensions up to 20 in. x 30 in. were initially preheated at 538°C, and then drop hammered using Kirksite dies and a steel-jacketed lead punch. The blank temperature was estimated to be between 316° and 371°C during forming, and the tools were cold. Pads of hard rubber were placed over the blank, while the die was lubricated with a heavy oil. The most successful procedure for working titanium at these temperatures involved either copper-plating or colloidal graphite as a lubricant. Of these, the graphite was preferred because it was simpler to apply and less expensive.

The lubricants available for cold forming of titanium and its alloys are somewhat better established. Often these lubricants are taken from tube drawing technology. The best known is the fluoride-phosphate chemical conversion coating, already discussed in Sections 4.41 and 10.8, which was used for warm forming of the 6Al-4V titanium alloy sheet by PERA [119], as discussed above. Patten [121] tested this coating in room-temperature pressing operations with commercial purity titanium sheets, which were formed both with and without additional lubrication. No failures occurred during pressing of a shallow dish from an oblong blank even with the unlubricated coating. During deep drawing of more difficult components, it was no longer necessary to relubricate between successive draws.

Other surface treatments for titanium which are claimed to be as efficient as or more so than the fluoride-phosphate coating have been tested by Howes [122], who used the Swift cupping test on commercial purity titanium.

A limited number of blanks were drawn with no surface treatment, while others were oxidized, Bonderized, or sulfidized. The oxidized coating was obtained by heating blanks in air at 630°C for 15 min; Bonderizing is a proprietary fluoride-phosphate coating; and sulfidizing involved treating blanks for up to 3 hr at 570°C in a salt bath composed of sulfur and cyanide compounds. Blanks were drawn dry or with one of three lubricants—a sulfonated fatty oil, a viscous chlorinated oil, and an acrylic resin dry film lubricant. Sulfidizing was found to be the best surface condition examined, as judged from the LDR and the surface finish of the drawn cups, while there was little difference between the oxidized and Bonderized conditions. The chlorinated oil was superior to the sulfonated fatty oil, both on treated and untreated surfaces. The acrylic resin, however, was the best lubricant of all, and could adequately prevent metal-to-metal contact without prior surface treatment. These results were confirmed in press shop trials.

The same methacrylic resin was examined by Mear, Topper, and Ford [84], who similarly recommended its use with titanium at room temperature. This lubricant was also tested by Mitchell and Brotherton [123], who compared its behavior with that of three other lubricants—molybdenum disulfide, PTFE dispersion in resin, and polyethylene sheet—and a surface diffusion treatment (liquid nitriding) in cupping and stretch forming of various titanium alloy sheets. The nitriding treatment involved immersing the blanks in a mixture of molten cyanides and carbonates at 570°C for 13 min. Both Swift and Ericksen tests were performed, and the lubricants were evaluated from the maximum cup height that could be produced without failure in both tests. The three plastic film lubricants displayed similar lubrication characteristics, but 0.002 in. thick polyethylene sheet was slightly superior to the PTFE and the methacrylic resin (Fig. 11.14). Increasing the thickness of the polyethylene sheet to 0.010 in. lowered the effectiveness in these tests. They also found that efficient lubrication had more influence in deep drawing than in stretch forming.

In summary, it appears that for room-temperature forming of titanium sheet the plastic dry-film or sheet lubricants are best recommended. Alternatives are a surface treatment such as a fluoride-phosphate coating or a sulfidizing treatment, both in conjunction with wax or dry soap type of lubricant [53]. For moderate duties such as a roll forming, an E.P. oil often suffices. A dry wax coating, capable of withstanding temperatures up to about 225°C, may be used for more severe cold stretch-forming operations.

