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THE EVALUATION OF GLASSES AS FORGING LUBRICANTS

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WESTINGHOUSE ELECTRIC CORPORATION

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Inaccuracies in the application of theoretical analysis to practical ring test results, due to bulging occurring at high friction levels, can be minimized by using specimens of small ratios of internal diameter and thickness to external diameter. When such precautions are taken, the method of analysis used in this work allows a value for the interface shear of the lubricant system to be determined. Under thick film lubrication conditions, this value would be independent of the flow stress of the workpiece material.

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FOREWORD

This report was prepared by the Westinghouse Electric Corporation, Astronuclear Laboratory, Pittsburgh, Pennsylvania, under U.S.A.F. Contract F33615-69-C-1198. The contract was initiated under Project No. 7351, "Metallic Materials", Task No. 735108, "Processing of Metals", and administered under the direction of the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, with Mr. Vincent DePierre (LLN) as Air Force Project Engineer.

The program was conducted under the technical direction of Dr. Alan T. Male, Westinghouse principal investigator. Significant contributions have been made to this program by Messrs. T.M. Brown, W.A. Houston, M.M. Myers and R.A. Sweeney of Westinghouse. Particular contributions of Mr. V. DePierre have been made in numerous discussions as to the method of analysis.

This report discusses research conducted from 1 March 1970 to 30 September 1970. It was submitted by the authors on 27 January 1971.

This technical report has been reviewed and is approved.

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ABSTRACT

The ring compression test has been successfully used to determine the relative efficiency of a number of lubrication systems for the high temperature forging of Type 300A maraging steel and titanium - 6 aluminum - 4 vanadium alloy. The results clearly indicate the advantage of using both a glass coating on the workpiece and a grease-base lubricant on the tooling. Data obtained has identified the optimum temperature range for use of each of the three glass coatings evaluated.

Inaccuracies in the application of theoretical analysis to practical ring test results, due to bulging occurring at high friction levels, can be minimized by using specimens of small ratios of internal diameter and thickness to external diameter. When such precautions are taken, the method of analysis used in this work allows a value for the interface shear of the lubricant system to be determined. Under thick film lubrication conditions, this value would be independent of the flow stress of the workpiece material.

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I. INTRODUCTION

Since the early work of Sejournet, glass lubrication has been increasingly used in the extrusion operation for the processing of materials requiring high deformation temperatures. The successful use of glass and glass-like substances for this application results from the ability of these substances, (a) to act as a relatively inert low shear strength interface at metalforming temperatures, (b) to retard reaction of the elevated temperature workpiece with the environment, and (c) to act as a thermal insulator to prevent excessive heat buildup in the tooling and to prevent chilling of the workpiece. The ability of glass coatings to favorably influence the interface condition for extruding such materials as high strength steels, titanium alloys, nickel-base superalloys and refractory metals has promoted an interest in the possibilities of using glass lubricants in other mechanical-working operations, particularly the hot forging of jet engine compressor and turbine blades and other shapes for aerospace applications.

The successful use of a workpiece coating to improve the interface condition is a prime factor in the economic production of a desired end product geometry with specific mechanical properties. The interface conditions are often the deciding factor in determining success or failure of a metalworking operation because they affect the total load required to perform the desired operation, the degree to which the metal will fill the cavities of the die, the uniformity of the metallurgical structure in the product and the quality of the surface of the product. Adequate control of metalworking processes requires that the friction and heat transfer effects occurring at the tool/workpiece interfaces be accurately known; a situation which is not yet a reality. It is this current inability to accurately describe the interface conditions that actually exist which is the primary obstacle in limiting the placement of metalworking operations on a rigorous mathematical basis.

The use of the ring compression test developed by Male and Cockcroft[1] allows the relative lubrication qualities of various workpiece coating substances to be easily determined. Under particular conditions, it also allows numerical values of an "apparent" coefficient of friction[2] to be obtained by means of an indirect calibration. Under similar conditions, an extension of the mathematical treatment of Avitzur[3] by Male and DePierre[4], and DePierre, Saul and Male[2] enables slightly different numerical friction data to be obtained. In addition, this latter treatment indicates the possibility of considering interfacial properties per se in a more fundamental scientific manner.

The objective of this work was to assess the feasibility of using the ring compression test for the evaluation of glass workpiece coatings as lubricants for hot forging operations and to provide data which would have immediate industrial application. A lesser objective was to attempt to formulate the interface characteristics rather more basically than has presently been done.

II. THEORETICAL BACKGROUND

The change in diameter of flat-ring shaped specimens produced by a given amount of axial compression between flat dies has been shown by Male and Cockcroft[1] to be related to the amount of frictional restraint acting at the interface between the dies and the specimen. If no restraint acts at the interface, the ring would deform in the same manner as a solid disk with the cylindrical surfaces of the ring remaining perpendicular to the flat surfaces. If a small but finite value of restraint exists at the interface, the outward flow of the specimen is reduced and, for the same degree of axial compression, the outside diameter of the specimen would be smaller than for the compression with zero frictional restraint. When the frictional restraint exceeds a critical value, it becomes energetically favorable for only part of the ring to flow outward and the remainder of the ring to flow inward toward the center, thus causing the outside diameter of the ring to be still further reduced for the same degree of axial compression. In addition to these changes, the cylindrical surface of the ring would not necessarily remain perpendicular to the flat surfaces, but would become contoured with the degree of contour depending upon the amount of frictional restraint, the value of the flow stress of the ring material and the thickness to diameter ratio of the ring specimen. Calibration of these shape changes as a function of the frictional restraint acting at the interface allows the evaluation of different lubricants to be conducted.

Mathematical expressions relating the change in internal diameter of a ring specimen after forging to the frictional restraint acting at the interface have been formulated by Avitzur[3], Hawkyard and Johnson[5] and also by Burgdorf[6]. The analyses of Avitzur and of Hawkyard and Johnson are based on the concept of a constant interface friction shear factor defining the frictional restraint whereas the analysis of Burgdorf is based on the concept of a constant coefficient of friction. The relative merits of these two concepts have been examined by DePierre, Saul and Male[2] who compared experimental ring test results with the predictions of the two mathematical formulations and concluded that the concept of a constant interface shear factor more closely defined the true situation.

The constant interface shear factor formulation is based on the assumption of constancy of the ratio of the shear stress of the interface substance separating the ring specimen from the dies to the flow stress of the deforming workpiece as expressed in the following equation:

$$m = \frac{\tau}{\sigma o/\sqrt{3}} = \text{constant} \qquad (1)$$

where m is the interface shear factor, τ is the shear stress of the interface substance (the frictional restraint to metal flow) and σ_0 is the specimen material flow stress. Since the shear stress, $\sigma_0/\sqrt{3}$, of a material is generally assumed to be constant for a particular set of conditions, the implication from Eq. (1) is that the frictional restraint, τ, is constant over the entire flat surface of the ring specimen.

The change in shape of the ring during forging has been shown mathematically by Avitzur[3] and by Hawkyard and Johnson[5] to be solely dependent upon the value of the interface shear factor and the amount of deformation. The ratio of the total deformation pressure to the flow stress of the ring material has been shown to be dependent on the same parameters. Measurements of the shape change of a ring after deformation and also of the total pressure required to achieve the deformation thus allows both the flow stress and the interface shear factor to be determined; and also a numerical value to be associated with the interfacial restraint through the use of Eq. (1). Under conditions of truly thick film lubrication, this technique would permit quantitative comparison of different interfacial layers independent of the direct value of the flow stress of the workpiece material. The determination of the variation of the interfacial restraint as a function of temperature and pressure would then allow the interfacial restraint determined in one series of tests to be directly applied to any other material under identical interfacial conditions, provided the interfacial substances were applied in the same manner and that reaction of the coating substance with the workpiece surface did not occur.

Deductions from Eq. (1) imply that sliding of the workpiece surface occurs, with respect to the die, if the restraint of the interface layer is less than the shear stress of the workpiece material. Sticking (no relative movement between die and workpiece surfaces) occurs when the interfacial restraint exceeds the shear stress of the workpiece material. An interface substance of some kind is generally present in all metalworking operations and the presence of this substance prevents or minimizes direct contact of the workpiece with the die. If this interface layer is sufficiently thin to allow interaction between the roughness of the die and workpiece surfaces, the frictional restraint would be partially governed by the flow properties of the workpiece material because of the plastic shearing of the workpiece surface asperities. If, however, the interfacial film were sufficiently thick to preclude such interaction, the frictional restraint would consist solely of the shear strength of the interface layer and would be independent of the flow properties of the workpiece. It is with this latter situation with which we are primarily concerned in this report.

The application of a lubricant substance at the interface between the workpiece and the dies allows consideration of the interface substance as a thin film of fluid (but thick with respect to the size of surface irregularities on the dies and workpiece) and thus to be analyzed by techniques of a Newtonian

fluid as suggested by Vdovin[8] and related by:

$$\tau = \frac{\eta \, \Delta v}{t} \qquad (2)$$

where τ is the tangential stress in the interface layer (the frictional restraint to metal flow), η is the viscosity of the interface substance, Δv is the relative velocity of the workpiece with respect to the dies and t is the thickness of the interface film.

An analysis of the manner in which the variables relating the fluid shear vary during the axial forging of a ring between two flat dies, as related by Eq. (2), shows that the frictional restraint may not actually be constant over the entire flat surface of the ring but can vary over the interface and be dependent upon the surface geometry of the ring. For the c die forging of a flat disk the relative velocity would be the greates edges, and zero at the center of the disk where no motion can occur. thickness would seemingly be smallest at the edges of the specimen possibility of loss of lubricating substance by squeezing out from b the dies and the disk occurs but might also be influenced by some degree by the increased die pressure. For most substances, the viscosity increases as the pressure is increased and would thus be greatest at the center of the disk where no flow occurs. The assumption of a constant value for interfacial resistance is now seen to be dependent upon the constancy of the combined parameters which compose it, however, a sort of balance can be deduced by considering the variation of the parameters as the distance from the edge of a specimen is increased.

The basic method of analysis[3] assumes a constant average value, through m, for the interfacial shear stress over the entire workpiece surface and deduces an average die pressure over that area. This is known not to be true but it does allow comparison of theoretical predictions with possible experimental measurements. For this reason, Eq. (2) must be modified in some way in order to utilize the basic measured viscosity property of the interface material. Once this has been realistically accomplished, knowledge of this viscosity as a function of temperature and pressure should allow the frictional restraint, τ, to be predicted provided that the expected film thickness and interfacial velocity are known.

An additional assumption in the theoretical treatment is that the workpiece flow properties are uniform throughout the entire volume. In certain instances this is not necessarily correct. For example, Sejournet[9] and Cook and Spretnak[10] have experimentally determined surface chilling effects in metalworking operations and have demonstrated that these can be significant.

Such chilling can lead to an increase in shear strength of the surface layers of the workpiece and considerably modify metal flow in this vicinity. The effect would generally be to force shear to occur in subsurface layers of the workpiece and thus possibly lead to surface cracking depending upon the relative strength and ductility as well as the thickness of the chilled layer. Such effects would then effectively mask the true surface friction by precluding relative motion between the die surface and the true workpiece surface.

Controlled thermal conditions which limit heat transfer at the interface are necessary to prevent surface chilling. These conditions are easily simulated when both the tooling and workpiece are at room temperature, but are not so easily achieved at elevated temperatures and are almost never obtained in practical metalworking operations. The practical problem is the one of interest to those individuals concerned with the actual production of components, since it influences the deformation loads, die filling, homogeneous structure and surface quality. The practical conditions should be kept in mind whenever experimental metal processing work is accomplished. These conditions require that consideration be given to the heat transfer occurring at the interface and thus to the thermal insulation properties of a coating substance and also to the degree to which the coating substance reacts with the workpiece and the tooling.

The evaluation of glasses as forging lubricants as described in this report was done with the idea of providing information to allow the field of metalworking to be placed on a more scientific basis and of providing information of direct value to those individuals concerned with the production aspects of metalworking.

III. EXPERIMENTAL TECHNIQUES

The evaluation was conducted by axial forging of rings of maraging steel, type 300A, and of a titanium alloy, Ti-6Al-4V. Uncoated rings and rings coated with three different glass compositions were evaluated in combination with a die lubricant and with unlubricated dies. The evaluation was conducted over a range of temperatures to include commercial practice, 1500°F to 2200°F; and over a range of deformation. The ring size used in this evaluation was 1.500 in. O.D., 0.750 in. I.D. and of thickness 0.500 in.

The forging was conducted between flat dies in a 500 ton vertical hydraulic press with a ram motion of approximately 1.5 in./sec. The dies were made of H-12 tool steel heat treated to Rc 48 and were circularly ground to approximately 16μ-in. finish. The dies were preheated to 500° F in an air atmosphere furnace prior to the forging operation and in some cases two specimens of identical material and lubricant condition were forged on the dies before reheating. Spacer plates were used in the forging operation to achieve the desired height reductions. Forging load measurements were obtained by using a strain gage instrumented load cell which completely supported the lower die.

The ring test specimens were prepared for forging by grit blasting and, where necessary, lubrication was achieved by coating the specimens with the appropriate glass slurry prior to preheating to forging temperature. Details of the glasses and coating techniques are given in a following paragraph. Preheating to the forging temperature was carried out in an electric muffle furnace without any atmosphere control and all specimens were heated for 30 minutes. The specimens were placed on their sides in a special stand in the furnace so that the flat faces of the rings were free of contact with other substances. Transference of the specimens from the furnace to the forging dies was carried out using long handled tongs and the time delay between removal from furnace and actual deformation was of the order of five seconds.

