AD 296 164

AEON LABORATORIES · Beech Hill · Ridgemead Road
Englefield Green · Egham · Surrey · England

Report No. DA-91-591-EUC-1709-01-7480-61

Date.

THE DEFORMATION OF SECTIONS DURING CUTTING.

REPORT FOR PERIOD UP TO 31st OCTOBER, 1962.

AEON LABORATORIES

Beech Hill
Ridgemead Road,
Englefield Green,
EGHAM, SURREY.

FINAL TECHNICAL REPORT.

31st December, 1962

THE DEFORMATION OF SECTIONS DURING CUTTING.

Contract No: DA-91-591-EUC-1709
OI-7480-61.

Report for Period - up to 31st October, 1962.

The research reported in this document has been made possible through the support and sponsorship of the U.S. Department of Army, through its European Research Office.

THE DEFORMATION OF SECTIONS DURING CUTTING.

INTRODUCTION.

The parameters of the cutting process and techniques for sectioning hard materials have previously been described. (Phillips, 1961, Glauert and Phillips, 1961). In these papers the main features of the microtomed sections of ductile metals as revealed in electron microscope transmission and replica studies have also been described and classified as being due to either defects of the cutting machine or to the stress system which exists in the section during cutting.

In the present paper it is proposed to describe the effects of the cutting stresses on a wide range of materials, and explore the sectioning of ductile face-centred-cubic metals more fully. As a common basis to both aspects of the paper, the results derived from the theories of orthogonal cutting are first reviewed.

THE THEORY OF CUTTING THIN SECTIONS OF AN ISOTROPIC PLASTIC MEDIUM.

Standard 'stopped-cut' experiments on the orthogonal cutting of metal show that the boundary between the section or chip and the bulk material is a shear plane extending from the cutting edge to the free surface (Figure 1). Using the definitions made previously and illustrated in figure 1, (Phillips, 1961) and making the further definitions that: -

(1) $\alpha + \beta = 90 - \gamma = \Theta$

(2) the angle between the shear and cutting planes is ϕ

and (3) the thickness of the cut and the section are t_1 and t_2 respectively.

the situation is described geometrically by equations (1) and (2). (Merchant, 1945, Merchant, 1950 and Shaw, 1950).

$$\tan \phi = \frac{t_1 \cos \gamma}{t_2 - t_1 \sin \gamma} \qquad (1)$$

$$\varepsilon = \frac{\sin \Theta}{\sin(\Theta + \phi) \quad \sin \phi} \qquad (2)$$

where ε is the strain in the section.

Equations (1) and (2) do not determine the values of the other parameters for given values of Θ and t_1. In order to obtain unique relations, it is necessary to apply the principle of least work (Merchant 1950).

Very thin ($<$ 1 micron) metal specimens have a yield strength approaching the theoretical value of $\frac{\mu}{2\pi}$ (Beams et al 1955) and where μ is the shear modulus and it seems reasonable therefore to expect the stress operating on the plane of maximum shear stress to approximate to this and to be approximately constant throughout the shear strain. Thus, in frictionless cutting the work done is a minimum where ε is a minimum which gives: -

$$\frac{\Theta}{2} + \phi = \frac{\pi}{2} \quad \text{and} \quad \frac{t_1}{t_2} = 1 \qquad (3)$$

also

$$\varepsilon = \frac{2(1-\sin \gamma)}{\cos \gamma} = \frac{2 \sin \Theta}{\cos \Theta + 1} \qquad (4)$$

Thus, although the material in the section has suffered shear deformation, the dimensions of the section are the same as those of the same material before cutting, a result which will be more fully investigated below. Other aspects of this analysis of frictionless cutting may be expressed as:-

(1) The shear plane bisects the angle between the rake face and the cutting plane.

(2) The greater θ, the greater the shear strain.

Figure 2 illustrates the nature of the deformation of an isotropic plastic medium by a method first used by Merchant (1945). Circles in the unstrained specimen are distorted into ellipses by the shear strain associated with cutting, and the direction of maximum elongation in the section is at an angle to the plane of maximum shear stress. The exact details of the transformation of a circle into an ellipse during frictionless cutting are shown in figure 3. Figure 3 illustrates graphically the results enumerated below, which can also be proved by co-ordinate geometry.

(1) The thickness of the section (t_2) is equal to the depth of cut (t_1).

(2) The distance between ellipse centres is a circle diameter, so that the length of the section is equal to the length of the same piece of material before it was cut. This result also follows from 1.

(3) Structures much larger than the section thickness will have virtually undistorted dimensions in the plane of the section.

(4) Structures of the same order of linear dimension

as the section thickness or less will have an increased dimension projected on to the plane of the section in the direction of cutting.

Application of co-ordinate geometry to figure 3 leads to the general relation

$$\varepsilon = 2 \cot 2\psi \qquad (5)$$

which combined with equation (4) leads to the solution:

$$\psi = \frac{\pi}{4} - \frac{\theta}{4} = \frac{\pi}{8} + \frac{\gamma}{4} \qquad (6)$$

Thus, for frictionless cutting, the direction of maximum elongation bisects the angle between the plane of maximum shear stress and the rake face of the knife.

If friction is now taken into account, and the coefficient of friction between the section and the rake face of the knife is taken as μ, so that: -

$$\mu = \tan^{-1}\tau$$

The work done against both shear and frictional forces must be minimised and Merchant (1945) has shown that:-

$$\phi = \frac{\pi}{2} - \frac{\tau}{2} - \frac{\theta}{2} \qquad (7)$$

That is, the effect of increasing friction is to make the plane of maximum shear stress more nearly parallel to the plane of cutting. Substitution of (7) in (2) gives:-

$$\varepsilon = \frac{2 \sin \theta}{\cos \tau + \cos \theta}$$

Therefore, the greater τ the greater the strain. This causes circles to be distorted into ellipses with a greater $\frac{a}{b}$ ratio than in the frictionless case, and with the direction of maximum elongation less steeply inclined to the direction of cutting.

In the presence of friction an isotropic plastic medium cut with a sharp edge will yield sections which are shorter in the direction of cutting, and thicker than the same piece of material before cutting. Then structures which are large compared with the thickness of the section will be shorter in the direction of cutting in the section, than they were originally. The projected dimension of structures whose size is less than the depth of cut will depend on the exact value of ϕ. While ϕ is greater than $(\frac{\pi}{2} - \theta)$, the projected dimension in the direction of cutting will appear enlarged on viewing the section normally. When ϕ is less than $(\frac{\pi}{2} - \theta)$ this dimension will appear decreased.

The foregoing account has related the shear strain to various cutting parameters and indicates the influence of this strain on the dimensions of structural features in section. It is now proposed to consider forces acting during cutting in some detail and to speculate the mechanism of separation of the section from the bulk.

The forces acting during cutting are discussed with the aid of figure 4. The knife exerts a force W on the section which consists of a normal component N and a tangential component, which is due to friction, T Following Gideon, Simon and Glover (1958), it is supposed that stresses between the section and the bulk can be represented by the shear stress system S, the compression B and the tensile stresses A. For simplicity the forces acting upon the shear plane are considered as A and B only acting at the extreme ends of the plane. Let W make an angle ϵ with the cutting direction and let $\phi + \epsilon = \delta$.

Resolving parallel to the shear plane

$$W \cos\delta = S$$

Resolving normal to the shear plane

$$B - A = W \sin\delta$$

Taking moments about the knife tip and considering W to be applied at a distance x from the tip

$$W x \cos(\gamma + \epsilon) = Bt$$

Taking moments about the other end of the shear plane

$$W(t \sin\delta - x \cos(\gamma+\epsilon)) = -At.$$

If $x \cos(\gamma+\epsilon)$ is greater than $t \sin\delta$.

$B > W \sin\delta$ and A is positive and constitutes a tensile stress as assumed. The stress system acting normal to the shear plane may be described more realistically as a tensile stress at the knife tip end which decreases as one progresses along the shear plane until it has zero magnitude; further along the stress is compressive and increases in magnitude as the free surface is approached. The point at which the normal stresses have zero magnitude depends on the exact magnitude of x and as $x \cos(\gamma+\epsilon)$ decreases and tends to $t \sin\delta$ the point approaches the knife tip end of the shear plane.

When $x \cos(\gamma+\epsilon) = t \sin \delta$, A is zero and the normal stresses are all compressive decreasing from W sin δ at the free surface to zero at the knife tip.

When $0 < x\cos(\gamma+\epsilon) < t \sin \delta$, A is negative and the normal stresses are compressive and of finite magnitude all along the shear plane. The variation in the magnitude of the compressive stress depends on the exact value of $x \cos(\gamma+\epsilon)$, thus when $x\cos(\gamma+\epsilon) = t \sin \delta$, A is zero and B is W sin δ but when $x = 0$, $A = -W \sin \delta$ and $B = 0$.

The effective point of application of W in practice is not easy to deduce. Presumably if the knife were infinitely sharp x would be very small and the normal stresses would be all compressive being of the greatest magnitude near the knife tip. Bluntness may be expected to increase the effective value of x and to lead to enhanced compressive stresses at the free surface end of the shear plane. Deformation under compressive force B may be the origin of cutting of metal sections to develop a concave upper surface.

Some of the materials used as embedding media in thin sectioning may be considered as isotropic media which, unlike metals, are capable of sustaining a permanent compressive strain. In this type of medium the effect of the compression stresses just described may be to superimpose a compressive strain on the shear which has already been treated in detail. Then all features in the section will tend to be shortened regardless of size. The magnitude of compressive strain to be expected is difficult to estimate especially as the compressive stress will be relieved as strain occurs under the shear stress.

The mechanism by which the section is separated from the bulk is virtually unconsidered in metal cutting literature. If a crack were nucleated ahead of the knife edge it would be expected to be virtually self propogating and to run out at the free surface; this would lead to a discontinuous section as is observed with brittle material. Discontinuous sections are not obtained from ductile metals and other plastic media and the nucleation of a crack in such material is very difficult. It is therefore necessary to explore whether separation can occur purely by plastic flow.

Figure 5 illustrates schematically how by simple alternate shear on planes about 45^{o} above and below the cutting plane, a section is separated from the bulk in such a way as to give a stepped upper and plane lower surface to the section. The earlier representations of section formation (e.g. Merchant, 1950) implicitly assumed the separation of the section from the bulk to be by a succession of short cleavages along the plane of cutting. Apart from the objection that such cracks, once initiated would tend to propogate through to the surface, the earlier mechanism predicts that the lower and upper surfaces of the section will be stepped whereas it is observed experimentally that only the upper surface is stepped (Phillips, 1961).

This should not, however, receive undue weight since figure 5 is only schematic and is inaccurate in many details. One would in fact expect the shear steps to tend to be very close together and the upper surface of the section and the cut surface on the specimen to tend to be smooth. Representing the shear process in discrete large elements does however allow the proposed nature of the separation of the section from the bulk to be emphasised, i.e. that the separation can be conceived in terms of atomic planes shearing over one another rather than being separated by a tensile strain.

It should perhaps be noted that in the mechanism depicted in figure 5 the dislocations produced in successive increments of shear in the bulk would tend to cancel each other and this could cause the cut surface to rise to a position such that the volume of the system is the same before and after the operation. In a practical case more complex dislocations, (i.e. mixed rather than simple edge), will be produced and they will interact with pre-existing defects so that a certain amount of damage will be stored immediately under the cut surface.

Replacing the sharp cutting edge of figure 5 with a blunt edge does not necessitate modification of the basic mechanism provided the radius of curvature of the cutting edge is small compared with the section thickness. The shear in the section is determined by the included angle of the planes which merge into the blunt edge. In practice there will probably be more stored damage below the cut surface when the cutting edge is blunt and this will affect the structure of the next section cut.

Local edge defects are most accurately regarded as decreases in the rake and in some cases clearance angles. The strain in the section is locally increased along the same path which in turn may locally modify the structure in the next section.

THE CUTTING OF MEDIA WHICH EXHIBIT TRULY ELASTIC PROPERTIES AND A DISCUSSION OF SECTIONING BIOLOGICAL EMBEDDING MEDIA.

Figure 6 illustrates the distortion which would be obtained in a truly elastic medium during cutting, and may be derived with a photo-elastic or rubber model. In the absence of friction the section recovers its natural undistorted shape except where it is being parted from the bulk. There the material is under a combined compressive and shear stress.

Friction between the section and the rake face of the knife produces further compressive strain near the knife tip and this will diminish as the loading between the section and the knife decreases with distance from the knife edge. A further effect of friction may be a local rise in temperature which may cause a material which is elastic in behaviour at room temperature (even at large strains) to behave as a plastic material during cutting.