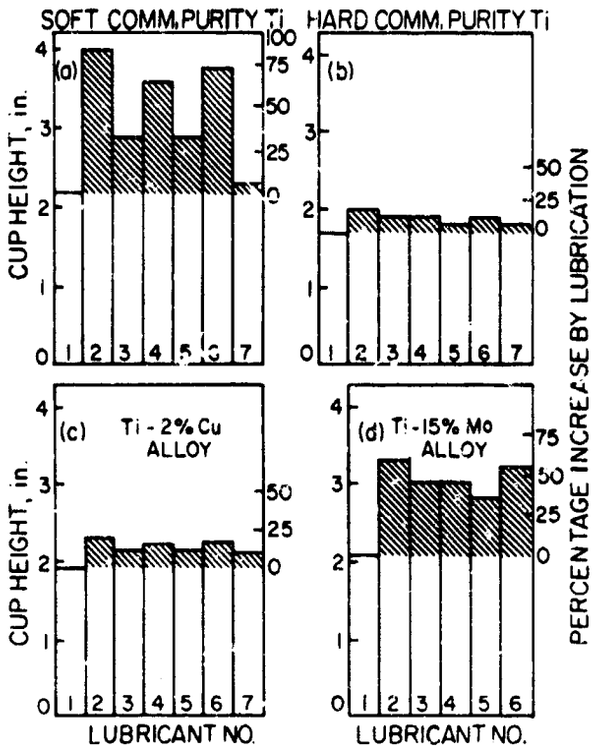

Fig. 11.14. Effects of lubricants and surface treatments on the deep drawability of titanium alloys. Lubrication: (1) none; (2) 0.002 in. polyethylene sheet; (3) 0.010 in. polyethylene sheet; (4) PTFE; (5) MoS_2; (6) methacrylic resin; (7) liquid-nitrided [123].

In wire and tube drawing, one of the most frequently used systems is an oxide coat in conjunction with a soap lubricant. This is preferred to other methods because of favorable economics rather than better surface protection, and it could well be used for sheet lubrication also. The material is preheated in an inert atmosphere, but air is allowed to enter the furnace just prior to taking the sheet out. This builds up an oxide on the surface, which gives protection from galling on subsequent forming.

For elevated temperature work, graphite lubricants and molybdenum disulfide are used industrially to temperatures of 700°C, provided prolonged exposure is not involved and a suitable carrier is employed. Glasses with

a low softening temperature are probably the most suitable lubricants for the higher strength titanium alloys which might require working above 800°C.

Recommendations are summarized in Table 11.4.

11.9 LUBRICANTS FOR OTHER SHEET MATERIALS

11.9a Magnesium and Its Alloys

Magnesium and its alloys have poor ductility at room temperature and are generally formed at temperatures between 150° and 400°C. Very little experimental work has been reported for magnesium sheet forming, but information is available covering industrial experience and recommendations.

With the above range of working temperatures, it is only to be expected that the generally favored lubricants are based upon graphite, although at temperatures around 400°C low-melting glasses could be as efficient.

Relatively low temperatures are permissible if very little deformation is required. At about 150°C, lubricants such as a neutral soap, beeswax, or tallow containing about 20% graphite [53] are satisfactory. Even oils and greases find application at lower temperatures, but shallow drawing at temperatures down to room temperature frequently involves rubber forming, so that neutral soap solutions, dry film soaps, or possibly light mineral oils must be employed to avoid chemical attack of the rubber die. Stretch-forming is normally done at just over 200°C, and hard, dry soap or wax films are adequate [67].

For deep drawing, high temperatures are always employed, and it is obvious from several sources [53, 65, 67, 124-127] that graphite is the most common lubricant constituent. Gillespie [126] notes that the best lubricant at temperatures above 250°C is colloidal graphite dispersed in a low boiling point naphtha. This has been confirmed elsewhere [127]. The lubricant is applied to the blanks prior to heating by spraying, dipping, or roller coating, and the naphtha carrier evaporates to leave a dry and uniform film of graphite. This dispersion of graphite cannot be used on heated dies since the naphtha will not wet the surface, and graphite in tallow or flake graphite grease provide efficient alternatives.