The three glasses used for lubrication in this study were a borate type (Corning No. 9772), a potash-lead type (Corning No. 8871) and a potash-soda-lead type (Corning No. 0010). The approximate chemical compositions were as follows:

CORNING NO.	APPROXIMATE COMPOSITION, %
9772	Predominately B_2O_3
8871	35 SiO_2, 7 K_2O, 58 PbO

CORNING NO.	APPROXIMATE COMPOSITION, %
0010	63 SiO_2, 7.6 Na_2O, 6 K_2O, 0.3 CaO, 3.6 MgO, 21 PbO, 1 Al_2O_3

All glasses were obtained as -100 mesh powders and were prepared in the following manner. A gel was first made by mixing 1 g. of carboxy polymethylene (Carbopol 934) in 375 ml of warm distilled water and then neutralizing to pH 7 with NaOH solution. 30 ml of the resulting gel was then combined with 200 ml glass powder and 100 ml water to produce the coating glass slurry. With the 8871 and 0010 glasses, the gel and the glass powder were first mixed together and the water then gradually added. With the 9772 glass, however, a slightly better slurry was obtained by first combining the gel and the water and then gradually adding the glass powder. The resulting slurries were then thoroughly mixed using an electric mixer.

Those specimens requiring the application of glass were preheated to 170-190° F prior to coating. The glass slurries were applied to the forging specimens by dipping the ring into a beaker of slurry. Such techniques gave slurry coating thicknesses of approximately 0.005 in. on the forging specimens which at normal working temperatures yielded liquid glass coatings of approximately 0.002 in. All coated specimens were dried at 170-190° F prior to preheating to working temperature.

For forging with unlubricated (bare) dies, the die surfaces were degreased with acetone prior to heating, and were wiped with clean rags between successive specimen deformations. Where lubricated dies were used, lubrication was achieved by smearing the working surfaces with Fiske 604D Hot Die Lubricant, which is a high viscosity oil base lubricant containing aluminum, graphite, lead and an inorganic jelling agent. The residues were removed and the lubricant uniformly reapplied between successive specimen deformations.

The specimens were cleaned by grit blasting after the forging operation to remove the adhered coating. Measurements were made on the ring to determine the actual as-forged dimensions. Non-circularity and bulging of the ring sides were experienced in all ring forgings. The non-circularity was compensated for by measuring the maximum and minimum diameters of the rings and taking a mean value.

The compensation for bulge in the maraging steel rings was made by measuring the actual contact diameters of the ring and the bulged diameters. A mean non-bulged diameter was computed by assuming that the bulge was parabolic and that the effective diameter without bulge would be at a position one third of the distance from the contact diameter toward the tip of the bulge. The actual mean contact area was obtained by averaging the contact areas of

both sides of the specimen. The average pressure was computed through use of this mean contact area.

Bulging in the Ti-6Al-4V specimens occurred to such an extent that attempts to account for its effect would be of negligible value. The forging pressures for the Ti-6Al-4V specimens were computed by use of the constancy of volume principle and the actual measurement of the ring thickness. This technique was adopted because of difficulties associated with measuring actual contact areas on these specimens. The error thus introduced is estimated to be less than 5% on the calculated pressures. The effect is to slightly underestimate the pressure.

The measured and calculated values of specimen geometry and forging pressure are presented in Tables I and II for each condition of specimen material, forging temperature, lubricant combination and reduction amount. The values of the interface shear factor, material flow stress and interface factor for the maraging steel ring were computed as described earlier and are presented in Table I.

IV. RESULTS AND DISCUSSION

Results of the evaluation as compiled for maraging steel in Table I are presented graphically in Figs. 1 through 11. All maraging steel data presented in graphical form are corrected for bulge as discussed previously. The peak forging pressure required to achieve a specific reduction in height of the ring is presented in Fig. 1 for the 1500°F specimen temperature and the various lubricant combinations evaluated. The highest deformation pressures are required for uncoated specimens forged on unlubricated dies. Some reduction in the deformation pressure is achieved by use of 0010 glass-coated specimens forged on unlubricated dies, but significant reduction in the deformation pressure is achieved when a die lubricant is used; in the case of this study the die lubricant used was Fiske 604D hot die lubricant. The results of Fig. 1 show that non-coated rings forged on lubricated dies actually required less deformation pressure to achieve a specific reduction in height than did 0010 glass-coated rings forged on lubricated dies. Use of 8871 glass coating on the rings or 9772 glass coating on the rings progressively reduced the required deformation load.

The measurement of the change in the internal diameter of the rings as a function of the reduction in height for the 1500°F forging of maraging steel rings, as presented in Fig. 2, shows somewhat complementary results to Fig. 1 in that the non-coated rings forged on non-lubricated dies show the greatest resistance to interface flow. Slight improvement is achieved by forging 0010 glass-coated rings on uncoated dies, but significant lowering of the interfacial restraint is achieved when the rings are forged on lubricated dies. As can be seen in Fig. 2, the non-coated rings forged on lubricated dies show less frictional restraint than either the 0010 glass-coated rings or 8871 coated rings forged in conjunction with the die lubricant. Those rings coated with the 9772 glass and forged on lubricated dies show the least frictional restraint for the 1500°F forging.

The apparent difficulty of the higher frictional restraint for 0010 and 8871 glass-coated rings forged on lubricated dies compared with uncoated rings forged on lubricated dies may be explained by the consideration of the expected value of interface shear of the glass coatings. Information published by Corning Glass Works[11] gives the viscosity of the 0010 type glass at 1800°F as 10,000 poises. By means of Eq. (2) using an effective coating thickness of 0.001 in. and an estimated mean relative interfacial velocity of 1.0 in./sec. the shear stress of the 0010 glass is computed to be approximately 28,000 psi at 1800°F. The value of the material shear stress, 0.577 times the flow stress, as deduced from Table I shows that the shear stress of the ring material at 1800°F is also approximately 28,000 psi. At temperatures above 1800°F the shear strength of the maraging steel is higher than that of the thin coating of 0010 glass and at temperatures below 1800°F the shear

strength of the 0010 glass coating is greater than that of the maraging steel. Use of a thin coating of 0010 glass at 1500°F thus retards the interface motion and thereby partially explains the results of Fig. 1 and Fig. 2.

It should be carefully noted that one side of the glass coating is in contact with the dies and die lubricant at 500°F and therefore the effective temperature of the glass coating is reduced, or its effective thickness at temperature is reduced. This would further tend to increase the value of the shear stress of the glass film. The chilling effect of the outer surface of the glass coating can thereby cause 8871 glass coating to be effectively higher in shear at 1500°F than the ring material even though the 8871 glass is of much lower viscosity than the 0010 glass and thus possibly explains the greater frictional restraint of 8871 coated rings forged on lubricated dies over non-coated rings forged on lubricated dies as shown in Fig. 2.

The effect of glass coatings in lowering the heat transfer from the workpiece to the dies has been shown by Cook and Spretnak.[9] The lower heat transfer effects experienced with glass-coated rings therefore cause them to be of lower effective flow stress than non-coated rings and in turn affect the results of Fig. 1. A sort of trade off of effects of the glass coatings at the 1500°F temperature can then occur by the glass coating providing a heat transfer barrier to retard chilling and thereby promoting metal flow and at the same time causing a high shear stress interface which tends to retard interface flow.

The general finding of Figs. 1 and 2 implies that the primary lubrication mechanism at the 1500°F test condition is the Fiske 604D die lubricant and that the glass coatings applied to the rings do not significantly alter the friction characteristics of the interface, but do provide a heat transfer barrier and thereby allow favorable metal flow. These deductions cannot be precisely supported by the results of this study, but should be further evaluated under carefully controlled die temperature forgings.

The results as used in this report are affected by the ability to accurately account for the bulging of the sides of the ring. This bulging affects the area of contact between the ring and the die and thereby the deformation pressure and the value of the flow stress. It directly affects the value of the change in internal diameter. The amount of bulging is smallest for the maraging steel rings forged with good lubrication and largest for those forged with poor lubrication; consequently, the ability to account for bulge is more accurate for the rings forged with good lubrication and less accurate for those forged with poor lubrication and the results as obtained and discussed in this report reflect this difficulty.

The results presented in Fig. 3 for some of the better lubrication conditions have been calculated using the computer solutions of Avitzur's equations generated by Saul, Male and DePierre[7]. Although true analysis

of the experimental data by this means is not completely justified, the calculated m values are seen to be constant over a reasonably wide range of deformation. Deviations noted at low deformations may be due to experimental inaccuracies involved in measuring very small changes in internal diameter. Flow stress values deduced from this data by the technique of Saul, Male and DePierre[7] tend to be independent of the friction conditions, as would be expected. The higher values observed at the higher deformations with non-glass coated specimens are almost certainly due to die chilling effects.

Information as presented in Figs. 1 through 5 for the 1500°F forgings has been plotted for all other temperatures. The values of each parameter at the 30 percent reduction level for each lubricant combination have been plotted as a function of temperature. The total pressure as a function of preheat temperature is illustrated in Fig. 6. The relative increase in the required deformation pressure for 9772 coated rings as the temperature is increased from 1500°F to 2200°F reflects its increased susceptibility to run off of the ring surface during the heating process. The increased benefits of the 8871 and 0010 glass coatings in serving as a lubricant and thermal insulator are evident at the higher temperatures. An increase in the required deformation pressure at the 1800°F temperature range is evident. The increase appears to be too large to be experimental error and may be owing to the growth of austenitic grains of the maraging steel in this temperature range and thereby causing the higher flow stress.

The general effect of the change in internal diameter of the ring as a function of processing temperature is shown in Fig. 7. The rapid decline in favorable properties of the 9772 glass coating with increased temperature is readily noticed. The favorable use range of the 8871 glass coating in permitting the outward flow of the ring can be seen to be the middle temperature range and the decline in the effectiveness of this glass coating at the high temperatures can easily be seen. The value of the 0010 coating at the high temperature region is easily seen. The overall effect of use of the die lubricant over non-lubricated dies is readily apparent.

The ratio of the interface shear stress to the material shear stress as shown in Fig. 8 indicates a general increase with increasing temperature while the shear stress of the interface substance indicates a general decrease with decreasing temperature as may be seen in Fig. 9. The significance of these two figures is that the lubrication condition can still be improving with increasing temperature, but its effect on metal flow can act as an increase in frictional restraint owing to the more rapid decrease in the value of the workpiece flow stress as temperature is increased which is shown in Fig. 10.

The crossover region of interface shear stress for 0010 glass-coated rings and non-coated rings forged on lubricated dies is seen in Fig. 9 to occur near the 1800°F temperature region; implying that the 0010 coating possesses

a lower shear stress than the workpiece above this temperature region as was previously discussed.

The general relation of the flow stress as a function of temperature as presented in Fig. 10 shows the same increase at 1800°F as was noted for the deformation pressure and the effect of the 0010 glass coating and the 8871 glass coating in retarding heat transfer from the workpiece to the cooler temperature dies can easily be seen.

The use of the bulged measurements of the internal diameter change in determining the useful temperature ranges of various lubricants can be seen by comparing the measured value of bulged internal diameter change as a function of temperature as shown in Fig. 11 with those of the corrected internal diameter change as a function of temperature as shown in Fig. 7. The general relationship is seen to be the same and crossover points are at somewhat similar positions on the temperature scale. Both the bulged and non-bulged relationship show nearly the same effective temperature range of useful application of the lubricant combination as noted for the interface factor as shown in Fig. 8.

The qualitative use of the change in bulged internal diameter as a function of temperature allows some information to be obtained from the forging of the Ti-6Al-4V rings. The flow stress for Ti-6Al-4V would be expected to be less than that for maraging steel and thus a higher ratio of interface stress to material shear stress would be expected and a subsequently greater degree of inward flow of the material would result. The general relationship of the various lubricant combination and crossover points would be expected to be the same provided that selective reaction of lubricant with the material does not occur and the general shape of the flow stress with temperature is the same.

The change in the bulged internal diameter of the Ti-6Al-4V as shown in Fig. 12 reflects the discussion just presented. A greater change in the internal diameter is evident, but the general relationship is quite similar to that presented for the maraging steel as shown in Fig. 11.

The regions of favorable lubrication characteristics for the three glasses evaluated in this report are seen from Figs. 8, 11, and 12 to be: for the 9772 glass - from somewhere below 1500°F up to 1700°F; for the 8871 glass - from 1650°F to 2100° F; and for the 0010 glass - from 2000°F to some unspecified temperature above 2200° F.

The surface qualities after deformation were determined by visual comparison of the rings after the specimens had been cleaned by grit blasting and are shown in Fig. 13 for the maraging steel and Fig. 14 for the Ti-6Al-4V.

When maraging steel is forged in combination with Fiske 604D die lubricant and 0010 glass coating on the workpiece, the resulting surface finish after forging is of generally good quality, but slight rippling can be noted. The rippling is most probably resultant from flow between the workpiece and the glass coating owing to the relative high strength of the 0010 glass at the 1500° F temperature. Forging at both 1650°F and 1800°F gave surface qualities which were still generally good but increasing deterioration was noted for forging at 2050°F and 2200°F. Similar trends were observed when forging rings coated with 0010 glass between unlubricated dies.

Workpiece coatings of 8871 glass and die lubrication with Fiske 604D gave good quality surfaces when forging at 1500°F, 1650°F and 1800°F. Some deterioration of the surface was noted at 2050°F and a poor surface was obtained after forging at 2200°F. At all the forging temperatures investigated, use of 8871 glass gave consistently better surface finishes than did the use of the 0010 glass.