Most discussions of the sectioning of biological specimens are based on the assumption that the embedding media behave elastically during cutting. This assumption has already been questioned (Phillips, R., 1962) and an alternative proposal made which is compatible with the experimental evidence currently available. Most biological thin sections are very much shorter after cutting; application of solvent vapour or a tensile force (through floating the section on a convex liquid surface) or a combination of these treatments increases the length of the section but does not in general restore it to its original value. This is usually discussed in terms of compressive plastic strain, but on any model of cutting it is clear that shear stresses are important and shear strain is to be expected. Investigation of the mechanical behaviour of methacrylate under stress shows that after high strain it recovers its original dimensions but the rate of recovery is very slow. Thus in cutting the embedding medium would be expected to behave as a plastically deforming material so that the shear stresses and strains will be of overwhelming importance. However, in the absence of any further factors in the cutting process, the section would be expected to recover to its original size after sufficient time floating freely on the trough liquid. In fact the section is usually observed to be 'wrinkled' and short and to remain in this condition until treated with solvent. The wrinkling has been explained (Glauert and Phillips, 1961) as due to local variations in the rake angle so that some strips of the section are more strained than others. It is suggested that the local temperature rise during cutting is sufficient to render the mechanical behaviour of the material truly plastic during cutting so that the deformed state is 'quenched in' upon subsequent contact with the cutting fluid. Under these conditions the overall length of the section must be that of the shortest (i.e. most deformed) strip, the excess length of the other strips being accommodated by curving into wrinkles. The treatment with solvent is considered to sufficiently soften the medium to allow the strips to adjust to some 'average' length or the length of the least deformed strip.

The true behaviour of biological sections may be intermediate between the 'elastic' and plastic models and the temperature rise may only be of sufficient height or duration for part of the strain to be permanently stored; it is clear that the processes in biological sectioning are complex and that much quantitative work will be necessary in order to ascertain exactly what they are.

It has been shown (Williams and Kallman, 1956, Morgan et al., 1955) that methacrylate sections have a surface structure, and the author has suggested (Phillips, 1962) that this is associated with the permanent deformation as in metals, (Phillips, 1961).

It is also possible that the surface layers of sections are more severely deformed than the rest of the section (the upper surface through having been rubbed on the previous cut and the lower surface through contact with the rake face of the knife), This local disruption may cause loss of contrast in the surface layers and could partially account for the difficulty which has been experienced in observing continuity of detail in serial sections. It follows from this suggestion that the region from which an image is obtained is thinner than the section itself and this would tend to invalidate methods of specimen preparation which rely on special features for indicating the section thickness. Such methods may also be suspect in that if a section thickness the dimension of the feature used for indicating section thickness also increases in the direction of the thickness of the section. This effect may be compensated, however, by application of the factor,

$$\frac{\text{length of section}}{\text{original length}}$$

THE SECTIONING OF BRITTLE MEDIA.

In brittle materials with well defined slip planes it might be expected that the microtome knife could be caused to nucleate cleavage cracks parallel to the plane of cutting in correctly oriented specimens, thus producing large thin areas of undeformed material. Attempts to achieve this result by cutting parallel to the (111) planes of UO_2 have failed and have yielded mainly sections of the type shown in figure 7. When each fragment has a smooth appearance and exhibits extinction contours the orientation of the section is (111) so that the dominant process in forming the section is fracture parallel to the direction of cutting.

Thus, many sections of brittle materials appear to be formed by a separation of material on a plane near to the cutting plane together with periodic fractures on a surface near to the plane of maximum shear stress. Figure 8 shows the fracture normal to the direction of cutting which results from the sectioning of coke. It would be expected therefore, that the exact form of the fragments constituting a section from a brittle crystalline material will depend on the exact orientation of material during cutting. This is borne out by figure 9 which contains areas with different structures corresponding to the different grains in the polycrystalline UO_2 from which the section was cut. Qualitatively, it is clear that preorienting the cutting plane near to a cleavage plane increases the spacing between fractures, but it is difficult to account quantitatively for the actual magnitudes of the spacing which occurs.

It is not clear how the fine furrowed areas were formed, but electron diffraction shows them to be of (110) orientation and that together with the surface topography suggests that they underwent a deformation closely analogous to that experienced by f.c.c. metals during sectioning.

THE SECTIONING OF DUCTILE METALS.

The stress which will exist during the cutting of ductile, f.c.c. metals will approximate to that described in the discussion of isotropic plastic media i.e. a large shear stress which is a minimum on a plane through the knife edge at an angle ϕ to the cutting direction, together with compressive stresses acting across the shear plane. The relation between ϕ, the coefficient of friction ($\tan\psi$) and the rake angle ($90-\theta$) is given by equation 7. Merchant (1945) has shown that the fresh surface in contact with a well rubbed rake face produces a very high coefficient of friction so that a reasonable value to assume for ψ is about 40 to 50°. θ is typically 60° for an ultramicrotome and the shear plane may therefore be expected to be approximately normal to the rake face of the knife.

The strain involved in cutting is given by equation 4 and is 1.7 for the conditions just described. It should be noted that plastic deformation is assumed in the derivation of equation 4 and that strictly the equivalent formula derived from the conditions represented in figure 6 should be used in the following argument.

A comparison of figures 6 and 4, however, indicates qualitatively that the use of equation 4 is justified. Thus in the absence of the parting of the section from the bulk by cleavage a strain of about 1.7 is required whereas the theoretical elastic limit in the ideal case is about 0.5 (Cottrell, 1953). Cleavage is not obtained in f.c.c. metals at room temperature and above, therefore plastic flow must be expected during the sectioning of this class of material.

The strains involved in cutting are much larger than are normally studied and are occurring in very thin pieces of metal which are known to have different mechanical properties from bulk material (Beams et al., 1955) It is therefore difficult to predict precisely the mechanism of deformation during cutting. Clearly, however, the exact mechanism must be orientation dependent and if the orientation is suitable, slip on a simple conventional system may be the mechanism by which the deformation is achieved. It is pertinent to enquire if the slip will be homogeneous or in discrete steps and how the systems will interact when the orientation is such that more than one system is required to produce the strain. Phillips (1961) has shown that many metal sections exhibit a fine structure approximately normal to the direction of cutting, figure 10. It was shown that the structure is associated directly with, or corresponds to the topography of the top surface of the section and it was suggested that this topography is the slip line structure produced during cutting. It should, perhaps, be emphasised that the lines are the product of the section formation: they are not due to instrumental vibration, for example, for the following reasons:-

1) the exact form is orientation dependent.
2) they are not exactly normal to the direction of cutting..
3) they are not continuous across the section.
4) they are only on the upper surface of the section and not on the lower surface formed on the bulk specimen.

Many micrographs of sections of metal which do not show a fine line structure have been published. Similar observations on occasional sections in this work led to an experiment in which the sections were tilted about angles up to 30° about an axis normal to the direction of cutting in the plane of the section. During such tilting experiments a fine line structure was revealed in areas where none was previously visible. The contrast on the lines is, therefore, orientation dependent and it is, consequently, difficult to prove the absence of a surface structure on any particular type of section by transmission electron microscopy.

Two other pieces of evidence support the theory of the orientation dependence of the contrast on the fine line structure. Firstly, figure 11 shows regions on a section which exhibit the periodic contrast and which end sharply at grain boundaries. The section was cut from a single crystal of aluminium so that the cutting conditions were constant for the whole field of view. It is therefore difficult to understand why different surface structures should develop at different parts of the section and why the boundaries of areas of periodic contrast should correlate with the internal boundaries introduced as a result of the cutting process. It is more reasonable to assume that the surface structure is constant all over the area of the micrograph and that the contrast produced by the structure is orientation dependent, so that it varies from grain to grain changing sharply at the boundary between grains. Such a dependence of the contrast of a periodic surface structure has previously been found by Wilsdorf (1958) in the case of an electropolishing structure on thin foils of aluminium. Secondly, figure 12 shows the contrast in the fine line structure to depend on the proximity to a fold and the exact position in an undulation, i.e. on the orientation.

Some of the predictions of the theory and the interpretations of the characteristic features of sections which have been proposed, (Phillips, R, 1961, Phillips V.A., 1961), are capable of being checked by experiments on carefully oriented single crystals. Suitable apparatus (Phillips and Lucas, 1962 (a) and 1962 (b)) was therefore constructed and applied to the precise orientation of single crystals of a number of f.c.c. metals in the Leitz ultra microtome according to the theory outlined above.

A particularly simple orientation is that in which the (111) plane is parallel to the cutting edge and together with the $[\bar{1}01]$ direction. normal to the rake face of the knife, because the (111) $[\bar{1}01]$ slip system is then specially favoured to relieve the shear stress during cutting (Figure 13). For $\theta = 50^{\circ}$ the orientation of the plane of cutting to favour (111) $[\bar{1}01]$ slip is (210) $[1\bar{2}1]$ with the $[1\bar{2}1]$ direction parallel to the knife edge. According to the theory of section formation so far developed, this orientation of the plane of cutting should produce a section of ($\bar{1}01$) orientation with the [$1\bar{2}1$] direction normal to the direction of cutting. This orientation should also give the maximum likelihood of forming long straight lines in the parallel line structure, although other forms of structure are possible and straight lines could originate from other orientations.

In the remainder of the paper, the orientation of the specimen during cutting will be referred to by the Miller indices of the plane of cutting followed by the Miller indices of the direction of the cutting edge in that plane. The chosen direction is fundamentally more important than any other (in particular the direction of cutting) since when the section is formed by a simple shear process the direction of the knife edge is the common zone of the plane of cutting and the plane of the section. Thus the orientation just discussed will be referred to as (210) [$1\bar{2}1$].

STUDIES OF ALUMINIUM SECTIONS CUT FROM (210) [$1\bar{2}1$].

Transmission Electron Microscopic Studies.

Sections were cut from the (210) [$1\bar{2}1$] orientation on to a distilled water surface under standard conditions (Leitz Ultra microtome, at a cutting speed of 10 cm/sec. and heating current 1.5 amp., giving sections in the thickness range 1000 to 2000 Å) and collected on carbon support films on standard copper grids. These sections were examined in transmission in the normal specimen holder in the electron microscope. Through focal series of photographs were found to be helpful because some surface detail was enhanced in slightly out of focus photographs, figure 14: sections were also examined in the tilting specimen holder due to Washington and Fernhead, (Kelly and Reed, 1961).

The fine line structure was generally found to consist of mutually parallel lines normal to the direction of cutting and was sometimes accompanied by a finer fainter set of lines at an angle to the more prominent ones, figure 10. The lines were straight and continuous over considerably greater lengths (up to several microns and then only limited by knife marks) and much more accurately parallel than had been observed on randomly oriented specimens. As previously reported (Phillips, R, 1961), out of focus fringes appear on the lines indicating that they are associated with surface structure, figure 14. The fine line structure is modified by knife marks and its appearance is modified by internal boundaries. Experiments with the tilting holder showed that the contrast of the lines depended on the exact diffracting condition of the area under observation (as Wilsdorf (1958) found for striae due to electropolishing) thus the apparent change in structure at internal boundaries is probably a diffraction contrast effect. The modification to the structure due to knife marks would be expected if the lines are slip lines since knife marks imply greater local deformation during cutting and possibly deformation of the material along the knife mark during the previous cut.

The spacing of the main parallel line pattern is in the range 400 to 700 Å while the finer lines have a spacing of about 200 Å.

The specimens exhibit Bragg contours which are continuous through much of the fine line structure but which end or are displaced on other lines which in some cases are coincident with one of the fine lines. This shows that the lines in the fine parallel structure do not in general correspond to internal boundaries but that the other lines are sub-grain and grain boundaries, figure 15. The original specimen was a single crystal but the section obtained from it contains grain boundaries, therefore the section appears to have recrystallised.

Although the fine line surface structure is very frequently observed, it may not be absolutely essential to the cutting process in ductile metals. For example, figure 16 shows a very thin section of aluminium apparently of great structural and surface perfection. Undoubtedly, however, this section has undergone severe, but apparently homogenous, local strain and recrystallisation since high-angle boundaries are present although the section was cut from a single crystal.

Replica Studies.

Platinum-carbon replicas (Bradley, 1959, Phillips, R 1961) were deposited at an angle of 30° to the cutting direction and the nominal plane of the sections. Both surfaces of the sections and the cut surface left on the bulk (the latter under identical shadowing conditions with the former) were studied. The replicas from the top surface of the sections generally showed a structure corresponding to the long parallel fine lines observed in the transmission studies, figure 17. These lines have a spacing in the range 500 to 800 Å; finer lines at an angle to the main lines are also discernable in some areas in agreement with the observations made in transmission. Occasionally areas of much less regular structure were observed, figure 18.

The sections do not lie perfectly flat so that the exact angle of shadowing is not known for any given area, furthermore there are no areas of plane reference surface on which to determine the density of deposit for a known condition so that relative angles of inclination of other planes can be deduced from the relative density of deposit on them. It is not therefore possible to derive the topography of the sections quantitatively from the replicas. Figure 19 (a) shows the profile which the top surface of the section would have if the shear strain were all accomplished by slip on planes with the same spacing as the parallel line structure observed on sections, Figure 19 (b) shows the contrast which would be obtained from the profile in (a) by 30° shadowing. The contrast is symmetrical about a peak and corresponds quite well with the intensity profile of figure 19(c) which is a photometric plot along a line on figure 17 parallel to the cutting direction. It must be recognised, however, that the replicas contain no information about the sides of the steps drawn vertical in figure 19(a) and replicas obtained by shadowing along the other direction at 30° to the cutting direction would be most useful.