Chemical cleaning of the blanks just prior to drawing is a disadvantage [126], since it makes removal of graphite after forming more difficult. A typical graphite removal method would involve these steps: a 10 to 20 min

etch in a caustic soda solution at 90° to 100°C, followed by rinsing in cold water and a 3 min chromic acid-sodium nitrate pickle at 20° to 30°C. It is the chromic acid bath that removes the graphite by reacting with the magnesium oxide or hydroxide layer under the graphite particles. Thus, chemical cleaning immediately before drawing with graphite might strip most of the oxide, which prevents removal of graphite in the normal way.

In certain instances, magnesium sheet may be stretch-formed cold, and here E. P. oils, lanolin, or dry wax or soap films are employed as lubricants. The same materials also find application in cold spinning, but for blanking and punching only oils are normally used.

The most recommended lubricants for magnesium sheet forming are listed in Table 11.4.

11.92 Nickel and Its Alloys

Very little information is available for the nickel-base superalloys in the context of sheet metalworking. Bastian [66] gave lubricant recommendations for nickel alloys suggesting a mineral-fatty oil blend or a straight fatty oil for use in blanking and stamping, shallow press drawing, and deep drawing. Considering the high pressures normally involved, these lubricants are fairly mild; in fact, an E. P. oil was recommended for heavy cupping operations. Grainger [112, 113] made an experimental investigation of the effect of various lubricants on the deep drawing of 9 in. diameter bowls, 9 1/4 in. deep from flat 19 in. diameter, 0.050 in. thick blanks of Nimonic 75, a nickel-base superalloy. His findings virtually confirmed the recommendations of Bastian in that a drawing oil, presumably containing E. P. additives, was the most effective lubricant for deep drawing of the untreated metal. Other lubricants tested were MoS_2 powder, MoS_2 in a synthetic carrier, and 2% MoS_2 in the same drawing oil. Evaluation was based on the power required for the operation and on the surface quality of the products.

Grainger also tested blanks which had been given a proprietary oxalate surface treatment. Superior performance was now observed with all lubricants tested, but the most efficient lubricant used in conjunction with the oxalate coating was the drawing oil containing 2% MoS_2. The straight drawing oil gave the worst behavior of the four lubricants tested.

The current British practice for the sheet working of the Nimonic series of nickel-base superalloys involves two basic lubricants, according to

Rowe [111]. The first is a mineral oil of high viscosity applied with a chlorinated solvent and containing chlorinated paraffin wax. This is applied by dipping, and the blanks are allowed to drain off. The second is a chlorinated polymer which sets to give a hard, even, and nontacky film, which gives better protection than the first material and is therefore used for heavier duties. The film thickness is important; on polished surfaces it should be about 0.0003 in., while on rougher surfaces 0.001 in. to 0.002 in. should be deposited. Greater thicknesses lead to buildup of the excess on the dies.

The type of lubrication required for nickel alloys will depend very much on the strength of the sheet material and on the operation involved. For severe operations with high-strength materials, the oxalate coating with an efficient E. P. lubricant, possibly containing MoS_2, is obviously suitable. Alternative lubricants include chlorinated polymer coatings, or high-viscosity chlorinated oils on untreated material. Graphite-base lubricants may find application for the hot spinning and hammer forming of superalloys, but once again difficulties in removal make these solid fillers unattractive. For more moderate cold operations, however, it is apparent that either a mineral E. P. oil blend or a straight E. P. oil will be adequate.

11.93 Zinc Alloys

Recommendations are also to be found for zinc alloys, once again by Bastian [65, 67]. For blanking and stamping, neutral soap solutions or light neutral oils may be used; for shallow and deep drawing, nonpigmented soap-fat compound emulsions and soap-based dry film lubricants are suggested.

11.94 Refractory Metals

Lubricants for the high-velocity forming of refractory alloys have been considered by Strohecker et al. [116]. Since refractory materials must be formed at high temperatures, the number of lubricants which can be used to prevent galling tendencies is limited, and Strohecker could only suggest glasses. Rogers and Rowe [128] have found basalt to be satisfactory for extrusion of high-temperature alloys, and this could also be useful in elevated temperature sheet forming.