Use of 9772 glass as a workpiece coating in combination with Fiske 604D die lubrication resulted in forged surface qualities which were generally similar, though slightly inferior to those obtained with the 8871 glass coating.

Rings forged without any glass coating, but using Fiske 604D die lubricant, resulted in excellent forged surfaces at temperatures up to, and including, 1800°F as shown in Fig. 13. Some deterioration was observed at forging temperatures of 2050°F and 2200°F although these surfaces were still superior to those obtained when using any of the glass coatings at similar temperatures.

Forging uncoated rings between unlubricated dies produced surfaces which were very similar in quality to those obtained when forging uncoated rings between dies lubricated with Fiske 604D.

Representative surface qualities of the Ti-6Al-4V rings obtained after forging under various conditions are shown in Fig. 14. The best surface finish when forging at 1500°F was obtained when using uncoated specimens and forging with unlubricated dies. Use of the various glass coatings gave surfaces which were similar amongst themselves but not quite as good as that given by the unlubricated conditions.

As the forging temperature was increased above 1500°F the chilling effect associated with contact with the cool dies apperared to become an important factor in determining the surface quality of the forged ring. This effect was especially noticeable on rings forged without glass coatings, as can be seen from Fig. 14. The best surfaces obtained when forging in the 1650°F - 2050°F range were produced by use of a workpiece coating of either 0010 or 8871 glass and forging between dies lubricated with Fiske 604D. Rings forged using a coating of 9772 glass began to show surface deterioration with increased rippling and some shallow pitting at temperatures of 1800°F and above.

For forging at 2200°F all surfaces were poor, irrespective of the lubrication coating, as shown in Fig. 14. The general appearance of the glass coated rings as compared to uncoated rings suggests that some form of reaction occurred between the titanium alloy and the glass coatings.

V. CONCLUSIONS

1. The use of the ring compression test can be successfully utilized for the ranking of forging lubrication systems. Inaccuracies due to bulging occurring at high friction levels can be minimized by using specimens of smaller ratios of internal diameter and thickness to external diameter than was used in this work. When such precautions are taken, the method of analysis used here allows a value for the interface shear of the lubricant system to be determined. Under thick film lubrication conditions, this value would be independent of the flow stress of the workpiece material.

2. The regions of favorable lubrication characteristics for use of the three glass lubricants evaluated in this report are: for the 9772 glass - 1500°F and below to 1700°F; the 8871 glass - from 1650° F to 2100° F; for the 0010 glass - from 2000° F to 2200° F and somewhat higher.

3. A significant portion of the favorable effect of glass coatings on workpieces subjected to metal deformation processes is directly attributed to the ability of the glass coating to act as a thermal insulator retarding heat flow from the surfaces of the workpiece. This is especially significant if a large temperature difference exists between the workpiece and the tooling with which the workpiece comes in contact. Therefore, consideration of coating substances for application to workpieces prior to heating should be based on the ability of the coating to provide three functions: a) anti-friction characteristics, b) thermal insulation, and c) protection of the workpiece from the environment while not reacting directly with the workpiece.

   Choice of the most favorable glass viscosity must be made on a compromise of the relatively high viscosity necessary to prevent the glass running off during preheating, and the low viscosity (shear stress) required during forming.

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TABLE I DATA FROM FORGING OF MARAGING STEEL RINGS

For Rings Preheated To 1500°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	As Forged Dimensions Height	Calc. I.D.	Bulged I.D.	Percent Change Height	Percent Change I.D.	Forging Pressure (KSI)	Flow Stress σ_0(KSI)	Interface Factor m	Interface Shear τ(KSI)
353	Bare	Bare	.365	.691	.617	27.0	7.88	92.5	70.0	.50	20.2
355	Bare	Bare	.247	.513	.437	50.6	31.60	126.2	76.0	.59	25.9
343	604D	Bare	.420	.800	.788	16.0	-6.66	82.9	78.9	.06	2.7
268	604D	Bare	.398	.793	.789	20.4	-6.14	84.3	77.3	.11	4.9
345	604D	Bare	.335	.823	.813	33.0	-9.75	87.6	78.9	.11	5.0
347	604D	Bare	.305	.840	.816	39.0	-12.00	100.0	90.1	.10	5.2
272	604D	Bare	.237	.783	.759	52.6	-4.40	94.3	78.5	.14	6.3
349	604D	Bare	.178	.789	.753	64.4	-5.20	115.4	93.1	.11	5.9
351	604D	Bare	.157	.755	.719	68.6	- .66	120.0	93.8	.11	6.0
436	Bare	0010	.417	.736	.713	16.6	1.74	93.2	77.7	.34	15.2
352	Bare	0010	.368	.713	.681	26.4	8.40	93.0	68.4	.38	16.4
437	Bare	0010	.304	.647	.575	39.2	14.20	113.0	87.3	.46	21.6
354	Bare	0010	.243	.568	.502	51.4	24.30	116.0	77.4	.43	19.2
342	604D	0010	.417	.786	.773	16.6	-4.81	84.3	77.5	.12	5.4
267	604D	0010	.395	.792	.760	21.0	-5.50	83.9	76.3	.12	5.3
344	604D	0010	.333	.769	.743	33.4	-2.50	91.6	79.0	.18	8.2
346	604D	0010	.303	.766	.730	39.4	-2.13	98.0	83.6	.17	8.2
271	604D	0010	.234	.690	.642	53.2	7.98	99.3	77.0	.21	9.3
348	604D	0010	.178	.619	.575	64.4	17.45	115.0	82.1	.20	9.5
350	604D	0010	.159	.570	.524	68.2	24.00	122.0	83.6	.19	9.2
265	604D	9772	.402	.811	.809	19.6	-8.13	81.2	78.2	.06	2.7
269	604D	9772	.234	.899	.871	53.2	-19.90	94.6	83.8	.08	3.9
266	604D	8871	.401	.789	.779	19.8	-5.20	82.8	76.0	.12	5.2
270	604D	8871	.232	.758	.730	53.6	-1.10	97.0	79.5	.16	7.4

TABLE I (CON'T)

For Rings Preheated to 1650°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	As Forged Dimensions Height	Calc. I.D.	Bulged I.D.	Percent Change Height	Percent Change I.D.	Forging Pressure (KSI)	Flow Stress σ_o(KSI)	Interface Factor m	Interface Shear τ (KSI)
356	Bare	0010	.367	.709	.661	26.6	5.47	75.9	59.8	.40	13.8
357	Bare	0010	.242	.558	.492	51.6	25.60	113.3	74.1	.44	18.8
358	Bare	0010	.242	.503	.453	51.6	32.93	119.1	67.0	.58	24.8
277	604D	0010	.364	.767	.755	27.2	-2.27	77.9	67.7	.18	7.0
278	604D	0010	.362	.762	.745	27.6	-1.60	74.1	63.3	.20	7.3
283	604D	0010	.231	.704	.650	53.6	6.13	93.0	72.7	.20	8.4
284	604D	0010	.231	.684	.634	53.6	8.80	96.7	74.4	.22	9.4
273	604D	9772	.367	.801	.775	26.6	-6.80	72.8	65.6	.12	4.5
274	604D	9772	.364	.775	.769	27.2	-3.33	72.1	63.2	.17	6.2
279	604D	9772	.230	.753	.709	54.0	- .40	91.1	74.7	.15	6.5
280	604D	9772	.230	.721	.719	54.0	3.87	94.1	74.7	.18	7.8
275	604D	8871	.357	.792	.780	28.6	-5.60	68.2	60.4	.15	5.2
276	604D	8871	.358	.780	.777	28.4	-4.00	71.1	62.4	.16	5.8
281	604D	8871	.233	.771	.717	53.4	-2.80	90.6	74.3	.15	6.4
282	604D	8871	.231	.768	.713	53.6	-2.40	93.8	76.9	.15	6.7

TABLE I (CON'T)

For Rings Preheated To 1800°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	As Forged Dimensions Height	Calc. I.D.	Bulged I.D.	Percent Change Height	Percent Change I.D.	Forging Pressure (KSI)	Flow Stress σ_0(KSI)	Interface Factor m	Interface Shear τ (KSI)
359	Bare	Bare	.363	.699	.639	27.4	6.80	70.4	54.6	.47	14.8
360	Bare	Bare	.363	.694	.630	27.4	7.47	77.5	59.2	.51	17.4
361	Bare	Bare	.241	.476	.404	51.8	36.53	117.1	66.2	.66	25.2
362	Bare	Bare	.241	.472	.400	51.8	37.07	125.0	70.2	.67	27.1
288	604D	Bare	.361	.787	.736	27.8	-4.93	70.6	61.9	.16	5.7
289	604D	Bare	.361	.785	.730	27.8	-4.67	68.2	59.8	.16	5.5
295	604D	Bare	.236	.695	.643	52.8	7.33	92.0	71.9	.21	8.7
296	604D	Bare	.236	.694	.644	52.8	7.47	97.3	76.0	.21	9.2
438	Bare	0010	.411	.738	.708	17.8	1.60	58.9	49.1	.32	9.1
290	Bare	0010	.363	.727	.684	27.4	3.07	72.6	59.5	.30	10.3
291	Bare	0010	.363	.724	.674	27.4	3.47	69.1	56.2	.30	9.7
297	Bare	0010	.230	.574	.494	54.0	23.47	94.6	63.9	.36	13.3
298	Bare	0010	.233	.559	.456	53.4	25.47	105.7	70.5	.40	16.3
287	604D	0010	.362	.772	.762	27.6	-2.93	65.5	57.0	.18	5.9
294	604D	0010	.230	.712	.663	54.0	5.07	88.3	69.5	.19	7.6
285	604D	9772	.359	.782	.734	28.2	-4.27	69.0	60.5	.16	5.6
292	604D	9772	.230	.720	.670	54.0	4.00	90.0	71.4	.18	7.4
286	604D	8871	.361	.820	.776	27.8	-9.33	71.2	64.7	.10	3.7
293	604D	8871	.229	.756	.712	54.2	- .80	95.1	78.0	.15	6.8

TABLE I (CON'T)

For Rings Preheated To 2050°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	As Forged Dimensions Height	Calc. I.D.	Bulged I.D.	Percent Change Height	Percent Change I.D.	Forging Pressure (KSI)	Flow Stress σ_0(KSI)	Interface Factor m	Interface Shear τ (KSI)
363	Bare	0010	.344	.680	.596	31.2	9.33	46.9	35.0	.47	9.5
364	Bare	0010	.225	.396	.320	55.0	47.20	92.5	47.4	.74	20.2
365	Bare	0010	.229	.422	.330	54.2	43.73	100.0	52.4	.72	21.8
303	604D	0010	.343	.754	.726	31.4	- .53	40.0	35.1	.20	4.1
304	604D	0010	.346	.753	.715	30.8	- .40	46.3	39.2	.21	4.7
309	604D	0010	.225	.693	.585	55.0	7.60	69.3	53.7	.20	6.2
310	604D	0010	.222	.660	.598	55.6	12.00	60.4	45.4	.23	6.0
299	604D	9772	.348	.757	.719	30.4	- .93	47.8	40.9	.21	5.0
300	604D	9772	.349	.755	.713	30.2	- .66	49.7	42.1	.22	5.3
305	604D	9772	.225	.701	.613	55.0	6.53	70.9	55.8	.19	6.1
306	604D	9772	.225	.717	.601	55.0	4.40	70.1	55.6	.19	6.1
301	604D	8871	.349	.785	.731	30.2	-4.67	45.0	39.5	.16	3.6
302	604D	8871	.350	.750	.722	30.0	0.00	46.8	39.1	.22	5.0
307	604D	8871	.219	.720	.654	56.2	4.00	65.4	51.5	.19	5.6
308	604D	8871	.219	.715	.653	56.2	4.67	63.0	49.2	.19	5.4

TABLE I (CON'T)

For Rings Preheated To 2200°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	As Forged Dimensions Height	Calc. I.D.	Bulged I.D.	Percent Change Height	Percent Change I.D.	Forging Pressure (KSI)	Flow Stress σ_o(KSI)	Interface Factor m	Interface Shear τ (KSI)
367	Bare	Bare	.347	.688	.600	30.6	8.53	47.4	35.9	.46	9.5
369	Bare	Bare	.226	.410	.330	54.8	45.33	78.4	40.0	.76	17.5
316	604D	Bare	.346	.754	.726	30.8	- .53	45.7	38.7	.22	4.9
320	604D	Bare	.219	.678	.590	56.2	9.87	71.2	54.4	.20	6.2
366	Bare	0010	.335	.682	.594	33.0	9.07	35.7	27.0	.43	6.7
368	Bare	0010	.220	.398	.304	56.0	46.93	79.2	40.6	.66	15.5
315	604D	0010	.335	.756	.730	33.0	- .80	35.9	30.4	.20	3.5
319	604D	0010	.209	.662	.608	58.2	11.73	53.9	40.5	.20	4.6
313	604D	9772	.347	.772	.732	30.6	-2.93	47.4	40.9	.18	4.2
317	604D	9772	.221	.647	.579	55.8	13.73	61.8	45.8	.24	6.4
314	604D	8871	.340	.756	.724	32.0	- .80	35.3	29.9	.21	3.6
318	604D	8871	.218	.626	.560	56.4	16.53	61.2	44.3	.24	6.2