Replicas from the lower surface of the sections showed no comparable structure of evenly spaced, parallel lines, but marks due to defects in the knife edge are clearly defined. In the mechanism of section formation proposed in figure 5, no parallel line structure is expected; the evidence is however not a direct confirmation of the proposed mechanism since any such structure running normal to the direction of cutting which is formed during cutting would probably be immediately rubbed smooth by the rake face of the knife. Absence of parallel line structure from the bottom surface of sections shows that the parallel line structure is not formed after cutting (.e.g. due to buckling) as this would have affected the top and bottom of the sections equally,

Replicas from the cut surface of the specimen are similar to those from the lower surface of sections. Thus no structure is developed on the cut surface which could contribute directly to the structure obtained on the top of the next section. It is possible, however, that the cut surface is deformed to a small depth by the passage of the knife and that this may affect the exact form of the structure produced on the top surface of the next section as was found by Heidenreich (1948) when studying slip line formation on aluminium deformed in tension. Deformation under the cut surface could also affect the internal structure of the next section.

The condition of the specimen near the cut surface is a subject for further investigation as it is important to be able to assess the value of this type of surface preparation for experimental work on surface reactions and to know the contribution which this makes to the internal structure of the next section. Laue back reflection x-ray patterns from cut surfaces possessed spots of excellent quality. This method is, therefore not sufficiently sensitive for the suggested work and glancing angle x-rays and reflected electron diffraction (possibly at low energies) would probably be more appropriate.

STUDIES OF SECTIONS OF SECTIONS.

Sections were mounted in a plastic block and recut in a plane normal to the original plane of cutting in such a way that both planes of cutting have the original direction of cutting as a common zone. The results of these experiments have been presented in detail (Phillips and Shortt, 1962) and they will only be summarised here. The technique was found to be reliable for the determination of section thickness and this was found to vary in the range 1000 to 2000 Å. It was deduced that the profiles of the sections would correspond qualitatively to the topography of the section surfaces. The profile corresponding to the lower section surface was always sensibly smooth. The profiles corresponding to the upper section surface varied but steps about 500 Å apart and 300 Å in height were frequently found. There were also several examples of apparently plain upper surfaces and, at the other extreme, some very coarse steps were found. Although there are these unexplained differences between the results obtained by resectioning and replica methods, the results were in qualitative agreement. The observation of plain upper profiles is strong evidence that the shear deformation may under certain conditions, be homogeneous.

In further work on section surfaces, reflection electron microscopy would be valuable.

SELECTED AREA DIFFRACTION STUDIES.

According to the simple theory of the formation of sections by shear, cutting the (210) $[1\bar{2}1]$ orientation of a single crystal aluminium should produce $(\bar{1}01)$

sections with $[1\bar{2}1]$ normal to the direction of cutting, figure 13. The experimentally observed orientations are as shown in figure 20. The orientations plotted in figure 20 were determined by the selected area diffraction technique. Each pattern was obtained from a circular area approximately two microns in diameter and this area was repositioned at random several times in the part of the section indicated.

The predicted orientation $(\bar{1}01)$ $[1\bar{2}1]$ is rarely observed and a section cut from a single crystal of aluminium is polycrystalline. The essentially similar results obtained from both edge and centre portions of the sections, which were about 100 micron in linear dimension indicates that the metallographic tip preparation is not responsible for the departures of orientation from $(\bar{1}01)$ $[1\bar{2}1]$. The orientations change abruptly from one to another at boundaries which appear as sharp lines where extinction contours are discontinuous. Thus although the sections are not always normal to the electron beam and are slightly buckled, these experimental dificiencies do not account for the departures from the $(\bar{1}01)$ $[1\bar{2}1]$ orientation. The diffraction maxima are unarced but are frequently split, indicating the polygonised nature of the sections.

The most probable explanation of these results is that the postulated shear does occur but is followed by a recrystallisation process which gives primarily a (101) texture and a grain size which is large compared with the thickness of the foil. Clareborough, Hargreaves and Loretto, 1961, quote the recrystallisation temperatare of pure aluminium deformed 70% in compression as being complete at 350°C at a heating rate of 6°C/min. Each part of the section can only be at an elevated temperature momentarily as it passes the knife edge because it must be very quickly quenched by the trough fluid. It seems therefore that a temperature which is probably in excess of 350°C passes as a zone along the section as it is parted from the bulk. It may be noted that in ordinary machining studies with dynamic cooling and lubrication, temperatures of several hundred degrees are recorded (Gideon et al, 1958). The material in the hot zone is, therefore, probably 'seeded' on to the adjacent, cut material and a relatively large grain size is propogated. The friction between the lower surface of the section and the rake face of the knife is a source of energy which could produce the temperature rise.*

In order to further test the suggestion that recrystallisation had occurred during cutting, sections were cut from annealed and heavily worked (50% in compression) aluminium and investigated by selected area diffraction. The quality of the spots was similar in both cases showing a high degree of polygonisation and very little arcing, thus indicating that the sections from the second specimen had no memory of the compression. This is consistent with the idea of recrystallisation during cutting. The sections cut from polycrystalline aluminium were studied within two hours of cutting. They were then stored two weeks at room temperature and re-examined. The two sets of results are compared in Table I and it is clear that they are not significantly different. This result is also consistent with recrystallisation during cutting and in a very short time

* See appendix.

TABLE I

A

Orientations of selected areas of sections cut from 10 polycrystalline aluminium sections as determined within two hours of cutting.

Orientation	(010)	(101)	(121)	(310)	(111)
Number of times observed.	10	17	8	2	1

B

Orientations of selected areas of sections cut from 10 polycrystalline aluminium sections as determined after two weeks.

Orientation	(010)	(101)	(121)	(310)	(111)	others
Number of times observed.	10	19	5	0	2	3

suggesting that the temperature must be very high. Such evidence as is available indicates that recrystallisation is impeded in thin foils (Bailey, 1960) which, together with the very short time at elevated temperature, would suggest that the maximum temperature attained must be considerably in excess of the normal recrystallisation temperature. Finally, the textures shown in Table I are very similar to those in part 3 of figure 20, showing that the textures in the sections of aluminium are very largely independent of the orientation of the crystals from which they were cut and are not therefore due solely to a mechanical shear. It is however, clear that certain low index orientations are favoured (firstly, (101) and secondly (010)) rather as in recrystallisation textures, suggesting that crystallographic shear deformation processes play an important part in determining the orientation of the sections.

The formation of a section is therefore concluded to involve the separation of the material from the bulk by a deformation process which severely shears the section and which is accompanied by a large rise in temperature for a very short time. In order to test the general applicability of this mechanism the sectioning of copper was investigated. Copper has a lower stacking fault energy than aluminium, a greater hardness and a slightly lower recrystallisation temperature. If the coefficients of friction are similar, the higher hardness should lead to the dissipation of more heat and recrystallisation should be readily accomplished. Nickel has a considerably greater room temperature hardness than aluminium, an intermediate stacking fault energy and a higher recrystallisation temperature. It was considered therefore that nickel might not reach a high enough temperature during sectioning to recrystallise and might therefore exhibit an orientation due to shear alone. The crystallography of the sectioning of copper and nickel was therefore undertaken.

TRANSMISSION ELECTRON MICROSCOPE AND SELECTED AREA DIFFRACTION STUDIES OF SECTIONS CUT FROM THE (210) $[1\bar{2}1]$ ORIENTATION OF COPPER.

The orientations of sections cut from the (210) $[1\bar{2}1]$ orientation of single crystal copper as determined by the selected area diffraction technique are summarised in Table II. Several orientations were found in each section. Where the orientation is (101) the fine line structure has the predicted $[1\bar{2}1]$ direction in 25% of the areas which is similar to the result for aluminium.

TABLE II

Orientation	(010)	(101)	(121)	(111)
No. of Occurrences	1	12	1	1

Thus, some rearrangement of orientation also occurs in copper after the shear deformation associated with cutting. It may be noted in passing that sections of copper cut from the (210) $[1\bar{2}1]$ orientation also exhibit long straight parallel lines normal to the direction of cutting and very fine polygonisation, figure 27.

Sections from two single crystals of a constant undetermined orientation of copper, one in the heavily worked and the other in the unworked condition were compared by selected area diffraction. The worked material when sectioned had recrystallised with a very small grain size and yielded sharp diffraction spots. The orientations however, were not completely random and exhibited some (100) and (110) texturing. The sections from the unworked crystal produced electron diffraction spots which appeared moderately arced, but close examination of micrographs and diffraction maxima showed that the effect was due to extremely fine polygonisation.

These experiments show that the sectioning behaviour of copper is similar to that of aluminium except that the copper sections seem to exhibit much finer polygonisation. Sections cut from worked copper had a much smaller grain size than those cut from worked aluminium.

TRANSMISSION ELECTRON MICROSCOPE AND SELECTED AREA DIFFRACTION STUDIES OF SECTIONS CUT FROM THE (210) $[1\bar{2}1]$ ORIENTATION OF NICKEL.

Sections cut from the (210) $[1\bar{2}1]$ orientation of nickel all had the predicted (101) orientation and 80% of the areas checked had the traces of the fine line structure parallel to $[1\bar{2}1]$. The dislocation content of the sections was very high, figure 22, and the spots of the diffraction pattern were considerably arced. Thus the evidence of orientation, dislocation density and quality of diffraction maxima all show the sections of nickel to be severely worked and not subsequently recrystallised. Further, in this absence of recrystallisation, the orientation was very largely that predicted.

A crystal of (112) $[1\bar{1}0]$ orientation was sectioned in order to check whether the fine line structure corresponded to slip on conventional systems. The chosen orientation would equally favour slip on two (111) planes using their common $[1\bar{1}0]$ direction. The lines in the fine structure were, however, found to be as long and straight and normal to the direction of cutting as previously. The traces of the (111) planes which were favoured were at 55° to this direction, therefore if the fine line structure corresponds to slip lines it must be accepted that unconventional slip systems may operate in sections. The sections did, however, have the (110) orientation predicted by the shear theory. The diffraction patterns from the sections exhibited very fine polygonisation.

THE SPACING OF THE FINE LINE STRUCTURE.

Strong experimental evidence has been adduced that the production of a section of metal is accompanied by a large shear deformation which generally produces a periodic ridge structure on the top surface of the section. The ridges have a characteristic spacing of about 600 Å. Clearly, a theory of cutting should be able to predict or at least offer some explanation of this spacing. A model such as that proposed in figure 5, however, if unmodified, predicts a homogeneous shear, when applied quantitatively. In figure 23, therefore, section formation is represented as a process in which the deformation is accomplished temporarily by the storage of dislocations in the section until the associated energy is such that the next dislocation formed can sweep away the barriers and emerge at the top surface. It is suggested that this dislocation will be followed by several more and this process will be accompanied by the slipping out of the stored dislocations at the lower surface and will continue until the energy is reduced to such a level that it can no longer nucleate new dislocations on the activated slip plane. This process would form a step on both section surfaces. It is however, possible that the serrations on the lower surface are subsequently rubbed smooth. The initial storage of dislocations could be due to interaction with dislocations introduced during the previous cut. In this context, it may be noted that the steps on sections are always very precisely formed when the specimen has been deliberately worked.

At the stage represented by figure 23(c), the shear stress on the slip plane extending from the knife tip is given by

$$\mu \frac{nb}{(n+N)\ a}$$

where μ is the shear modulus, n is the number of slip planes on which dislocations have been stored, b is the resultant Burgess vector of the dislocation stored on each slip plane, a is the separation of slip planes and N is the extra number of planes over which the elastic distortion due to the stored dislocations may be expected to spread. The strength of barriers to dislocation motion of the Cottrell Lomer lock-type is about 0.1μ.

Thus a dislocation will break through when

$$\frac{\mu nb}{(n+N)\ a} = 0.1\mu$$

$\frac{b}{a}$ is approximately 2 in the usual practical case

$$2n = 0.1n + 0.1N$$

$$n = \frac{1}{20} N$$

a plausible value for N in the section thickness, thus the model predicts a fine line spacing of about 100 Å which is the correct order of magnitude. It has been implicitly assumed that there is a slip plane parallel to the knife edge which was in fact the case for many of the experiments described here.

METALLURGICAL APPLICATION OF THE ULTRA MICROTOME.

There are two main reasons for undertaking the work which has been described: -

1) To elucidate the fundamentals of the cutting process.

2) To establish the value of the microtome technique in the preparation of specimens for the electron microscope.

It is therefore suitable to discuss the second aspect at this stage.

The microtome sectioning technique has gained wide acceptance in cytology and the analysis of cutting of the embedding media performed here would only suggest that care would have to be taken in the application of quantitative measurements to these specimens.

The shear stress involved in the sectioning process renders it unsuitable for studies of dislocation distribution, but, providing the temperature rise does not modify the results and care is taken in the selection of the cutting fluid sections can be used where the main information required is selected area diffraction, 'd'-spacings or the distribution of second phases or holes.

The microtome technique has been usefully applied to a study of second phases in a wide variety of alloys (V.A. Phillips 1961) to the identification of inclusions at stress corrosion crack nuclei, and distributions of cavities and gas bubbles in creep and particle irradiated specimens. The technique is specially useful where the specimen is of a form unsuitable for electropolishing, providing the limitation on the information which can be obtained are realised. Examples of problems in this category are: -

1) Thickness of surface films (plated, evaporated, anodic, etc.)

2) Topography and composition of interfaces, e.g. between deposited film and substrate.

3) Composition and topography studies of fibres, powders and green sinters.