It should be noted that graphitic lubricants and molybdenum disulfide are frequently employed at temperatures above that at which they theoretically cease to have lubricating action. This largely determined by dwell

time at temperature; graphite will adequately lubricate at 1000°C if the dwell time is short enough or if the graphite is carried by a suitable material—for example, tar, pitch, or grease.

Babel and Bonesteel [129] used infrared quartz lamps to heat tungsten sheet to its forming temperature. With such equipment, only about 90 sec were required to heat 0.15 in. thick tungsten sheet from room temperature to 1000°C. Graphite served adequately not only as a lubricant but also provided a dull black surface to the sheet so that heat could be absorbed more rapidly. Hot shearing of tungsten sheet was performed at a temperature of 1100°C with this technique. High-temperature rubber forming and hammer forming also utilized the same method successfully, showing that parts which would conventionally be formed by spinning could be formed by other methods.

Tantalum tends to gall severely on most die materials but, according to Everhart [130], sheet tantalum can be formed successfully with sulfonated tallow as a lubricant. It is possible that this might be effective in very low pressure operations, but generally more drastic measures must be taken to prevent seizing and galling. Batista et al. [131] tested chrome-plated steel, tungsten carbide, and aluminum bronze dies with various lubricants in the drawing and deep drawing of tantalum. They found that beeswax and beeswax-base lubricants used in conjunction with aluminum bronze dies were the most successful means of preventing galling. However, because of the relatively low strength of the dies, a high rate of wear must be tolerated. Batista et al. [131] also found that tantalum could be swaged after developing an unspecified hard surface precoat, with a viscous liquid (also of unspecified composition) superimposed as a lubricant.

The same authors also found that uranium sheet could be most effectively deep drawn in aluminum bronze dies with beeswax as a lubricant. However, they also noted that chrome-plated steel dies were satisfactory with colloidal graphite in water. In rubber die forming, sheet is drawn at about 200°C, with the steel punch at a similar temperature, employing colloidal graphite in naphtha, a volatile carrier, as lubricant.

Molybdenum alloys have been discussed by White [132] and Jackson [133]. White [132] reported that a ductile molybdenum sheet could be drawn into a deep cup serving as an anode, whereas previously the same component was formed by spot welding a shallow drawn cup to a ribbed tube with a roller welded seam. For the deep drawing operation, aluminum bronze tools were

used, with castor oil as a lubricant. The tools were heated to an unspecified temperature, and the 0.015 in. thick molybdenum sheets of 4 7/8 in. diameter were drawn into 1 1/2 in. diameter anodes, 2 3/4 in. deep.

Jackson [133] considered the forming of TZM, a molybdenum-0.5% titanium-0.08% zirconium alloy. This alloy could be hammer-formed at temperatures between 90° and 200°C with tools of Kirksite, which were greased with a lubricant containing MoS_2 prior to the operation. The sheet blanks were 3 in. x 50 in., and several beads of 0.20 in. depth were formed across their width. Other sources confirm that graphite and MoS_2 are fairly common lubricants in hammer forming of TZM. These same lubricants are also effective in spinning.

The forming of beryllium sheet by spinning or by brake forming is also carried out with graphite in a volatile vehicle serving as lubricant.

11.10 SUMMARY

A wide variation in interfacial conditions occurs in the various types of sheet metalworking operations. As a direct result, the requirements of the lubricant vary greatly. Deep drawing and ironing are usually accomplished with far more powerful and more costly lubricants than in, for example, blanking. However, selection of an optimum lubricant depends not only upon interface conditions, which can be adjusted to some extent by variation of factors such as pressing speed and lubricant viscosity, but also upon important secondary considerations like ease of application and removal, convenience in handling, toxicity, and staining propensity.