Bare - No Lubricant
604D - Fiske 604D Lubricant
0010 - 0010 Glass Lubricant
9772 - 9772 Glass Lubricant
8871 - 8871 Glass Lubricant

TABLE II DATA FROM FORGING OF Ti-6Al-4V RINGS

For Rings Preheated To 1500°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	Dimensions After Forging Height	Dimensions After Forging O.D.	Dimensions After Forging I.D.	Percent Change Height	Percent Change I.D.	Deformation Press KSI
525	Bare	Bare	.371	1.678	.562	25.8	25.1	59.6
377	Bare	Bare	.364	1.687	.546	27.2	27.2	69.2
528	Bare	Bare	.248	1.924	.296	50.4	60.5	97.1
387	Bare	Bare	.247	1.933	.265	50.6	64.7	112.1
371	604D	Bare	.417	1.637	.745	16.6	.7	84.1
375	604D	Bare	.371	1.723	.736	25.8	1.9	78.7
379	604D	Bare	.341	1.801	.731	31.8	2.5	85.7
381	604D	Bare	.300	1.885	.707	40.0	5.7	82.1
385	604D	Bare	.238	2.017	.630	52.4	16.0	101.4
389	604D	Bare	.184	2.277	.551	63.2	26.5	122.9
391	604D	Bare	.157	2.395	.481	68.6	35.9	152.2
493	Bare	0010	.411	1.632	.688	17.8	8.3	77.5
376	Bare	0010	.364	1.697	.597	27.2	20.2	73.6
494	Bare	0010	.363	1.698	.610	27.4	18.6	85.2
526	Bare	0010	.358	1.701	.606	28.4	19.2	51.9
495	Bare	0010	.333	1.748	.566	33.4	24.5	82.2
496	Bare	0010	.299	1.821	.497	40.2	33.7	78.2
386	Bare	0010	.240	1.987	.383	52.0	48.9	94.7
497	Bare	0010	.235	1.973	.354	53.0	52.8	93.0
529	Bare	0010	.235	2.002	.372	53.0	50.4	68.5
498	Bare	0010	.192	2.155	.096	61.6	87.2	154.0
499	Bare	0010	.171	2.276	.120	65.8	84.0	207.6
370	604D	0010	.419	1.645	.744	16.2	.8	79.0
374	604D	0010	.394	1.748	.726	25.8	3.2	84.3
378	604D	0010	.340	1.812	.721	32.0	3.8	84.3
380	604D	0010	.300	1.851	.687	40.0	8.4	86.6
384	604D	0010	.236	2.034	.585	52.8	22.0	100.4
388	604D	0010	.180	2.293	.471	64.0	37.2	101.9
390	604D	0010	.150	2.460	.338	70.0	54.9	128.1
372	604D	9772	.364	1.749	.741	27.2	1.2	71.4
382	604D	9772	.239	2.128	.757	52.2	- .9	87.5
373	604D	8871	.358	1.729	.699	28.4	6.8	68.5

TABLE II (CON'T))

For Rings Preheated To 1500°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	Dimensions After Forging Height	Dimensions After Forging O.D.	Dimensions After Forging I.D.	Percent Change Height	Percent Change I.D.	Deformation Press KSI
527	604D	8871	.357	1.748	.720	28.6	4.0	48.4
383	604D	8871	.234	2.052	.557	53.2	25.7	76.4
530	604D	8871	.233	2.067	.587	53.4	21.7	60.6

TABLE II (CON'T)
For Rings Preheated To 1650°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	Dimensions After Forging Height	Dimensions After Forging O.D.	Dimensions After Forging I.D.	Percent Change Height	Percent Change I.D.	Deformation Press KSI
500	Bare	Bare	.417	1.622	.638	16.6	14.9	72.2
502	Bare	Bare	.248	1.916	.255	50.4	66.0	134.6
501	604D	Bare	.417	1.640	.696	16.6	7.2	78.5
503	604D	Bare	.239	2.026	.531	52.2	29.2	105.3
409	Bare	0010	.360	1.708	.568	28.0	24.3	65.2
408	Bare	0010	.356	1.714	.583	28.8	22.3	55.9
417	Bare	0010	.239	1.977	.352	52.2	53.1	105.0
416	Bare	0010	.236	1.972	.344	52.8	54.1	99.6
407	604D	0010	.362	1.731	.654	27.6	12.8	58.2
406	604D	0010	.361	1.736	.679	27.8	9.5	54.6
414	604D	0010	.238	2.030	.535	52.4	28.7	90.8
415	604D	0010	.238	2.027	.549	52.4	26.8	92.2
403	604D	9772	.364	1.742	.707	27.2	5.7	63.7
402	604D	9772	.363	1.743	.699	27.4	6.8	57.9
410	604D	9772	.238	2.015	.599	52.4	20.1	92.2
411	604D	9772	.236	2.036	.614	52.8	18.1	88.4
404	604D	8871	.357	1.745	.672	28.6	10.4	60.2
405	604D	8871	.357	1.747	.679	28.6	9.5	62.4
531	604D	8871	.353	1.761	.707	29.4	5.7	35.2
412	604D	8871	.235	2.030	.532	53.0	29.1	96.5
413	604D	8871	.235	2.036	.565	53.0	24.7	97.9
532	604D	8871	.228	2.043	.544	54.4	27.5	98.2

TABLE II (CON'T)

For Rings Preheated To 1800°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	Dimensions After Forging Height	Dimensions After Forging O.D.	Dimensions After Forging I.D.	Percent Change Height	Percent Change I.D.	Deformation Press KSI
426	Bare	Bare	.356	1.720	.515	28.8	31.3	37.6
425	Bare	Bare	.352	1.720	.513	29.6	31.6	40.4
434	Bare	Bare	.248	1.911	.101	50.4	86.5	121.3
435	Bare	Bare	.246	1.920	.091	50.8	87.9	129.2
535	604D	Bare	.362	1.711	.561	27.6	25.2	27.5
422	604D	Bare	.356	1.729	.528	28.8	29.6	45.2
421	604D	Bare	.355	1.727	.543	29.0	27.6	40.6
538	604D	Bare	.237	2.974	.245	52.6	67.3	75.4
430	604D	Bare	.239	1.965	.201	53.1	73.2	102.8
431	604D	Bare	.239	1.967	.265	53.1	64.7	105.0
515	Bare	0010	.353	2.728	.586	29.4	21.9	31.9
424	Bare	0010	.349	1.741	.621	30.2	17.2	30.4
423	Bare	0010	.348	1.744	.618	30.4	17.6	30.2
533	Bare	0010	.348	1.736	.626	30.4	16.5	15.6
516	Bare	0010	.235	1.972	.279	53.0	62.8	86.0
432	Bare	0010	.234	2.014	.392	53.2	47.7	80.4
433	Bare	0010	.230	2.012	.389	54.0	48.1	78.5
536	Bare	0010	.225	2.041	.433	55.0	42.3	53.5
508	604D	0010	.399	1.664	.658	20.2	12.3	39.0
473	604D	0010	.353	1.745	.541	29.4	27.9	45.7
474	604D	0010	.351	1.747	.610	29.8	18.7	43.4
509	604D	0010	.350	1.750	.610	30.0	18.7	41.9
420	604D	0010	.343	1.772	.630	31.4	16.0	30.9
510	604D	0010	.324	1.794	.553	35.2	26.3	41.3
511	604D	0010	.294	1.872	.550	41.2	26.7	54.4
476	604D	0010	.236	1.995	.401	52.8	46.5	89.1
475	604D	0010	.233	2.014	.414	53.4	44.8	78.7
512	604D	0010	.232	2.008	.349	53.6	53.5	90.3
477	604D	0010	.230	2.025	.417	54.0	44.4	80.5
429	604D	0010	.227	2.043	.436	54.6	41.9	70.7
513	604D	0010	.181	2.233	.250	63.8	66.7	118.9

TABLE II (CON'T)

For Rings Preheated To 1800°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	Dimensions After Forging Height	Dimensions After Forging O.D.	Dimensions After Forging I.D.	Percent Change Height	Percent Change I.D.	Deformation Press KSI
514	604D	0010	.149	2.473	.342	70.2	54.4	162.9
418	604D	9772	.359	1.752	.639	28.2	14.8	40.2
427	604D	9772	.237	2.044	.453	52.6	39.6	75.4
419	604D	8871	.355	1.753	.626	29.0	16.5	36.4
534	604D	8871	.353	1.747	.653	29.4	12.9	19.1
428	604D	8871	.237	2.005	.453	52.6	39.6	88.0
537	604D	8871	.234	2.032	.437	53.2	41.7	62.9

TABLE II (CON'T)

For Rings Preheated To 2050°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	Dimensions After Forging Height	Dimensions After Forging O.D.	Dimensions After Forging I.D.	Percent Change Height	Percent Change I.D.	Deformation Press KSI
517	Bare	Bare	.352	1.717	.525	29.6	30.0	6.3
519	Bare	Bare	.232	1.958	.118	53.6	84.3	55.6
518	604D	Bare	.351	1.729	.530	29.8	29.3	5.3
520	604D	Bare	.233	1.984	.225	53.4	70.0	56.4
445	Bare	0010	.342	1.749	.580	31.6	22.7	14.3
446	Bare	0010	.340	1.738	.527	32.0	29.7	15.2
453	Bare	0010	.225	2.013	.209	55.0	72.1	63.5
454	Bare	0010	.222	2.038	.270	55.6	64.0	58.1
444	604D	0010	.344	1.756	.598	31.2	20.3	18.6
443	604D	0010	.343	1.750	.578	31.4	24.4	16.5
451	604D	0010	.227	2.030	.380	54.6	49.3	59.3
452	604D	0010	.227	2.023	.334	54.6	55.5	60.6
439	604D	9772	.348	1.749	.548	30.4	26.9	21.9
440	604D	9772	.347	1.754	.563	30.6	24.9	15.5
447	604D	9772	.234	2.003	.385	53.2	48.7	62.2
448	604D	9772	.234	2.018	.409	53.2	45.5	62.9
441	604D	8871	.339	1.757	.589	32.2	21.5	19.3
442	604D	8871	.339	1.769	.617	32.2	17.7	16.2
449	604D	8871	.226	2.032	.402	54.8	46.4	65.1
450	604D	8871	.224	2.057	.406	55.2	45.9	59.3

TABLE II (CON'T)

For Rings Preheated To 2200°F And Forging Dies Preheated To 500°F

Forging Number	Lubrication Dies	Lubrication Rings	Dimensions After Forging Height	Dimensions After Forging O.D.	Dimensions After Forging I.D.	Percent Change Height	Percent Change I.D.	Deformation Press KSI
460	Bare	Bare	.335	1.735	.535	33.0	28.7	10.9
466	Bare	Bare	.228	1.966	.145	54.4	67.3	64.2
458	604D	Bare	.341	1.740	.545	31.8	27.3	16.2
464	604D	Bare	.218	2.022	.252	56.4	66.4	50.6
459	Bare	0010	.338	1.757	.593	32.4	20.9	12.1
465	Bare	0010	.226	2.033	.330	54.8	56.0	50.3
457	604D	0010	.343	1.758	.601	31.4	19.9	15.5
463	604D	0010	.223	2.036	.363	55.4	51.6	53.2
455	604D	9772	.337	1.747	.538	32.6	28.3	17.1
461	604D	9772	.231	2.002	.300	53.8	60.0	60.9
456	604D	8871	.335	1.759	.568	33.0	24.3	7.5
462	604D	8871	.225	2.037	.375	55.0	50.0	46.8

Bare - No Lubricant
604D - Fiske 604D Lubricant
0010 - 0010 Glass Lubricant
9772 - 9772 Glass Lubricant
8871 - 8871 Glass Lubricant