Finally, it is worthy of note that the cut surface on the bulk of the specimen is very clean and relatively strain free and is useful in surface reaction studies, (Euddery) for replica studies of cavitation and as a metallographic preparation for materials particularly prone to flow and twinning in normal grinding and polishing.

Figures 24 and 25 are presented and discussed as an illustration of the application of the principles of cutting and metallography to the analysis of sections.

Figure 23 is of an Al-Mg-Zn alloy and shows isolated regions in darker contrast; these regions exhibit periodic fractures, they are therefore more brittle than the bulk of the material and are therefore inclusions. A boundary runs diagonally across the photograph; it is particularly clearly shown by the contours which end abruptly at it. Dark-field indexing of the contours would enable one to deduce whether the boundary is high or low angle. The presence of 200 Å precipitates which are not generally in evidence on the boundary indicates that it existed in the bulk specimen during heat treatment and was not introduced into the section during cutting.

Figure 25 was obtained from the same sample with the same cutting conditions, except that a blunt knife was used. The whole section now exhibits periodic fractures showing that the strain involved in cutting is now sufficiently great to cause the material to behave in a brittle manner.

<u>CONCLUSIONS.</u>

Thin sectioning is a complex subject which is extremely difficult to treat precisely. The experimental impossibility, at present, of adequately controlling and measuring all the parameters and in particular the cutting edge, makes it impossible to treat the subject exactly either in the specification of experimental conditions or in the manupilation of theoretical models. However, by means of a wide range of experimental methods it has been possible to reach a number of conclusions and to propose models for most practical cases of sectioning.

It is concluded that in all important cases of sectioning, the material in the section suffers severe shear deformation or fracture on a plane more or less normal to the rake face of the knife. The shear deformation is accompanied by a considerable rise in temperature of very brief duration. The surface condition of the section is largely determined by the mechanical properties of the material, the internal structure or degree of prior hardening which the specimen has experienced. The internal structure(dislocation density, subgrain, grain size) is largely determined by the combination of shear strain and temperature rise.

The immediately obvious features of many sections are topographical and are due to knife edge defects and the effect of the relief on the shear stress. Easily recrystallised f.c.c. materials are textured with (110) as the principle and (100) as the secondary orientation. Less easily recrystallised f.c.c. metals exhibit an orientation which may be derived from the orientation of the plane of cutting by the shear appropriate for the rake angle.

The duration of the temperature rise is insufficient for appreciable long range diffusion to occur.

Therefore the distribution of the second phases is unmodified and metallographically useful sections can often be obtained if the interest centres on chemical hetrogeneities (e.g. inclusions, precipitates ($>$100 Å in diameter), cavities, surface layers, etc.)

It is a pleasure to acknowledge the experimental help of J.V.W. Evans and A.J. Brown and the encouragement and advice of A.W. Agar.

R. PHILLIPS.

A P P E N D I X

THE TEMPERATURE RISE DURING CUTTING.

The high resistance to shear which may be expected because of the very small length of shear plane over which strain is produced and the high coefficient of friction which may be expected to operate in microtomy lead to an expectation of a very high quantity of heat generated per unit volume of the section. It turns out that too few of the values required for substitution in the appropriate equation of metal cutting are known for a significant value of the equilibrium temperature of the section near the knife edge to be calculated.

A rather naïve expression of the relation between the equilibrium temperature T, the shear modulus μ, and the thermal conductivity k is: -

$$\frac{T}{d} = \frac{2\mu}{k} \times 10^{-7}$$

where d is the distance over which the temperature falls from T to that of the bulk of the specimen. For metals $\frac{\mu}{k}$ is of the order 5×10^{11} so that a rather high value of d (tens of microns) has to be assumed to account for values of T of hundreds of degrees C. However, since the effect of the severe shear on k and the effects of a knife edge which is less than perfect are not known this is not really serious.

However, it is of great significance that for plastics $\frac{\mu}{k}$ is greater by 100 than for metals and this indicates that there is a very good case for expecting a significant increase in temperature in biological sectioning. Of course, the effect is self limiting in that, as the temperature rises the stresses decrease and the tendency for the temperature to rise decreases. Qualitatively this reasoning argues strongly for a plastic deformation model of the sectioning of biological embedding media as postulated in the paper.

R E F E R E N C E S

Bailey, J.E., 1960, Phil. Mag. 5, 833

Beams, J.W., Brezeal, J.B. and Bart, W. L., 1955, Phys. Rev., 100, 1957.

Bradley, D.E., 1959, Brit. J. Appl. Phys., 10, 108.

Bridgeman, P.W., 1953, J. Appl. Phys., 24, 560.

Buddery, J.H. and Haynes, M.E., 1962, J. Inst. Met., 90, 178.

Clarebrough, L.M. Hargreaves, M.E. and Loretto, M.H., 1961, Phil. Mag., 6, 807.

Cottrell, A.H., 1953, 'Dislocations and Plastic Flow in Crystals', Oxford, 8.

Glauert, A.M. and Phillips, R. 'Techniques for Electron Microscopy', Ed. D. Kay, Blackwells, Oxford, 199.

Gideon, D.N., Simon, R. and Grover, H.J., 1958, 'An Evaluation of the Present State of Metal Cutting', A.S.T.E., U.S.A.

Heidenreich, R.D. and Shockley, W. 1948, 'Report on Strength of Solids', (London Phys. Soc.), 57.

Kelly, P.H. and Reed, R., 1961 Brit. J. Appl. Phys., 12.

Merchant, M.E., 1945, J. Appl. Phys., 16, 267.

Merchant, M.E., 1950, 'Machining - Theory and Practace', A.S.M., Cleveland, Ohio, 5 - 44.

Morgan, C., Moore, D.H. and Rose, H.M., 1956, J. Biophys. Biochem. Cytol., 2, No. 4 (suppl.), 21.

Phillips, R., 1961, Brit. J. Appl. Phys., 12, 554.

Phillips R, 1962, J. Roy. Mic. Soc., 81, 41.

Phillips R. and Lucas, J.H., 1962 (a), J. Sci. Instr., 39, 23.

Phillips R. and Lucas, J.H., 1962 (b), J. Sci. Instr., 39, 224.

Phillips, R. and Shortt, T. 1962, to be published.

Phillips, V.A., 1961.

Shaw, M. 1950, 'Machining - Theory and Practice', A.S.M., Cleveland, Ohio, 45 - 68.

Williams, R.C. and Kallman, F., 1955, J. Biophys. Biochem., Cytol. 1, 301.

Wilsdorf, H., 1958, Sym. Adv. Elect. Met., A.S.T.M. Special Publications No. 245, p. 43.

LIST OF ILLUSTRATIONS

14. Through-focal series of the parallel line structure on a section cut from a (210) [121] orientation, showing changes in the appearance of the line due to the formation of over and under focus fringes. The inter-line spacing is 600 Å

a) Overfocused.

b) focused.

c) underfocused. X 30,000.

15. Section cut from a single crystal of aluminium showing the discontinuity in Bragg contours at internal boundaries. X 60,000.

16. A section of aluminium which appears to be of great internal perfection and to have plane surfaces. Note, however, that the section contains grain boundaries although it was cut from a single crystal. X 20,000

17. Platinum - carbon shadowed replica from the top surface of a section cut from a (210) [1$\bar{2}$1] crystal of aluminium. These are surface steps of1600 to 700 Å spacing which run normal to the direction of cutting. X 20,000

18. Platinum - carbon shadowed replica from the top surface of a section cut from a (210) [1$\bar{2}$1] crystal of aluminium. The structure is less regular and consists of relatively widely spaced, well defined steps with irregular, shallower steps in between. X 40,000

19. The contrast (b) which would be obtained from an idealised slip line profile (a) and the profile of intensity (c) measured along a line parallel to the cutting direction on figure 16.

20. Orientations determined from randomly selected areas of sections of aluminium cut from the ($\bar{1}$01) [1$\bar{2}$1] orientation. The direction of the normal to the direction of cutting is shown as a trace on the

reciprocal lattice plane corresponding to the plane of the section. The number of observations of a given plane and trace is indicated by the number adjacent to the trace.

21. Section of copper cut from the (210) [1$\bar{2}$1] orientation, showing long, fine parallel lines normal to the direction of cutting and very fine saale polygonisation X 40,000.

22. Section of nickel cut from the (210) [1$\bar{2}$1] orientation, showling long, fine parallel lines normal to the direction of cutting and very fine scale polygonisation X 40,000.

23. Schematie representation of a model for the shearing of sections during cutting, by means of slip on planes several atomic spacings apart.

24. Thin section of Al-Mg-Zn alloy showing inclusions and precipitation on a sub-boundary. X 180,000.

25. Thin section of Al-Mg-Zn alloy cut with blunt knife showing fractures running normal to the direction of cutting. X 40,000.