The success of lubrication in presswork is also very strongly influenced by the surface roughness of the tooling and of the sheet material. Deeper draws, or heavier reductions, can be obtained by purposely roughening selected areas of the punch. In the same way, if lubricant is applied only to selected regions of the sheet workpiece, leaving other regions unlubricated, large gains in drawability may be obtained. Similar improvements are possible by suitable die design, as discussed in Sections 11.21 and 11.29.

For each specific workpiece material, it is apparent that numerous lubricant compositions are employed commercially. Lack of standardization is particularly evident in less severe operations, where there is a larger range of adequate lubricants, whereas in heavier presswork there is increasing use of the dry film type of lubricant in preference to E. P. oils.

For aerospace materials such as titanium alloys, superalloys, or refractory alloys, elevated temperature forming will have increasing importance, and here the solid lubricants such as graphite and MoS_2 find wide application. However, these materials are rather difficult to remove and there is a need for other, more suitable compositions. Materials which are attractive in this respect are the synthetic lubricants (for example, silicone oils described in Section 4.27) for temperatures up to 350°C, or polyethylene wax compositions [134] for use as phase-change lubricants (for example, in stretch forming) at 150°C or above. Glasses may find increasing use at about 600°C or above. Compositions based upon borax have relatively low melting temperatures and are attractive in the warm forming range. Many of the phosphate glasses are water-soluble, so that removal problems and the associated waste disposal problem (which is very critical if hydrofluoric acid must be employed) are minimized. Some of these glasses could also provide surface protection against oxidation during preheating and forming, which is very important with materials such as titanium. In this respect, these compounds warrant far more attention than they have so far received.

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APPENDIX—DEFINITIONS AND CONVERSIONS

Physical Properties

Density: the mass of liquid per unit volume at 15°C (e.g., in units of kg/liter).

Specific gravity: the ratio of the mass of a given volume of liquid to the mass of an equal volume of pure water at the same temperature (e.g., in units of 60/60 F).

API gravity in degrees:

$$\text{API, deg} = \frac{141.5}{\text{sp. gr.}} - 131.5$$

Viscosity: kinematic viscosity (in centistokes, cs) or dynamic viscosity (product of kinematic viscosity and density of liquid—in centipoises, cp), determined in calibrated glass capillary instruments; units given are the preferred ones.

Efflux viscometer readings are still widespread; for example, Saybolt Universal viscosity is the efflux time in seconds (SUS) of a 60 ml sample flowing through a calibrated "Universal" orifice. Conversion may be made from Figure A.

Distillation range: obtained by distilling a sample at atmospheric or reduced pressure. Results are reported as initial boiling point (first drop of distillate), percent recovered at a given temperature, and end point or final boiling point (the maximum temperature measured during the test).

Flash and fire point: A test flame is passed, under specified conditions, over a slowly heated sample contained in an open cup. The lowest temperature at which vapors ignite is the flash point; the temperature at which the oil ignites and burns for at least 5 sec is the fire point (often given as COC: Cleveland Open Cup).

Pour point: A heated sample is slowly cooled and examined at intervals of 5°F (3°C). The lowest temperature at which flow is observed is the pour point (also expressed in multiples of 5°F or 3°C).

Melting point: Drop melting point is the temperature at which the wax or other solid drops from the thermometer used in the test. Melting point