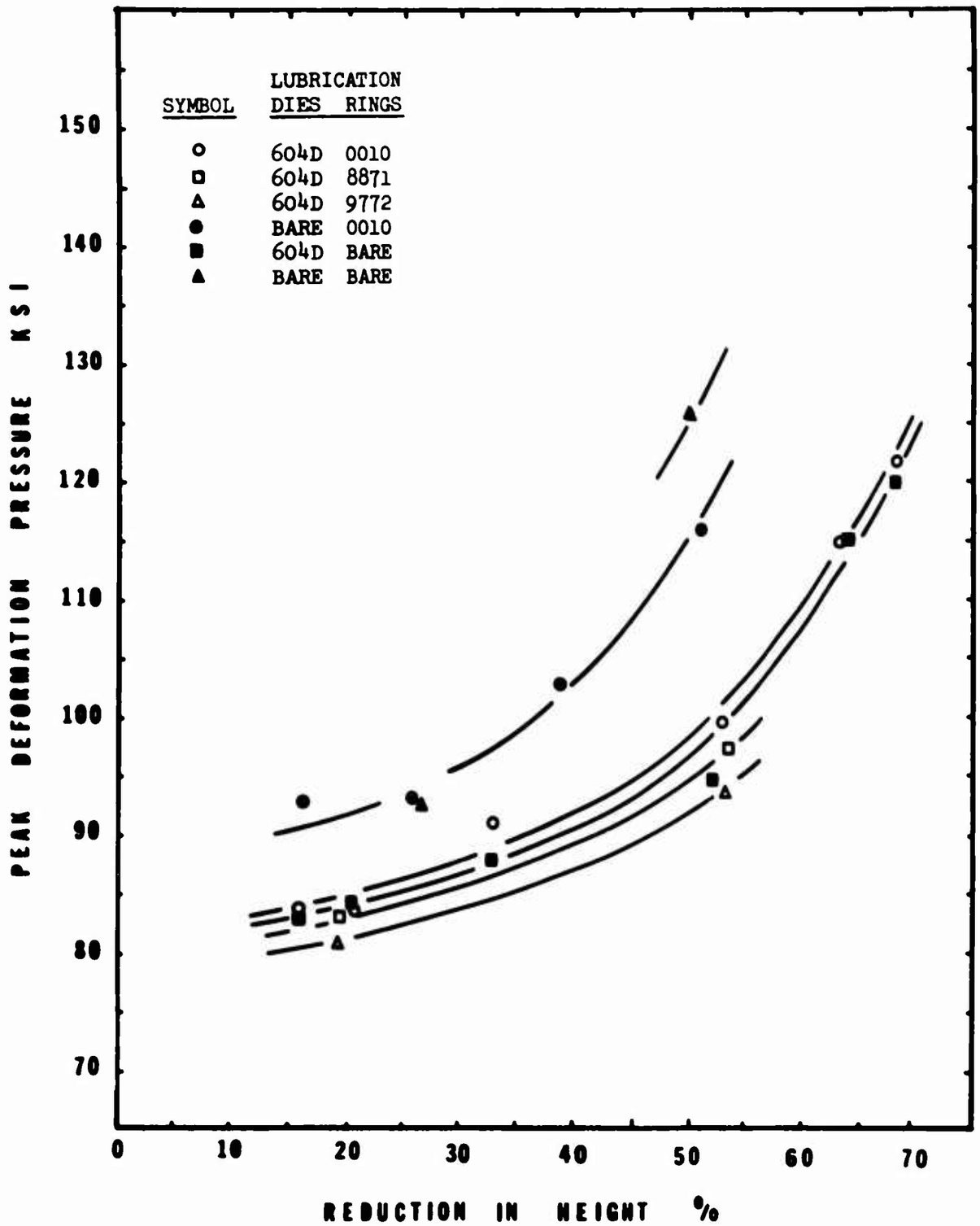

FIGURE 1. Variation of the peak deformation pressure with reduction in thickness as a function of the lubrication system for the 1500°F forging of maraging steel rings. Data are based on the measured value of the contact area.

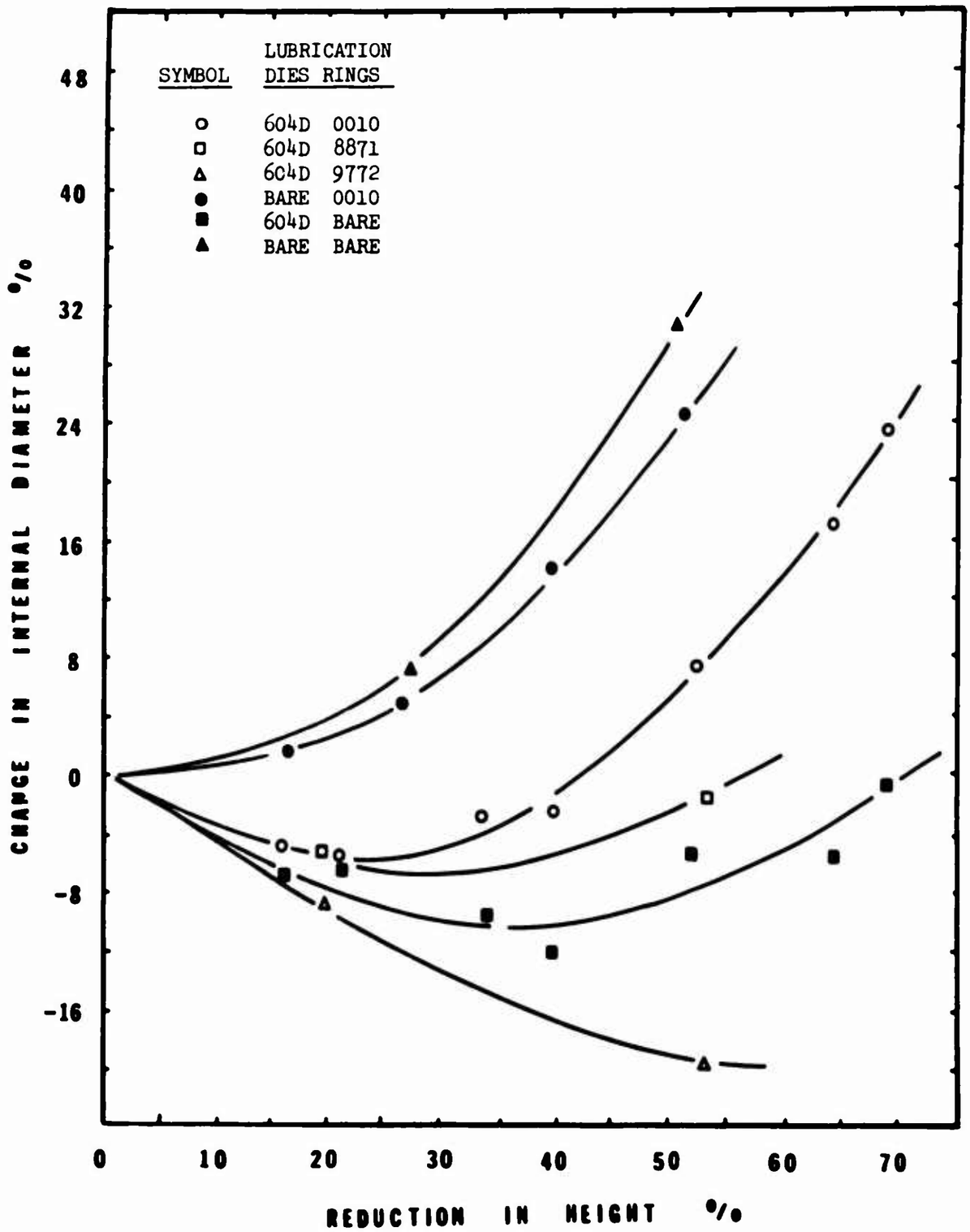

FIGURE 2. Change in the internal diameter of the maraging steel rings with reduction in thickness as a function of the lubrication system for the 1500°F forging of maraging steel rings. Data are based on a corrected value of the internal diameter.

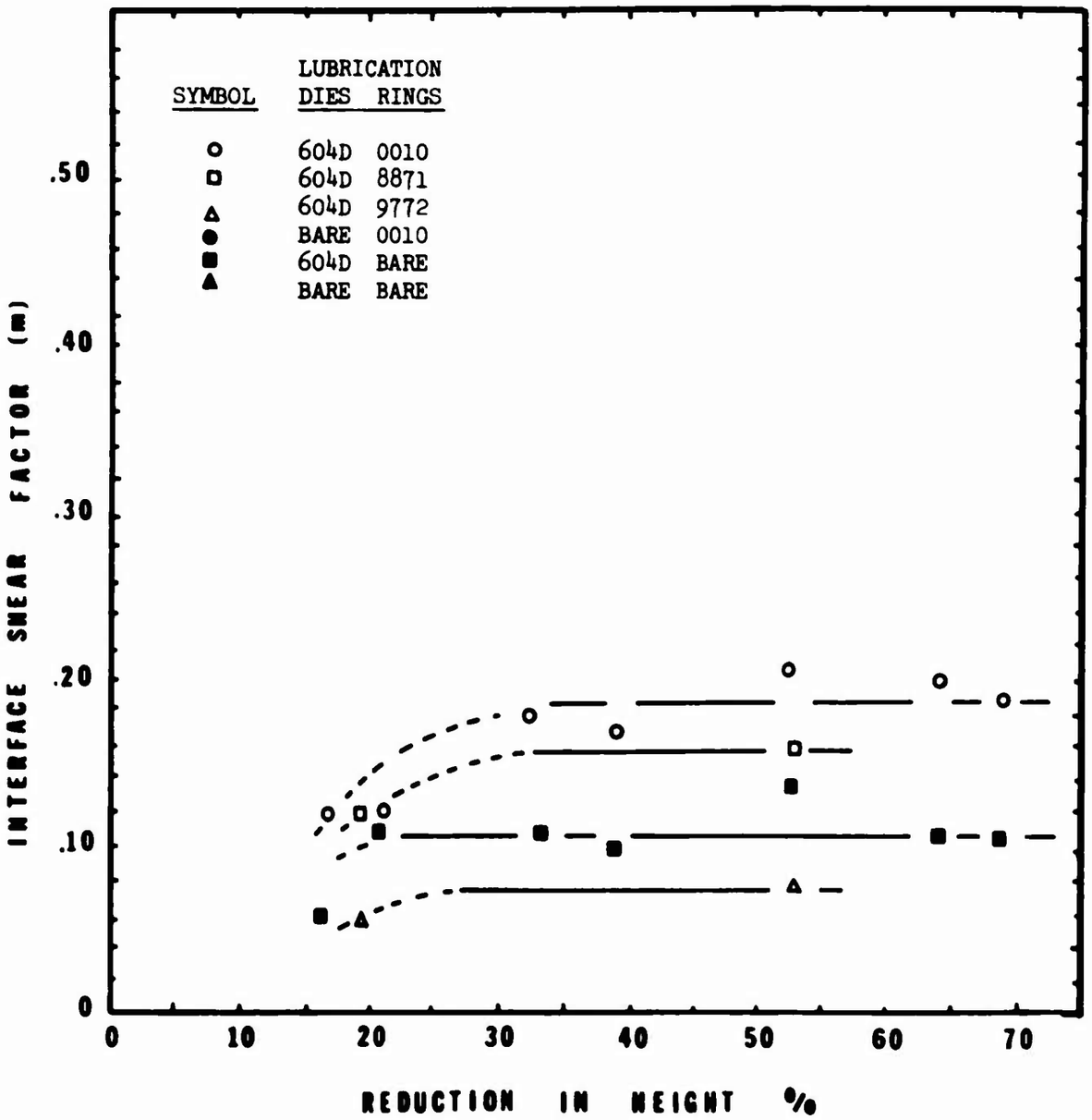

FIGURE 3. Variation of the interface factor with reduction in thickness as a function of the lubrication system for the 1500°F forging of maraging steel rings. Data are based on the corrected value of the internal diameter.

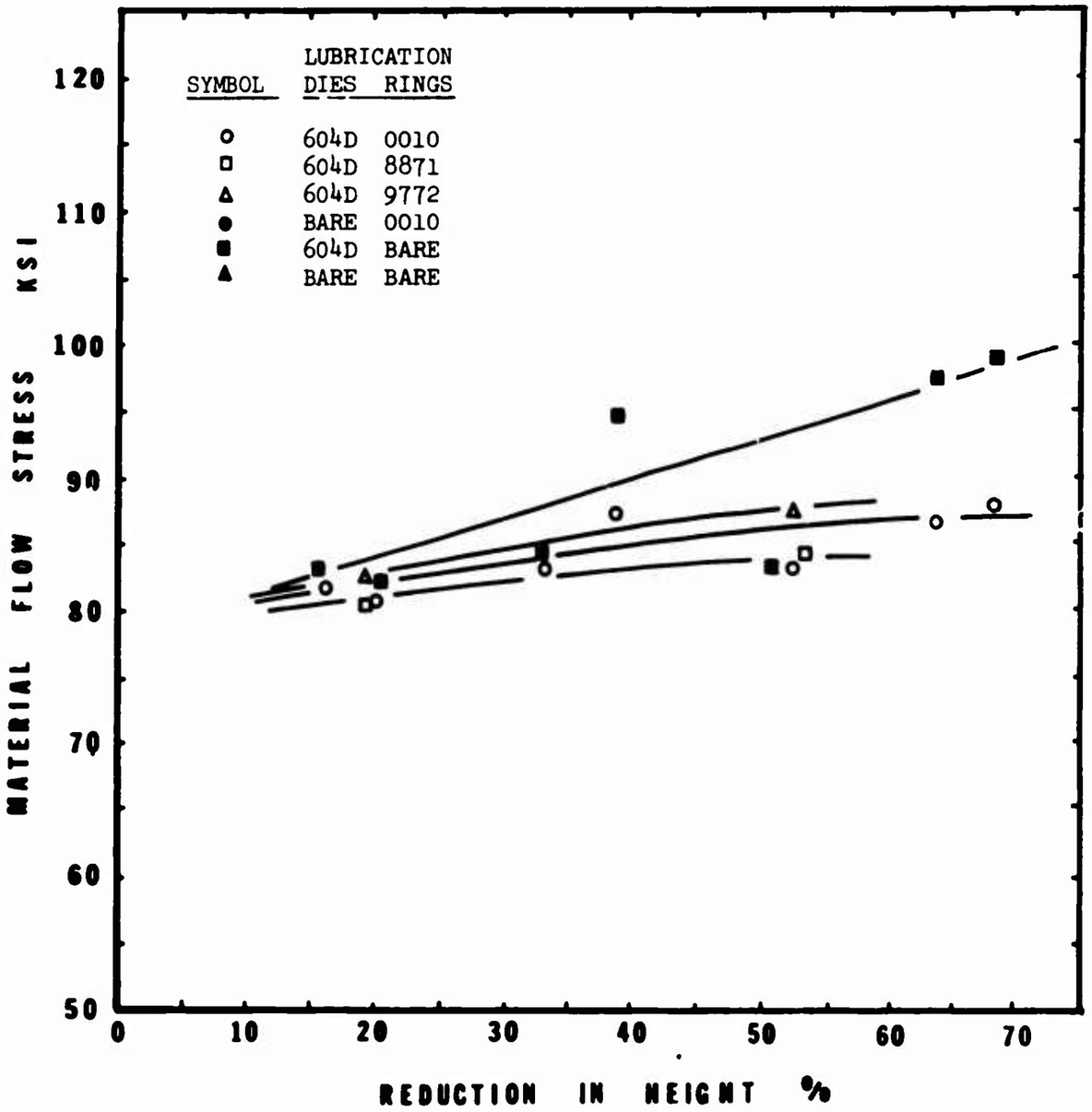

FIGURE 4. Variation of the effective value of the material flow stress with reduction in thickness as a function of the lubrication system for the 1500°F forging of maraging steel rings. Data are based on the corrected value of the internal diameter and the measured value of contact area.