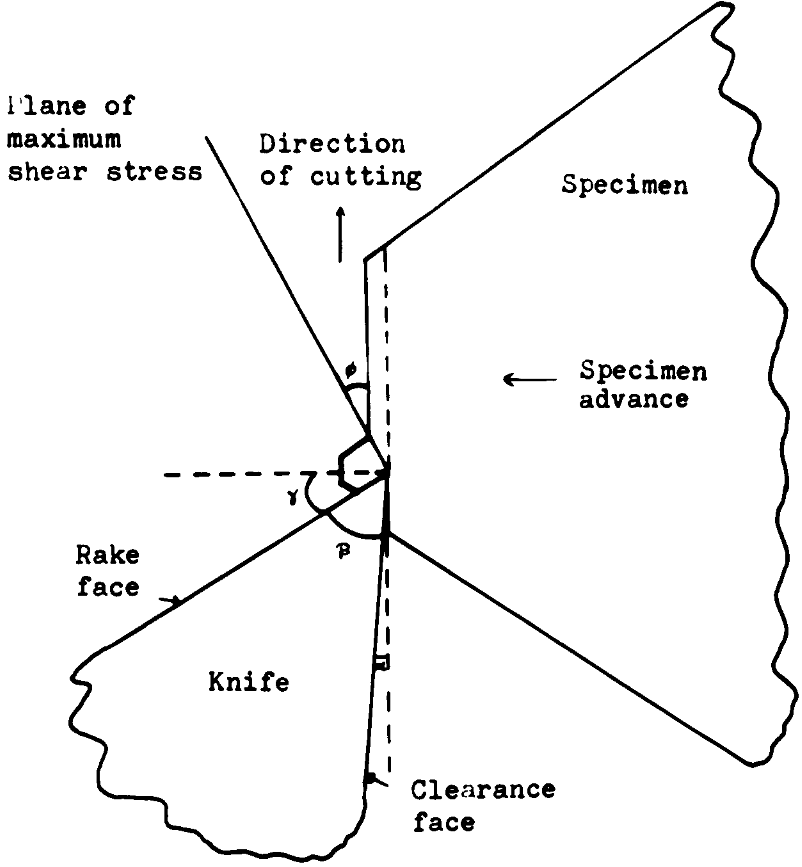


Figure 1

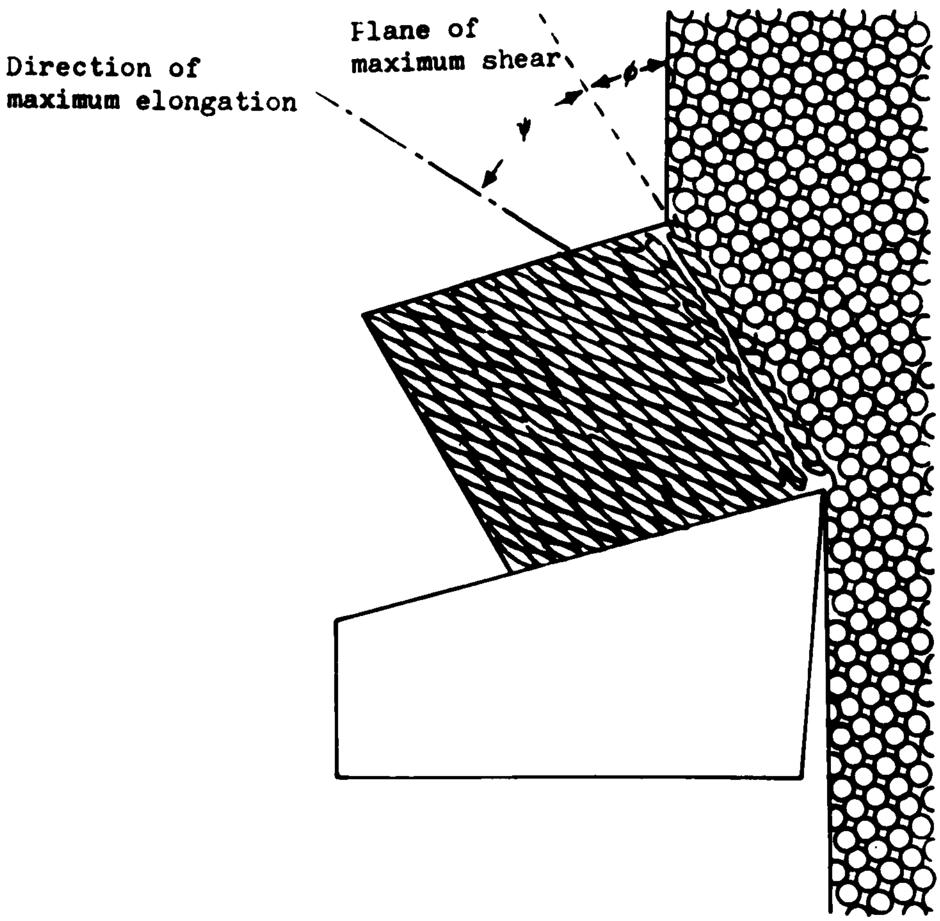


Figure 2

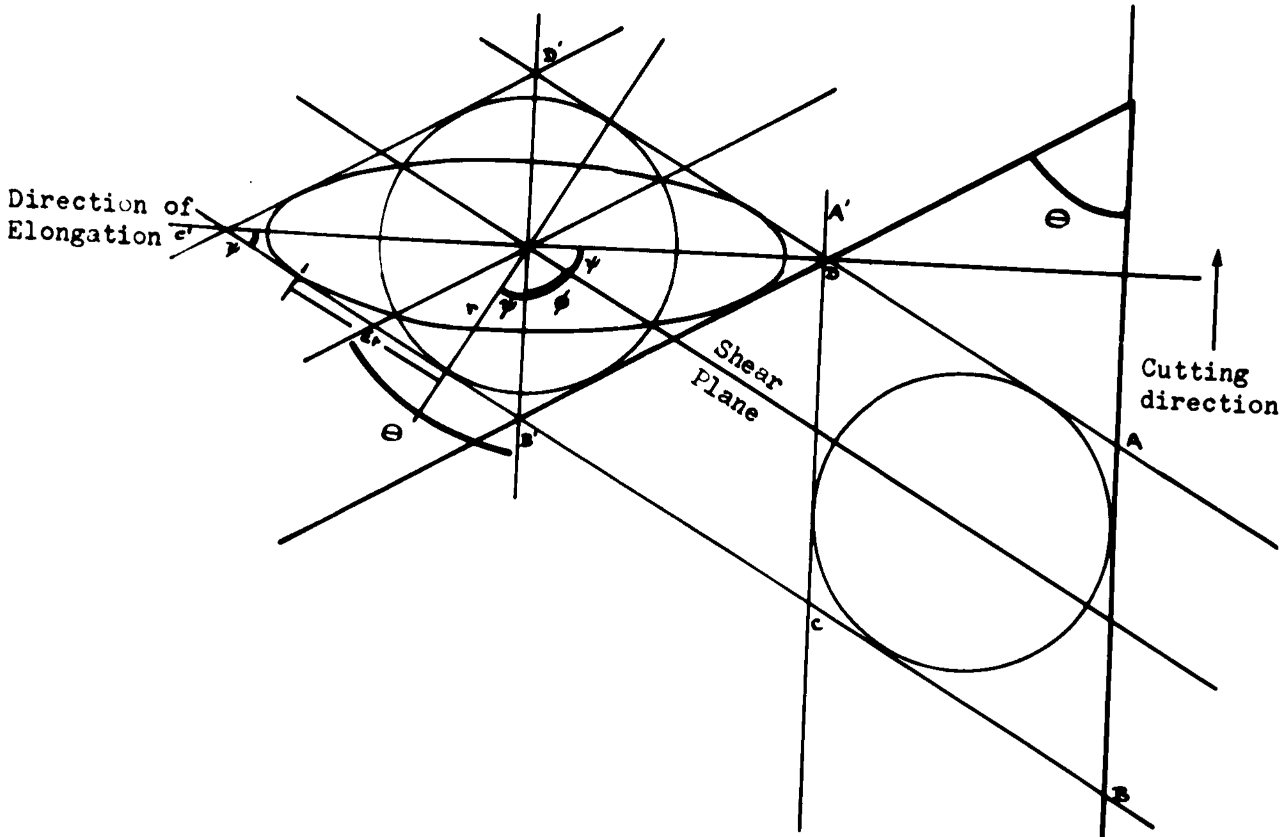


Figure 3

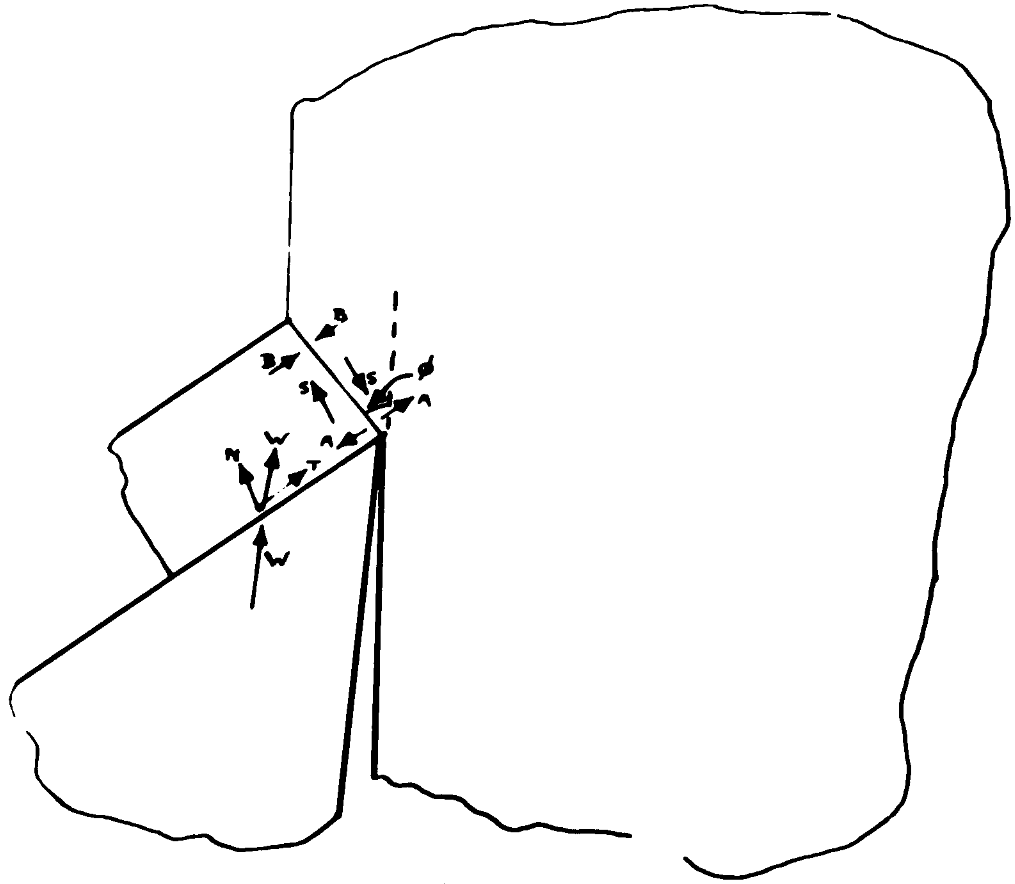


Figure 4

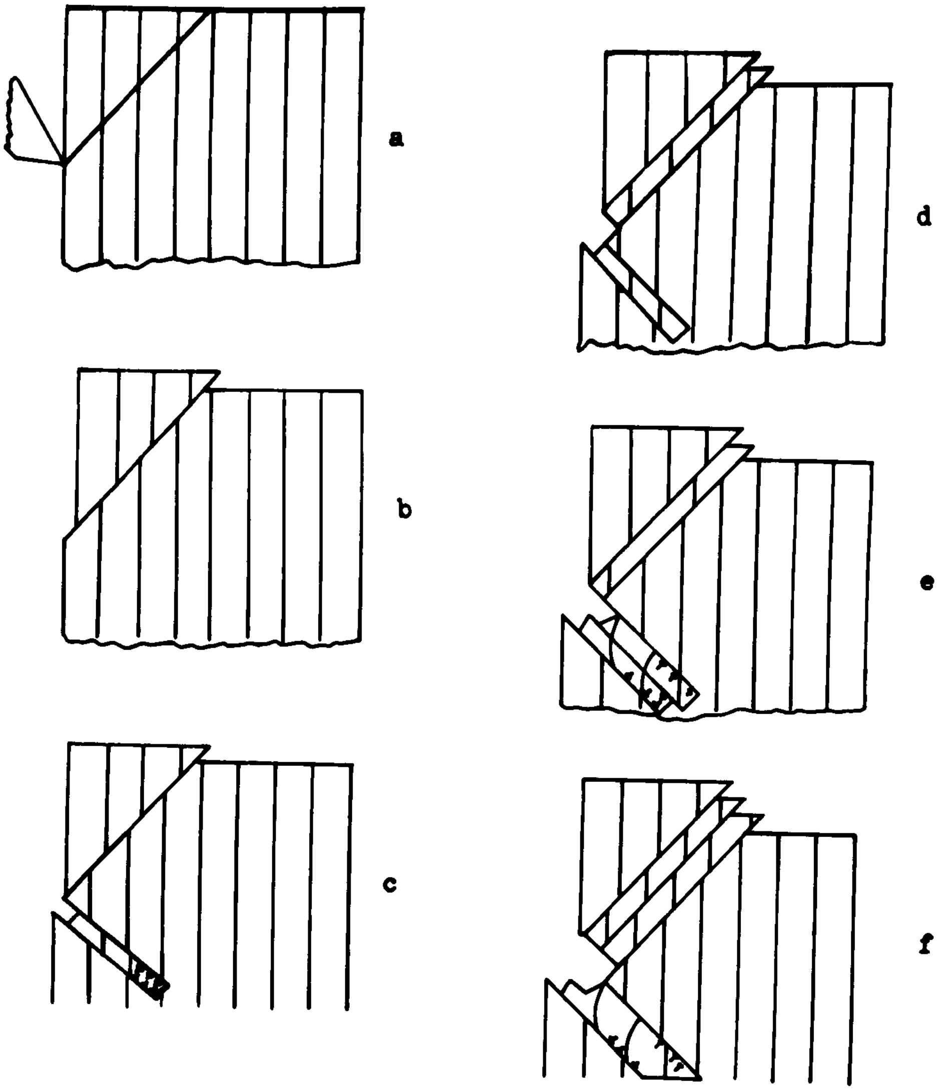


Figure 5

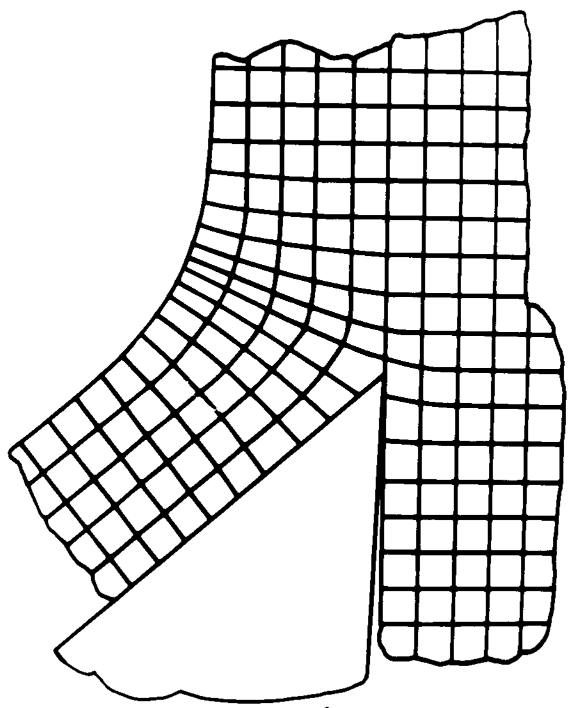