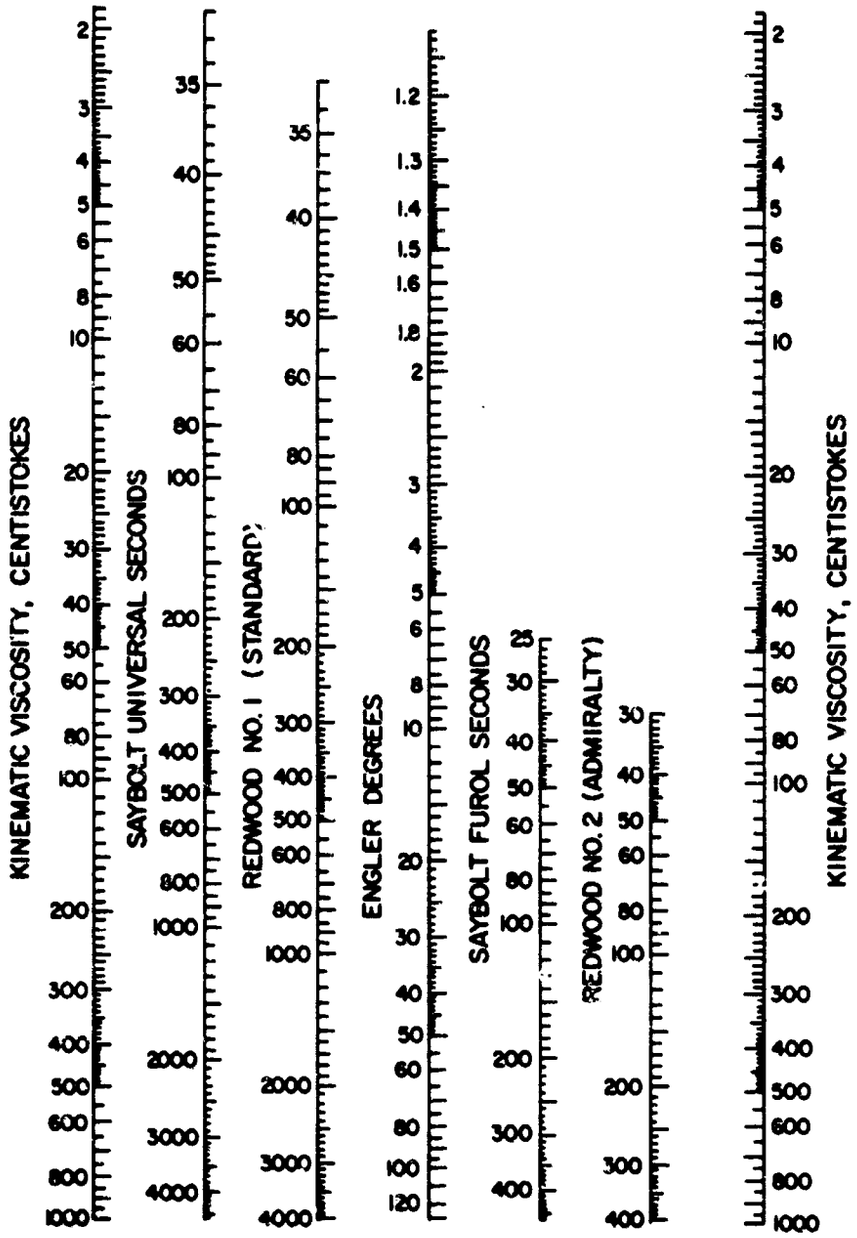

Fig. A. Viscosity conversion nomograph. Line up straight edge so centistoke value on both kinematic scales is the same. Viscosities at the same temperature on all scales are then equivalent. To extend range of only the kinematic, Saybolt universal, Redwood No. 1, and Engler scales: multiply by 10 the viscosities on these scales between 100 and 1000 cs on the kinematic scale and the corresponding viscosities on the other 3 scales. For further extension, multiply these scales as above by 100 or a higher power of 10. (Example: 1500 cs = 150 x 10 cs ≅ 695 x 10 SUS = 6950 SUS.) (By courtesy of Texaco.)

(cooling curve) is the temperature at which the wax first shows a minimum rate of temperature change while cooling under standardized conditions.

Titer: The temperature at which there is a break in the cooling curve as solidification begins (usually applied to fatty acids).

Color: determined in comparison with standard red and yellow glasses. More recently, a spectrophotometric method is used to characterize the color as 100 times the absorbence at two specified wavelengths. Sometimes the color is also given against Gardner color standards (solutions made up of basic chemicals). The applicable standard must be shown in all descriptions.