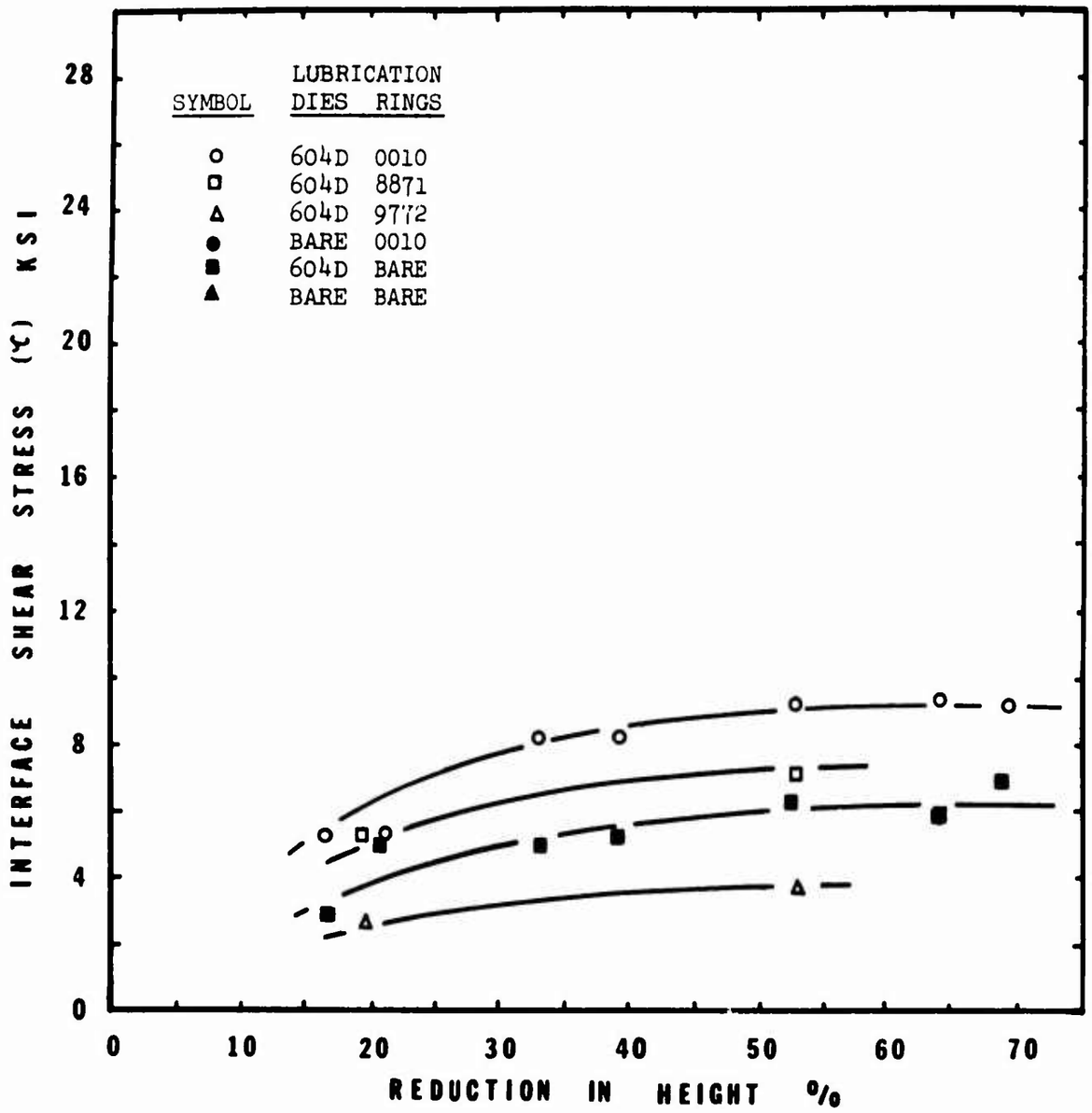

FIGURE 5. Variation of the interface shear stress with reduction in thickness as a function of the lubrication system for the 1500°F forging of maraging steel rings. Data are based on the corrected value of the internal diameter.

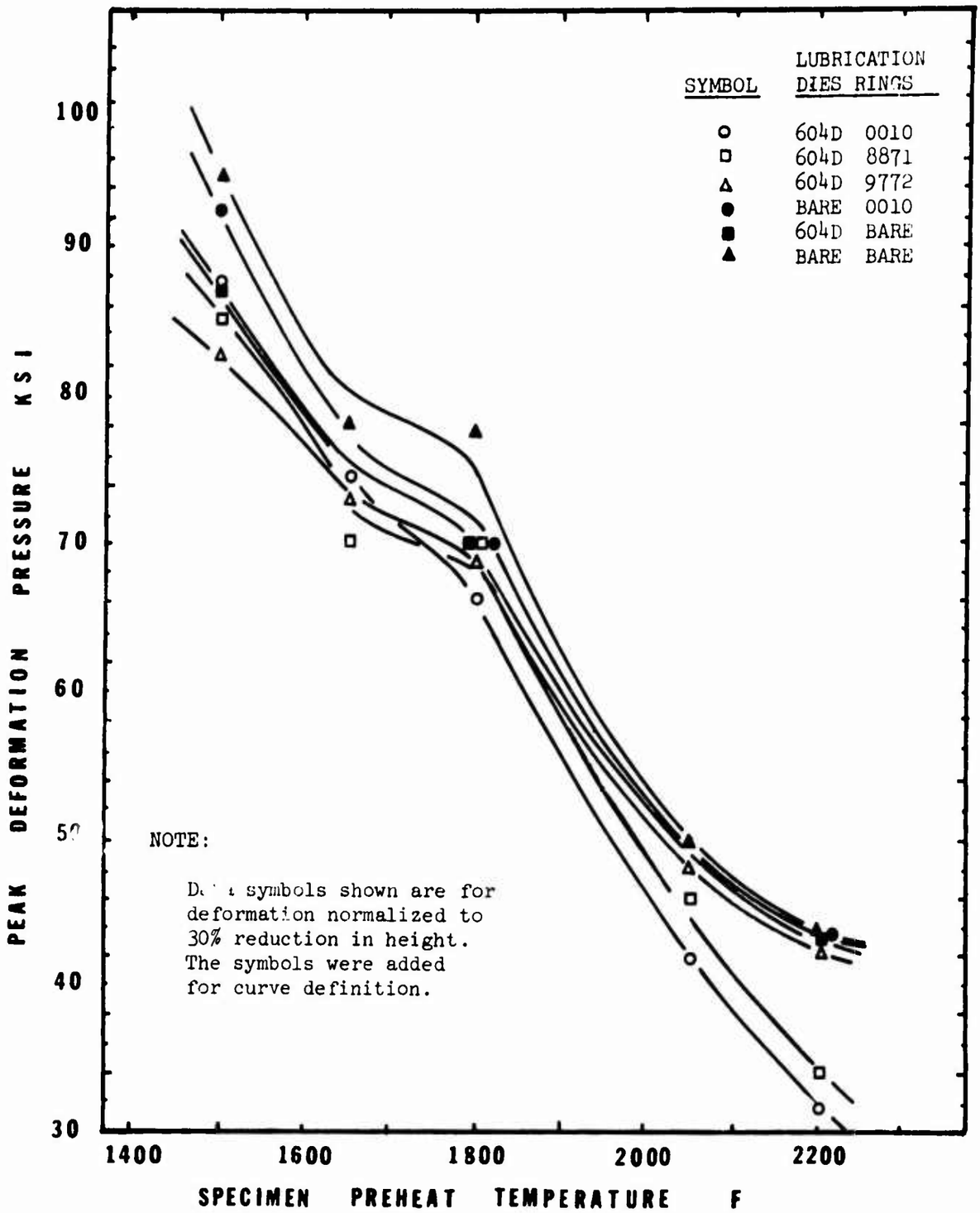

FIGURE 6. Variation of the peak deformation pressure with forging temperature as a function of the lubrication system for the forging of maraging steel rings to 30% reduction in height. Data are based on the measured value of the contact area.

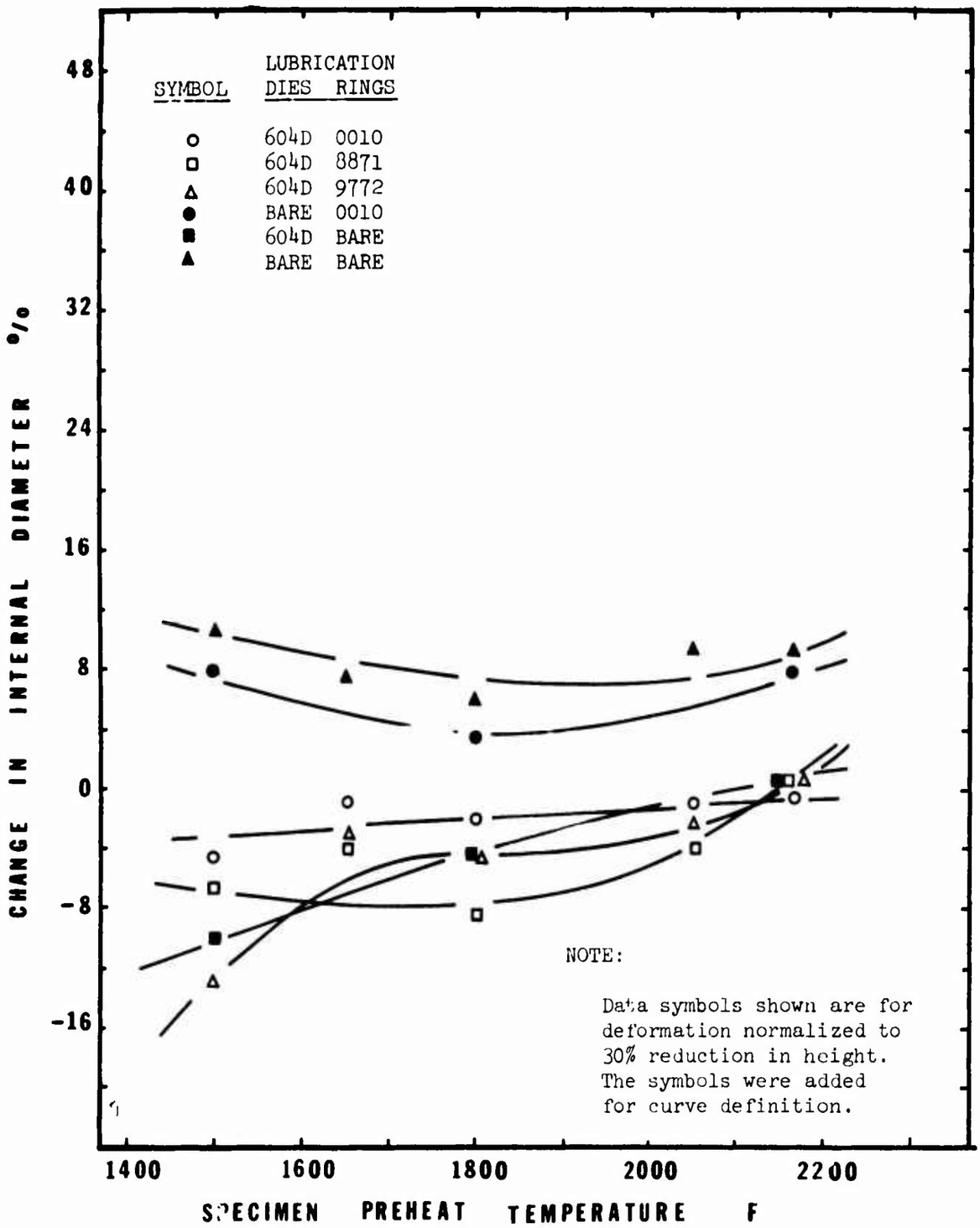

FIGURE 7. Change in the internal diameter of maraging steel rings with forging temperature as a function of the lubrication system for the forging of maraging steel rings to 30% reduction in height. Data are based on the corrected value of the internal diameter.