Figure 6

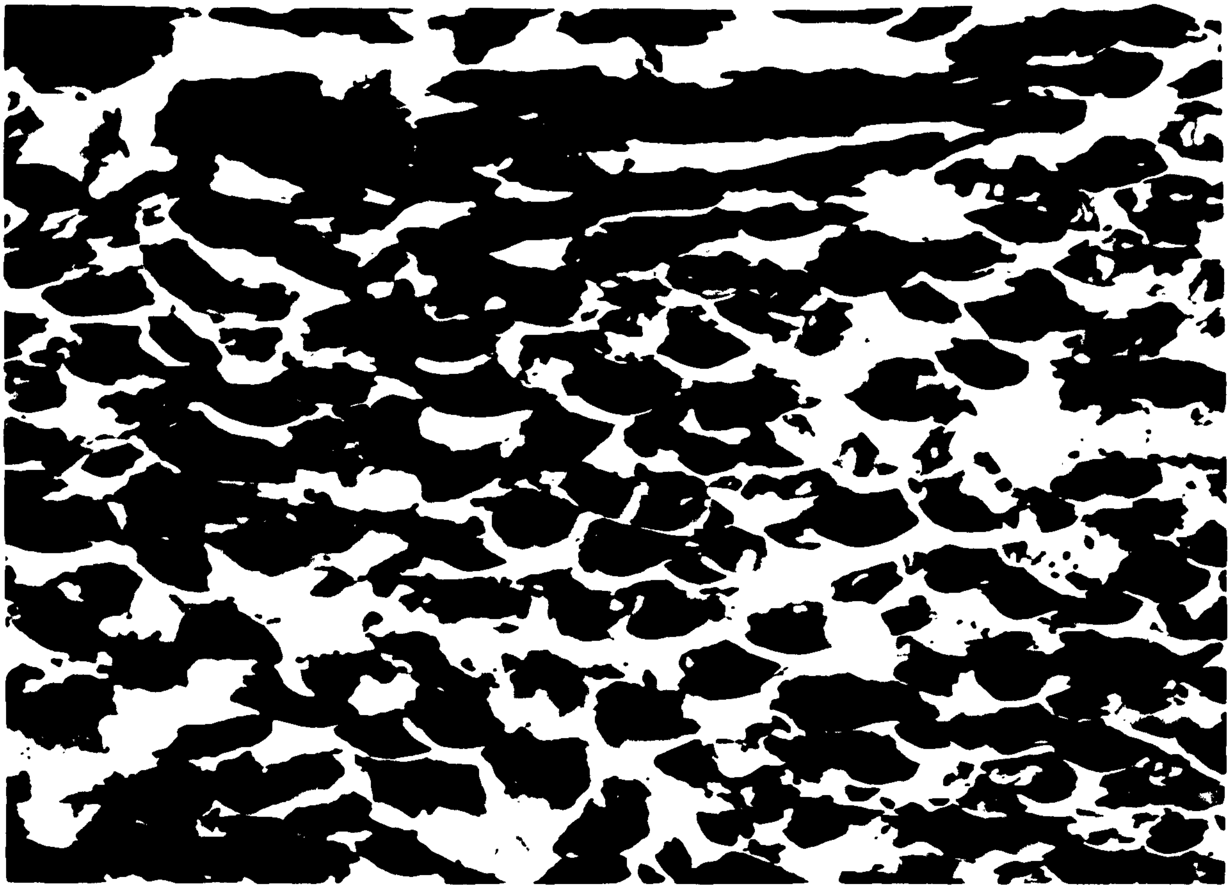


Figure 7

Figure 8

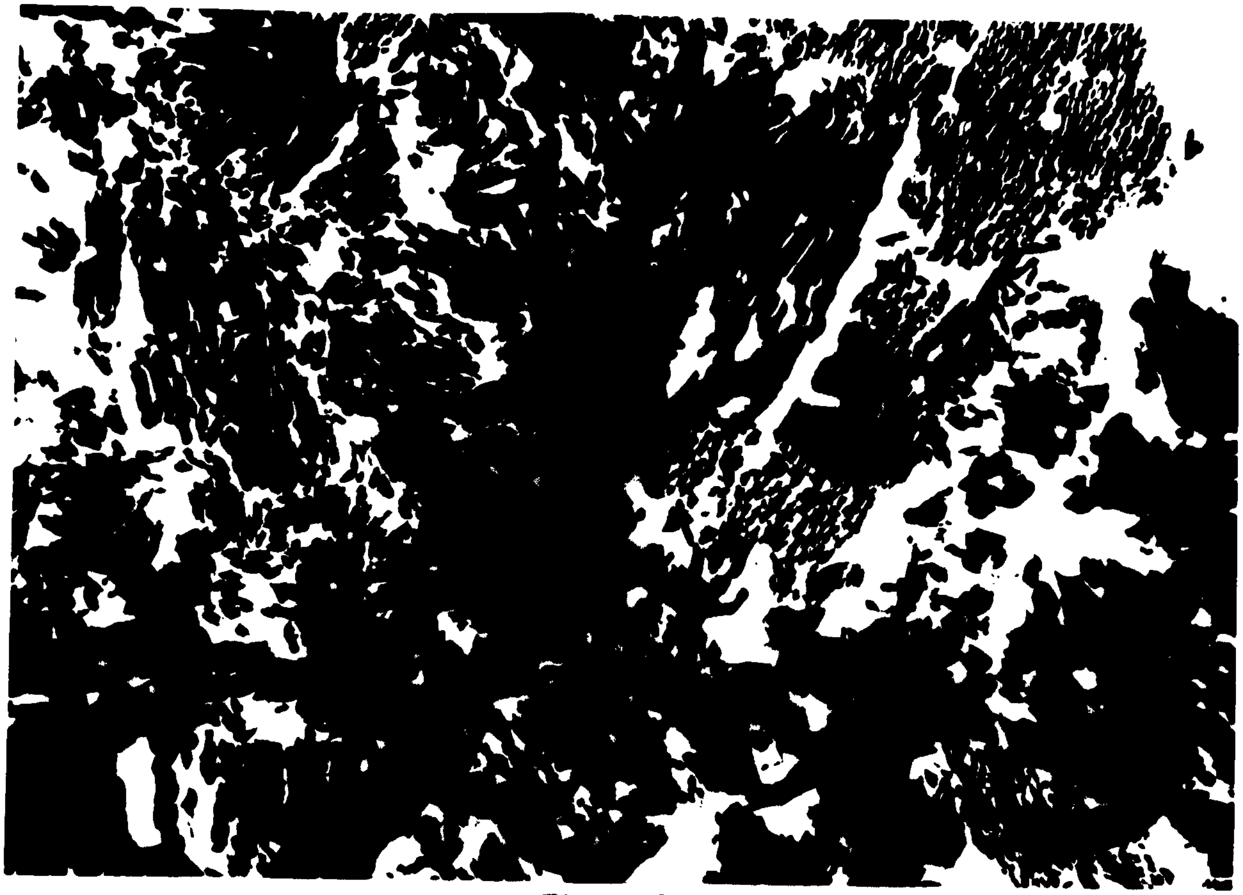


Figure 9

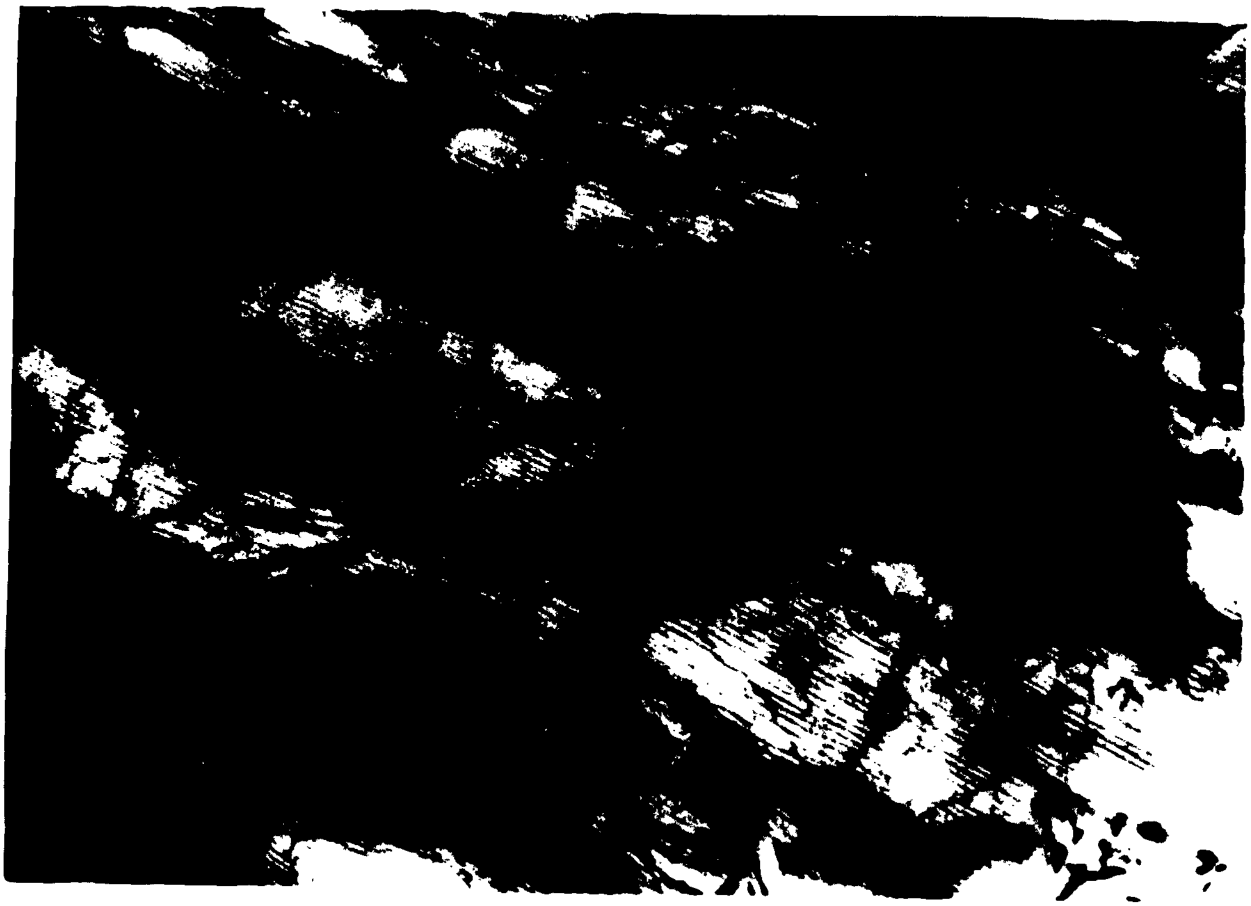


Figure 10

Figure 11

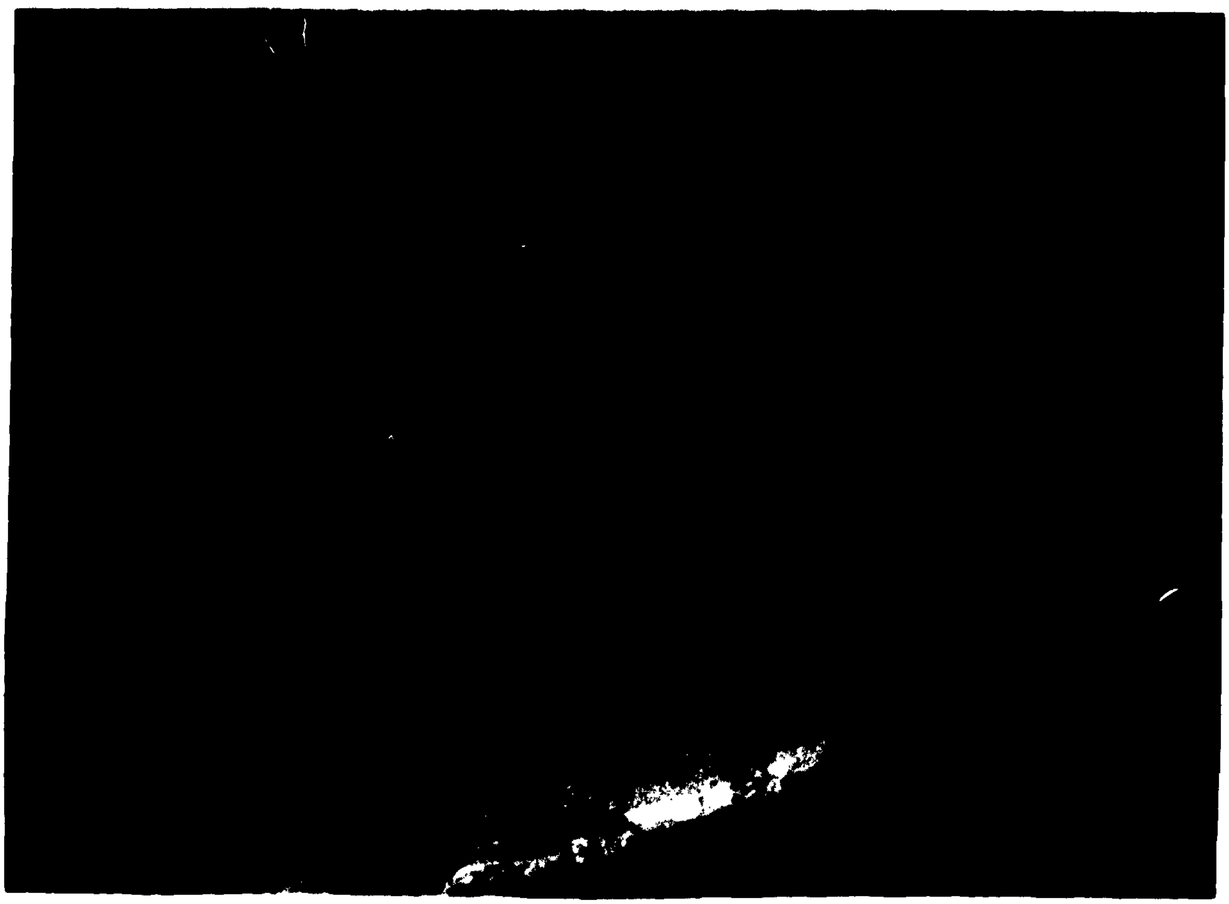
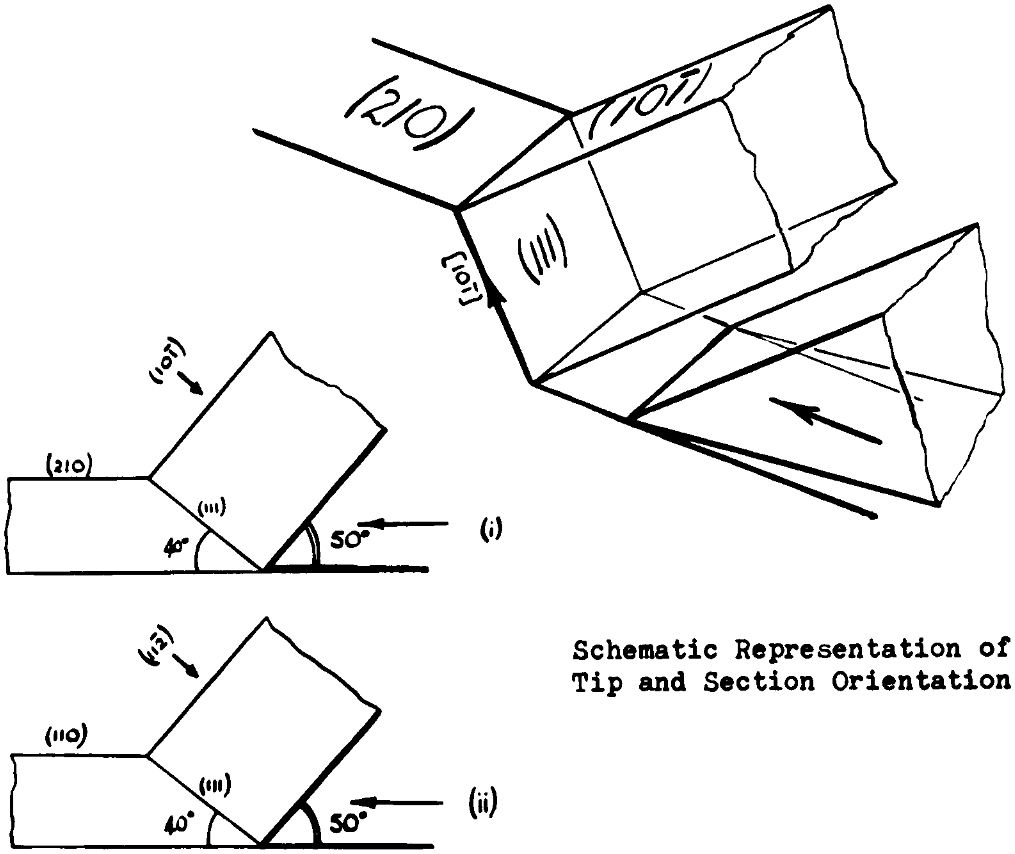