Chemical Properties

Most of these are specified for fatty oils and their derivatives.

Saponification value: the number of milligrams of potassium hydroxide required to react completely with all fatty material present in 1 g of substance. It is a direct relative measure of the mean molecular weight of the acids, whether they are present as a free fatty acid or esterified. Therefore, the saponification value is identical with the acid value for an ester-free acid.

Acid value: expressed as milligrams of potassium hydroxide required for neutralization of the free carboxyl groups present in a 1 g sample, equivalent to the percent free fatty acid expressed as oleic acid, multiplied by 1.986. The acid value is inversely proportional to the mean molecular weight of the acids.

Ester value: the difference between saponification value and acid value. It is a measure of the unsplit or partially split glycerides present.

Free fatty acid: expressed as percent oleic acid, it is 0.504 times the acid value.

Iodine value: expressed in terms of the number of centigrams of iodine absorbed per gram of sample. It is a measure of the amount of unsaturated fatty acids present.

Polyunsaturated acids: determined in percentages from ultraviolet absorption.

Acid composition: data are obtained by several methods, including gas chromatography; occasionally given in percentage terms.

Hydroxyl value: the number of milligrams of potassium hydroxide required to neutralize the acetic acid capable of combining by acetylation with 1 g of the fat.

Unsaponifiable impurities: given in percentages. Impurities which cannot be saponified by alkalis but which are soluble in the ordinary fat solvents.

Carbon residue: an indication of the relative coke-forming propensity of the lubricant. The sample is heated under specified conditions and the residue reported in percent as Conradson or Ramsbottom carbon residue (these values are not convertible). It is sometimes regarded as a measure of staining propensity, although the relationship has not been proven.

Ash: the percentage of nonorganic materials, as determined by heating at a high (775°C) temperature the residue that is left after burning the lubricant.

Corrosion: usually attack of copper strip by the lubricant, described by the surface appearance after exposure at specified (often elevated) temperature for a specified time. Strip standards of (1) slight, (2) moderate, (3) dark tarnish, and (4) corrosion (black surface) classes are available.

Rust-preventing characteristics: The lubricant is mixed with distilled water (Procedure A) or synthetic seawater (Procedure B), and corrosion of a polished steel cylinder immersed at 140°F (60°C) for 24 hr is observed.

Emulsion characteristics: measures the ability of the lubricant to separate from water by measuring the time required for separation of a well mixed (stirred) sample of the lubricant with equal amount of distilled water. If separation is not complete after 1 hr, the volumes of oil, water, and emulsion are reported.

Interfacial tension: determined by measuring the force necessary to detach a platinum wire ring from the surface of the liquid of higher surface tension (upward from the water-oil interface); reported in dynes per centimeter.

Conversion Factors

Temperature:

$$°F = \frac{9}{5}(°C) + 32$$

$0°C = 32°F$

$21.1°C = 70°F$

$37.8°C = 100°F$

$60.0°C = 140°F$

$100.0°C = 212°F$

Dimensions:

1 m = 39.370 in.	1 in. = 25.4 mm
1 mm = 0.394 in.	0.001 in. = 25.4 μ
1 μ = 10^4 Å = 39.4 μin.	1 μin. = 0.0254 μ = 25.4 mμ

Weights and Pressures:

1 kg = 2.2046 lb	1 lb = 0.45359 kg
1 ton (metric) = 2204.6 lb	1 ton (U.S.) = 2000 lb = 907.2 kg
= 1.1023 tons (U.S.)	1 ton (imp.) = 2240 lb = 1016 kg
= 0.9842 tons (imperial)	
1 kg/mm^2 = 1422.33 lb/in^2 = 1.42 kpsi	1 kpsi = 1000 psi
= 0.635 ton (imp)/in^2	= 0.703 kg/mm^2
1 atm = 1 kg/cm^2 = 14.697 psi	= 0.4465 ton (imp)/in^2

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