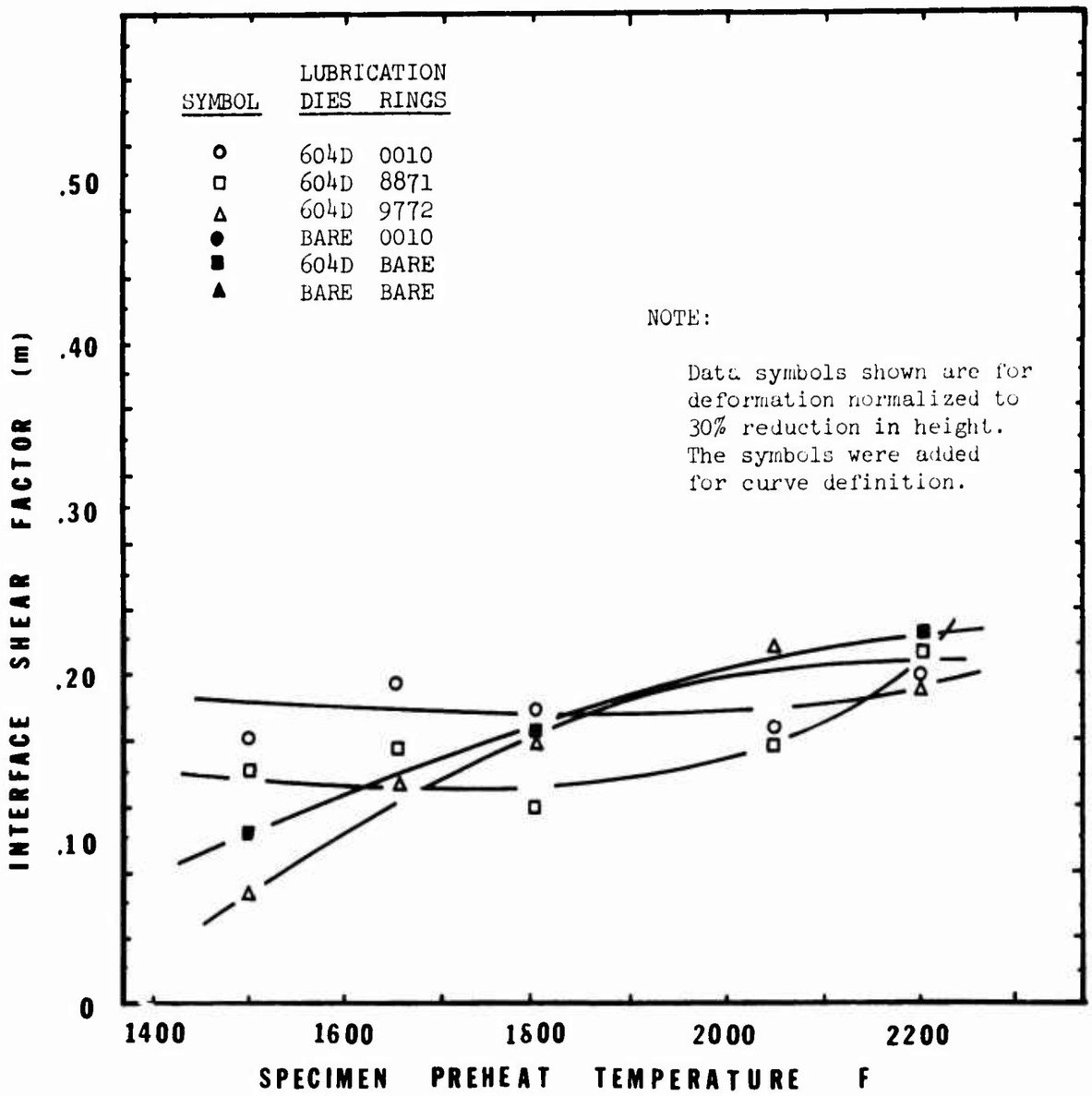

FIGURE 8. Variation of the interface factor with forging temperature as a function of the lubrication system for the forging of maraging steel rings to 30% reduction in height. Data are based on the corrected value of the internal diameter.

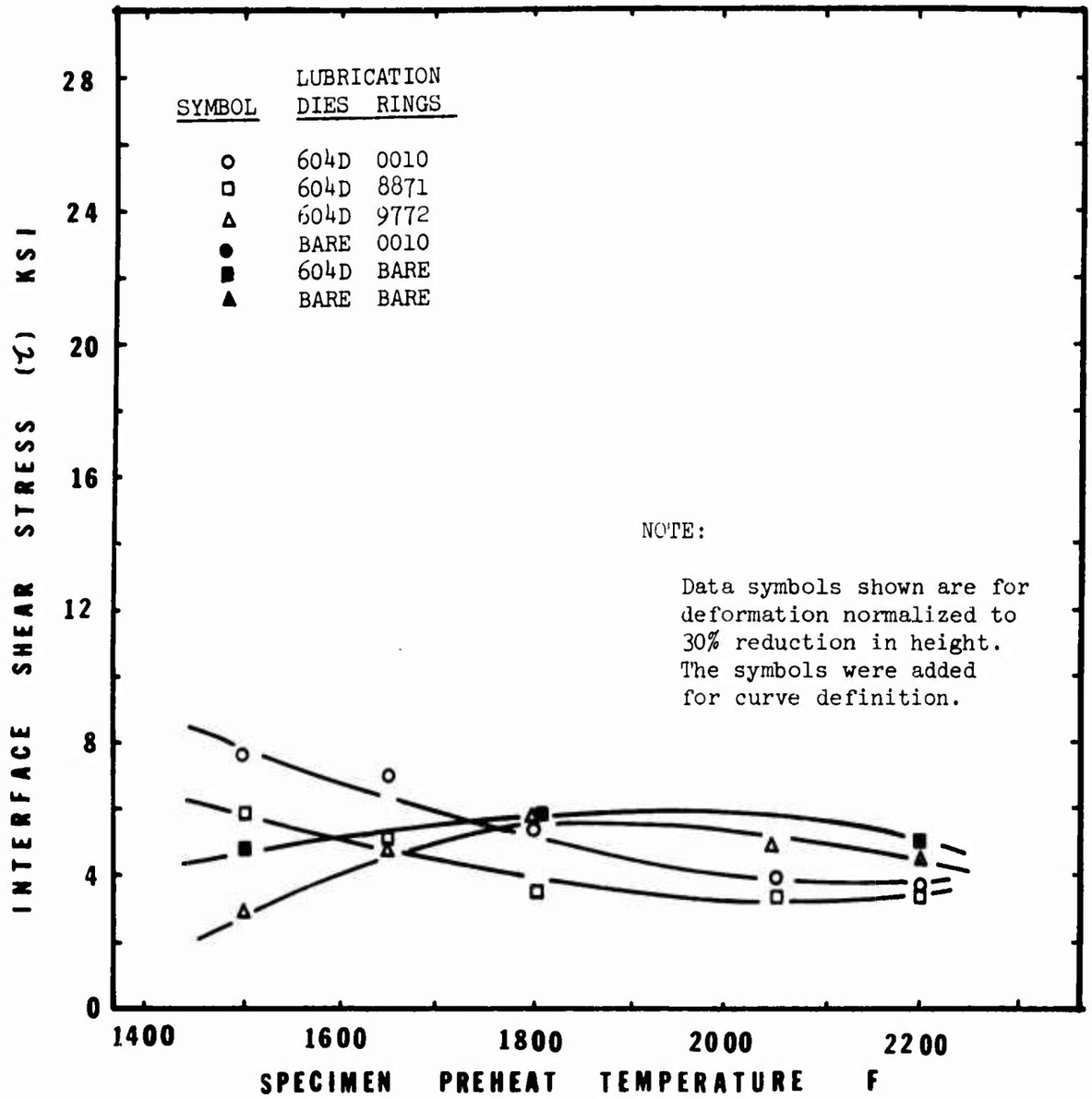

FIGURE 9. Variation of the interface shear stress with forging temperature as a function of the lubrication system for the forging of maraging steel rings to 30% reduction in height. Data are based on the corrected value of the internal diameter.

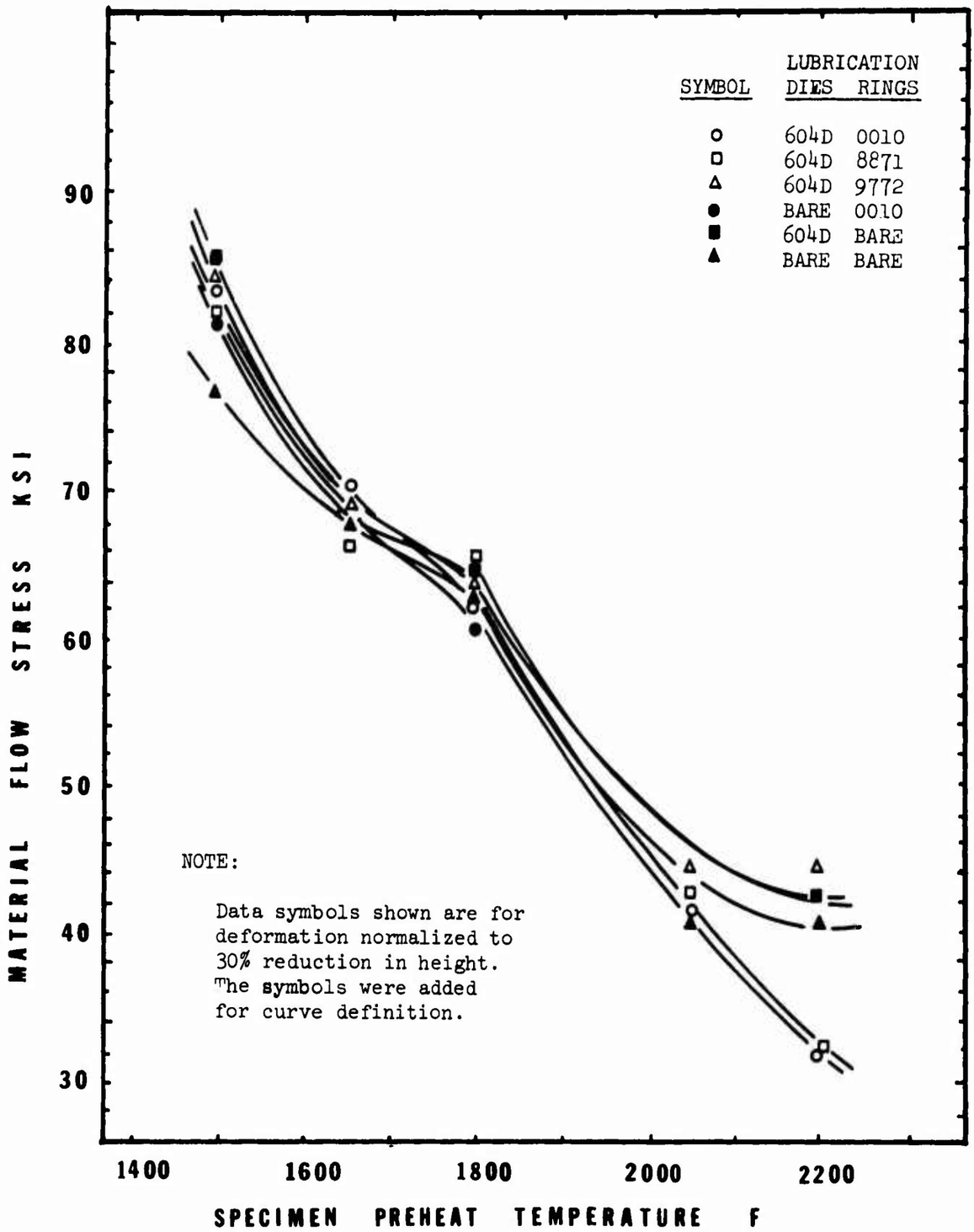

FIGURE 10. Variation of the effective value of the material flow stress with forging temperature as a function of the lubrication system for the forging of maraging steel rings to 30% reduction in height. Data are based on the corrected value of the internal diameter and measured value of contact area.

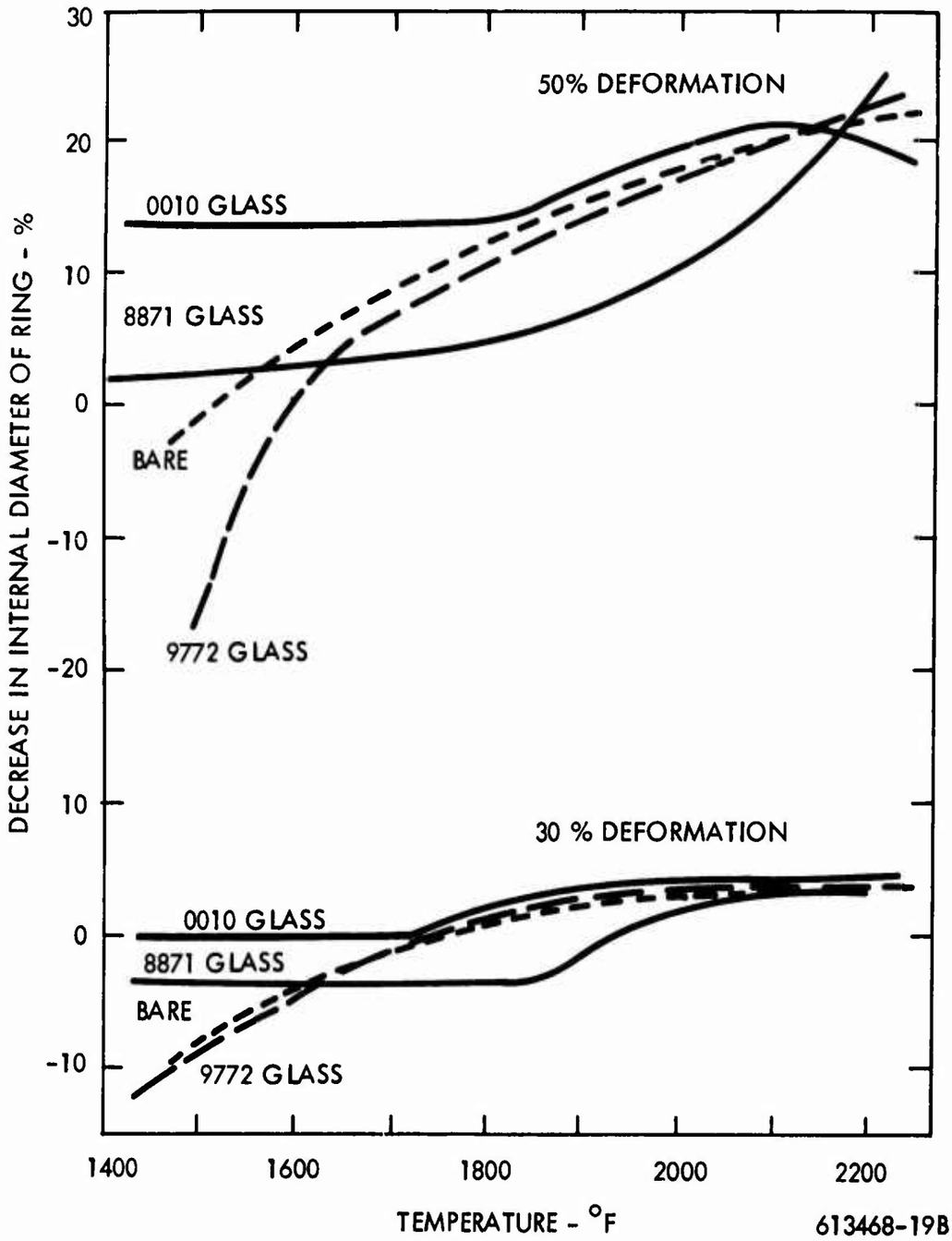

FIGURE 11. Change in the internal diameter at the bulged surface with forging temperature as a function of the lubrication system for the forging of maraging steel rings to 30% and 50% reduction in height.