Figure 12



Schematic Representation of Tip and Section Orientation

Figure 13

a

b

c

Figure 14


Figure 15


Figure 16

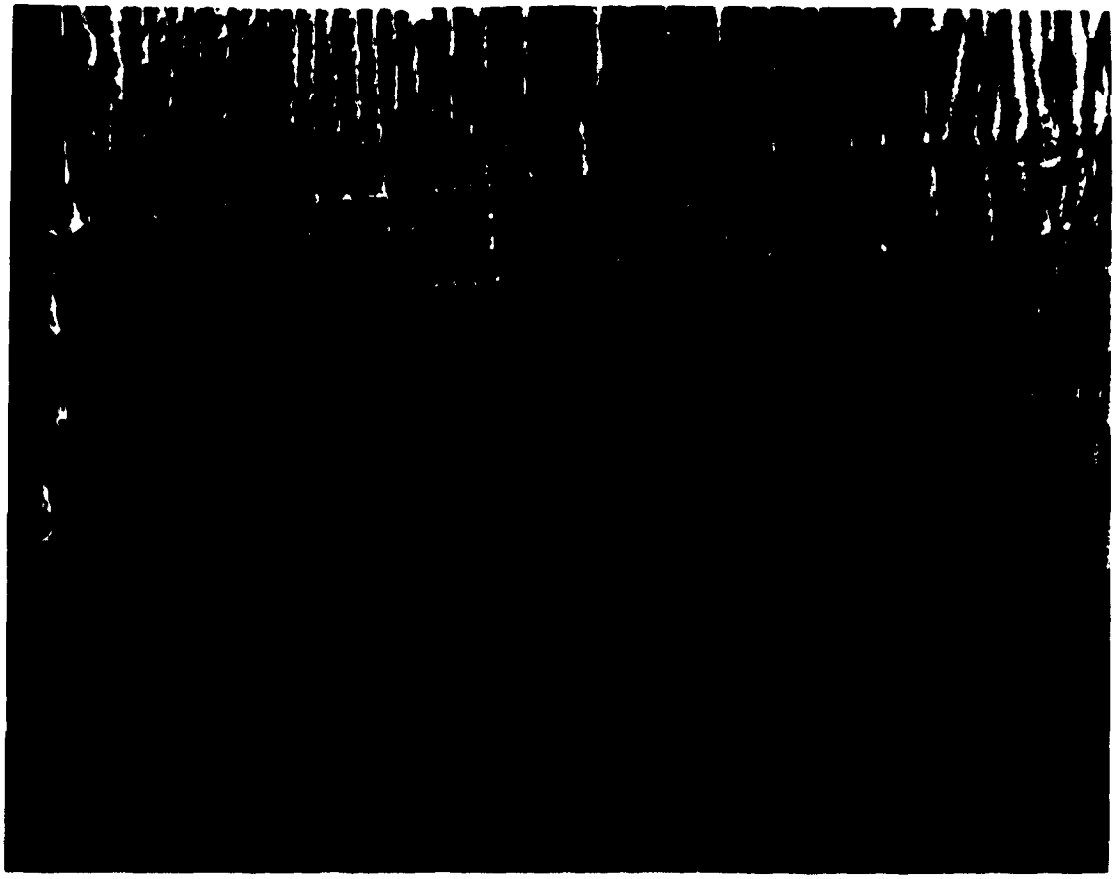


Figure 17

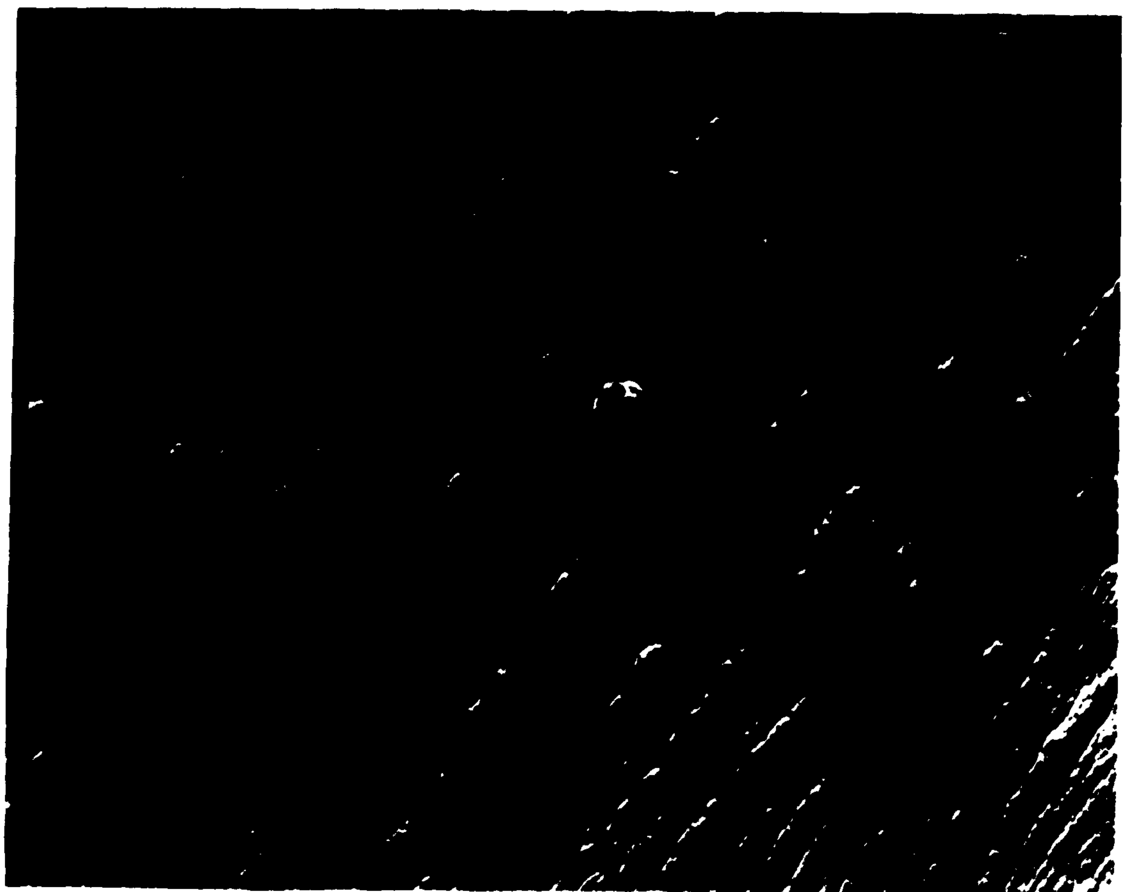


Figure 18

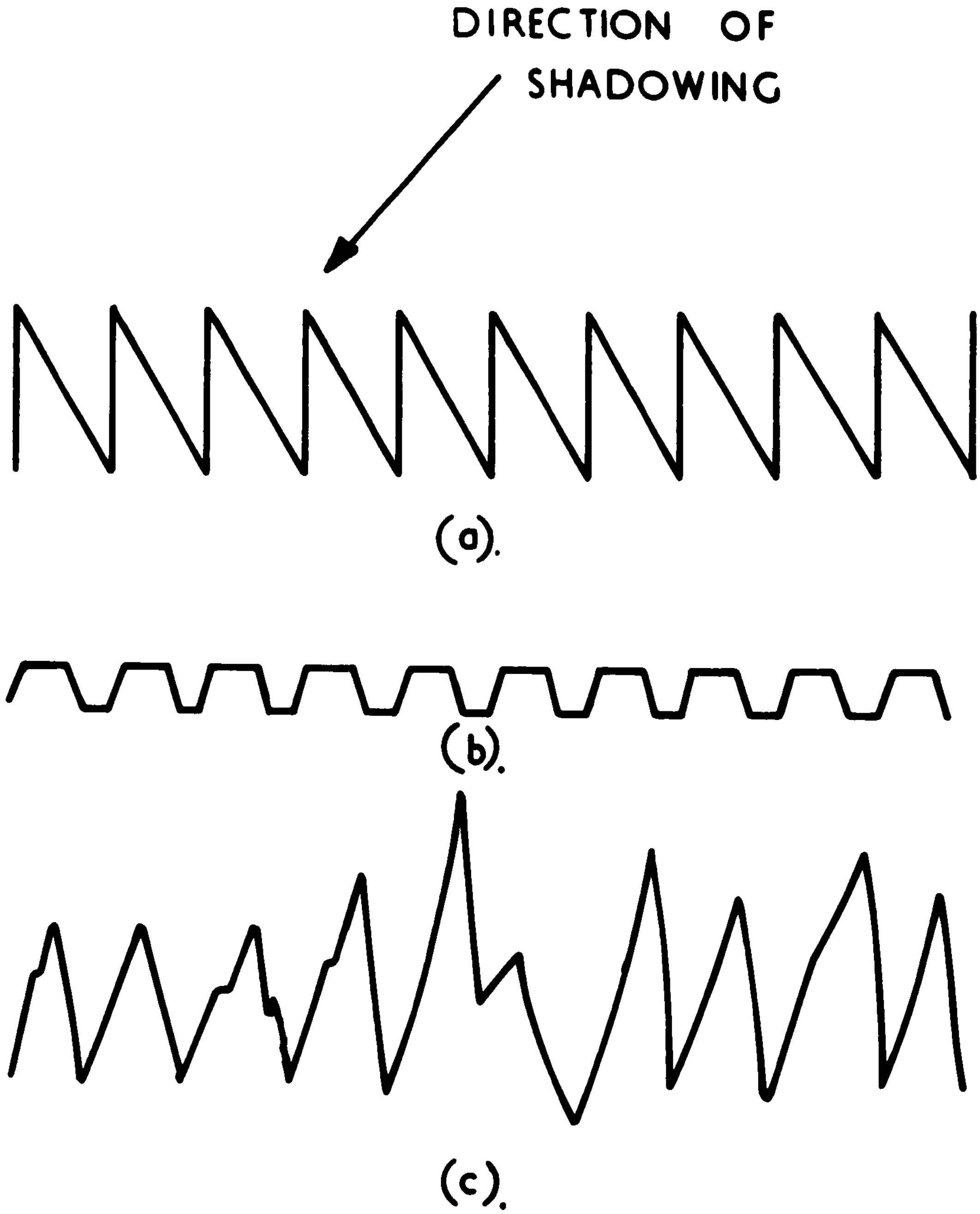


Figure 19

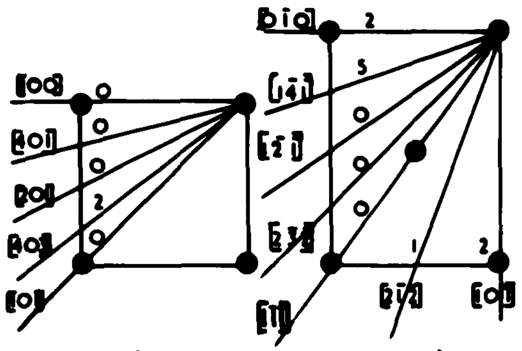
ORIENTATIONS DETERMINED FROM RANDOMLY SELECTED AREAS OF SECTIONS OF ALUMINIUM CUT FROM THE ($\bar{1}$01) [1$\bar{2}$1] ORIENTATIONS.