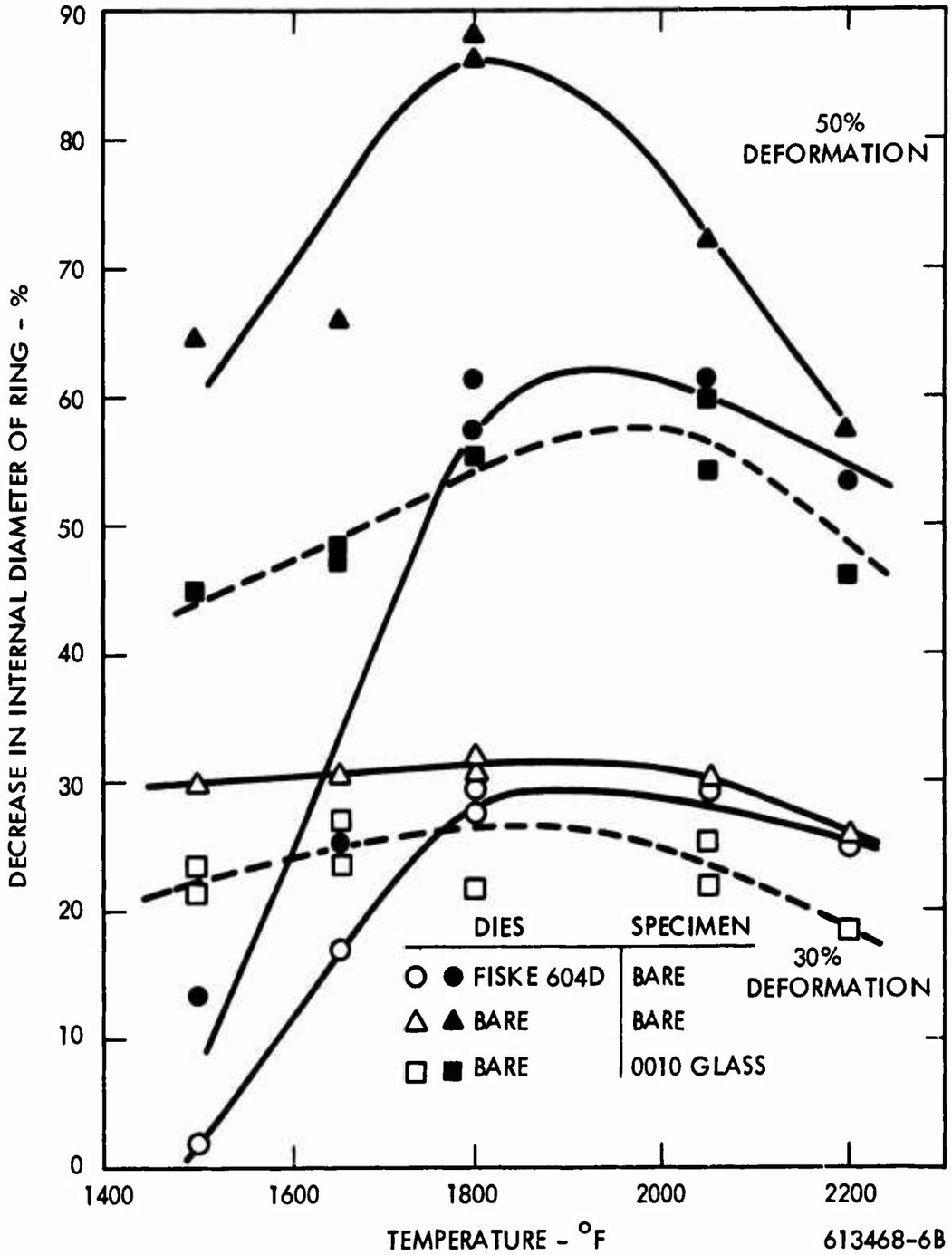

FIGURE 12. Change in the internal diameter at the bulged surface with forging temperature as a function of the lubrication system for the forging of Ti-6Al-4V rings to 30% and 50% reduction in height.

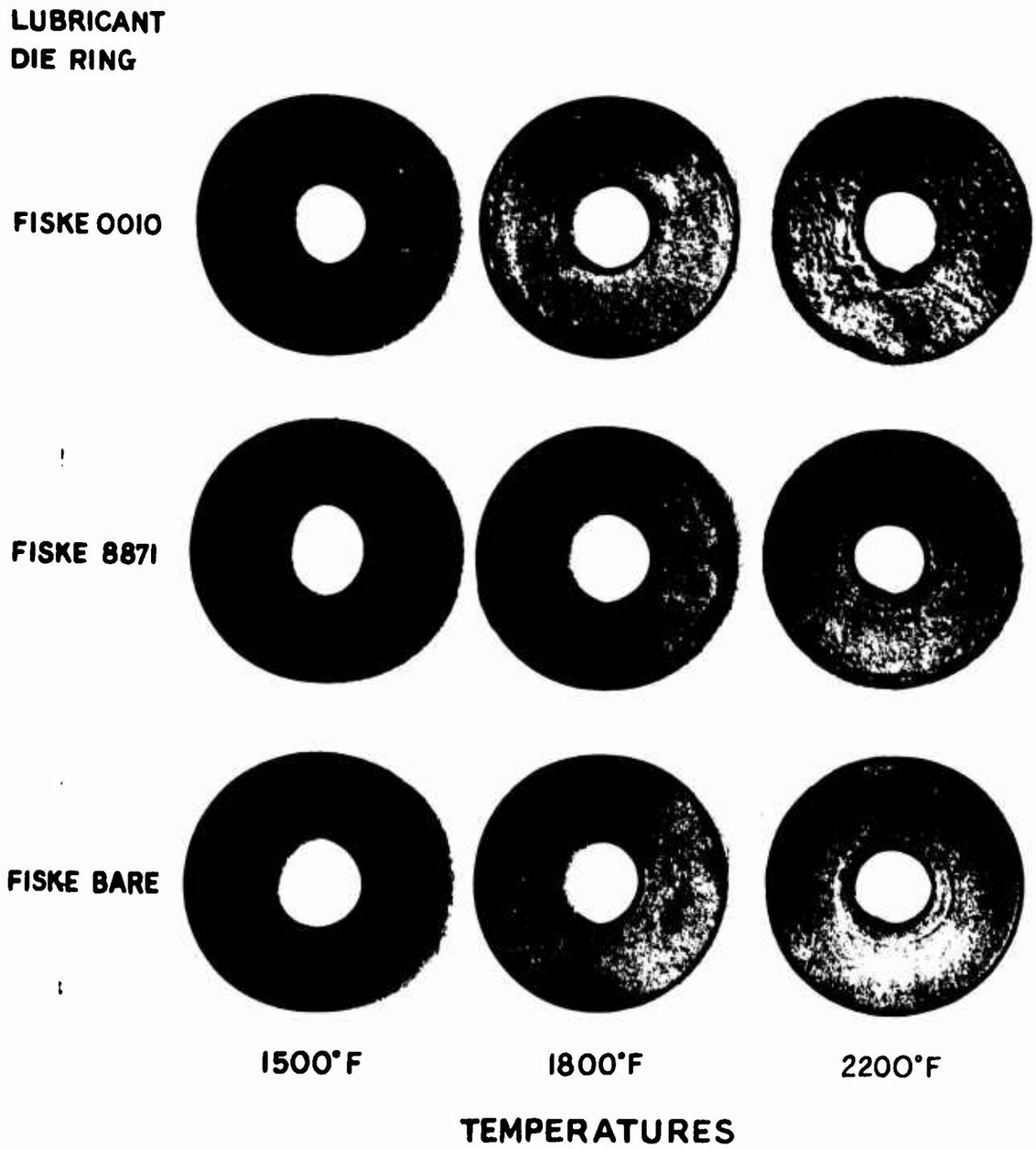

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FIGURE 13. Influence of various specimen and die lubricants on the surface quality of maraging st-el rings forged at various temperatures to 50 percent reduction in height.

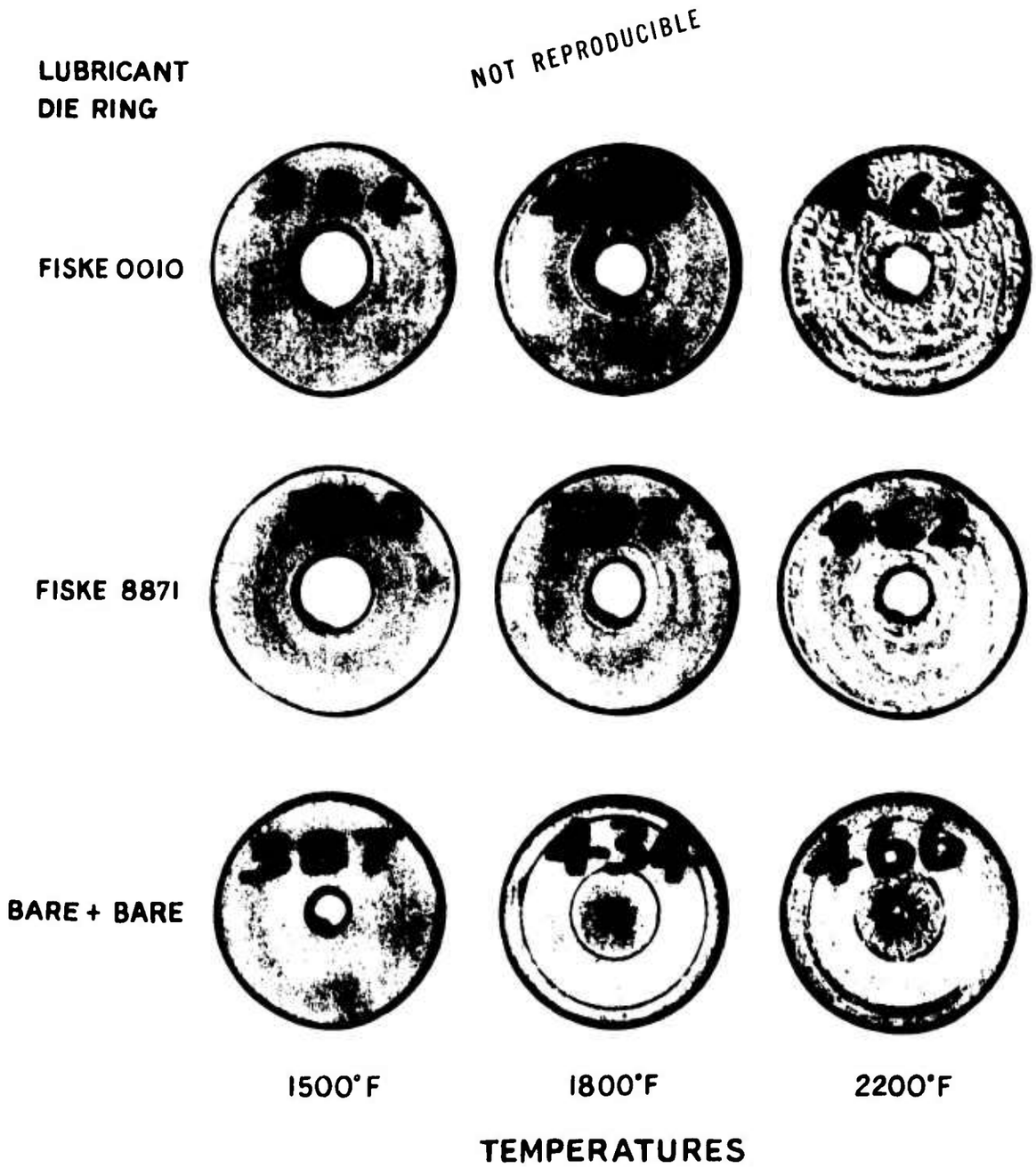

FIGURE 14. Influence of various specimen and die lubricants on the surface quality of Ti-6Al-4V rings forged at various temperatures to 50 percent reduction in height.