THE DIRECTION OF THE NORMAL TO THE DIRECTION OF CUTTING IS SHOWN AS A TRACE ON THE RECIPROCAL LATTICE PLANE CORRESPONDING TO THE PLANE OF THE SECTION. THE NUMBER OF OBSERVATIONS OF A GIVEN PLANE AND TRACE IS INDICATED BY A NUMBER ADJACENT TO THE TRACE.

1. ORIENTATIONS AT EDGE OF SECTIONS.

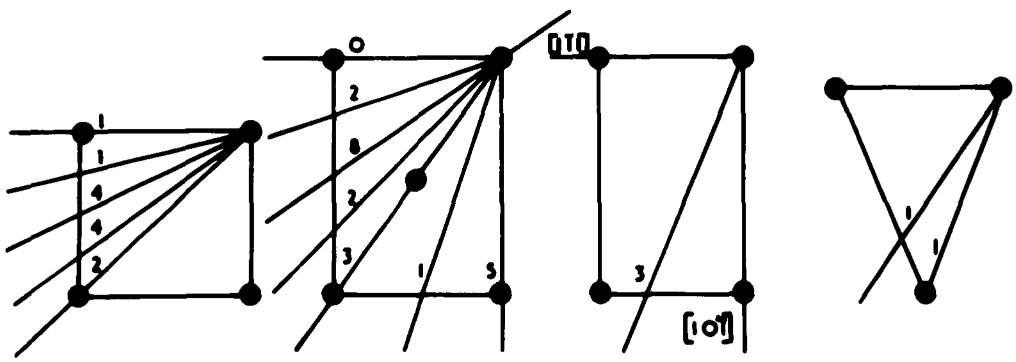
TOTAL NUMBER OF DETERMINATIONS.

TRACE AND ORIENTATION PREDICTED BY SHEER THEORY.



	(010)	(101)	TOTAL NUMBER OF DETERMINATIONS
TOTAL TRACES	2	10	12

2. ORIENTATIONS AT CENTRE OF SECTIONS.



	(010)	(101)	(121)	(310)	
TOTAL TRACES	12	21	3	2	38

3. RESULTS OF 1 AND 2 TOGETHER.

	(010)	(101)	(121)	(310)	
TOTAL ORIENTATIONS	14	31	3	2	50

Figure 20

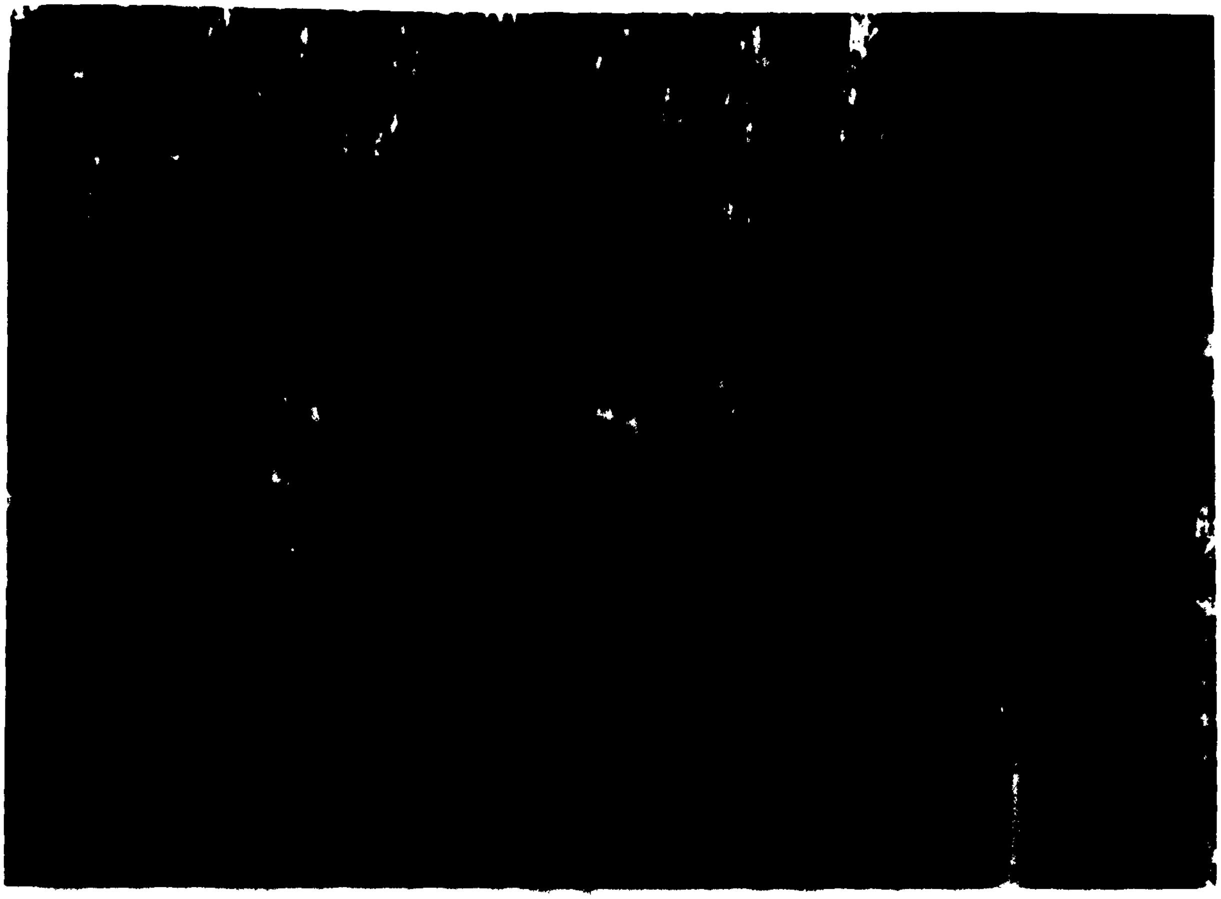


Figure 21

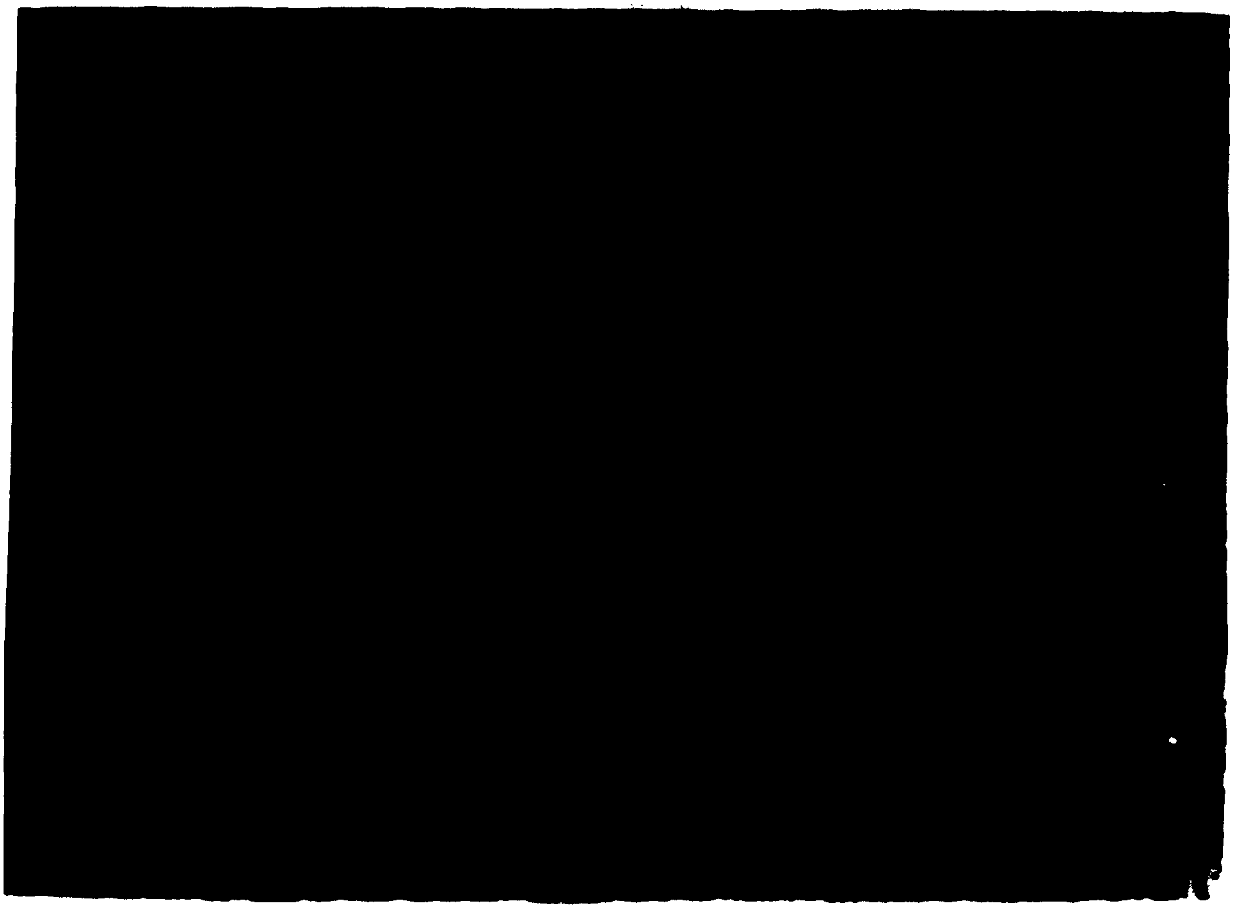


Figure 22

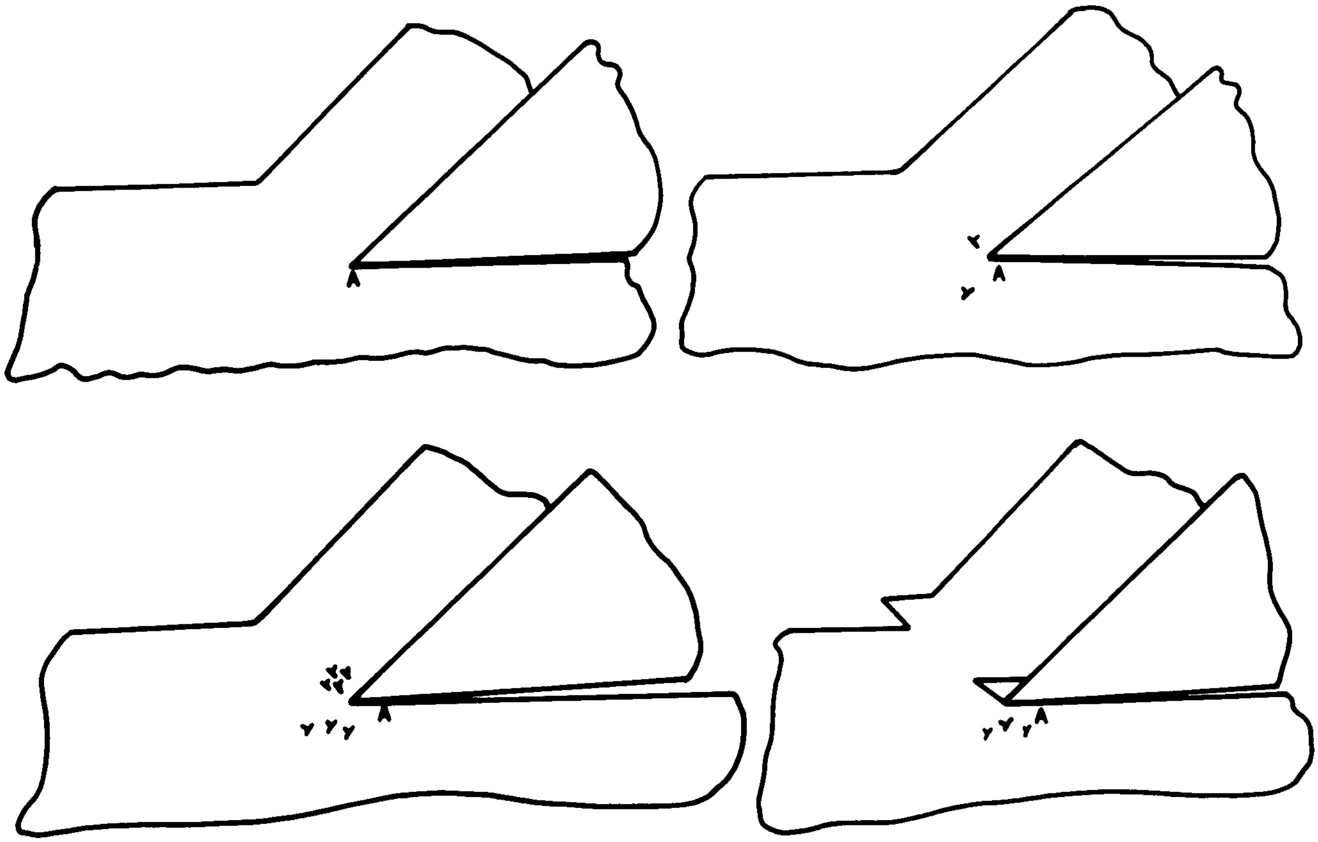


Figure 23

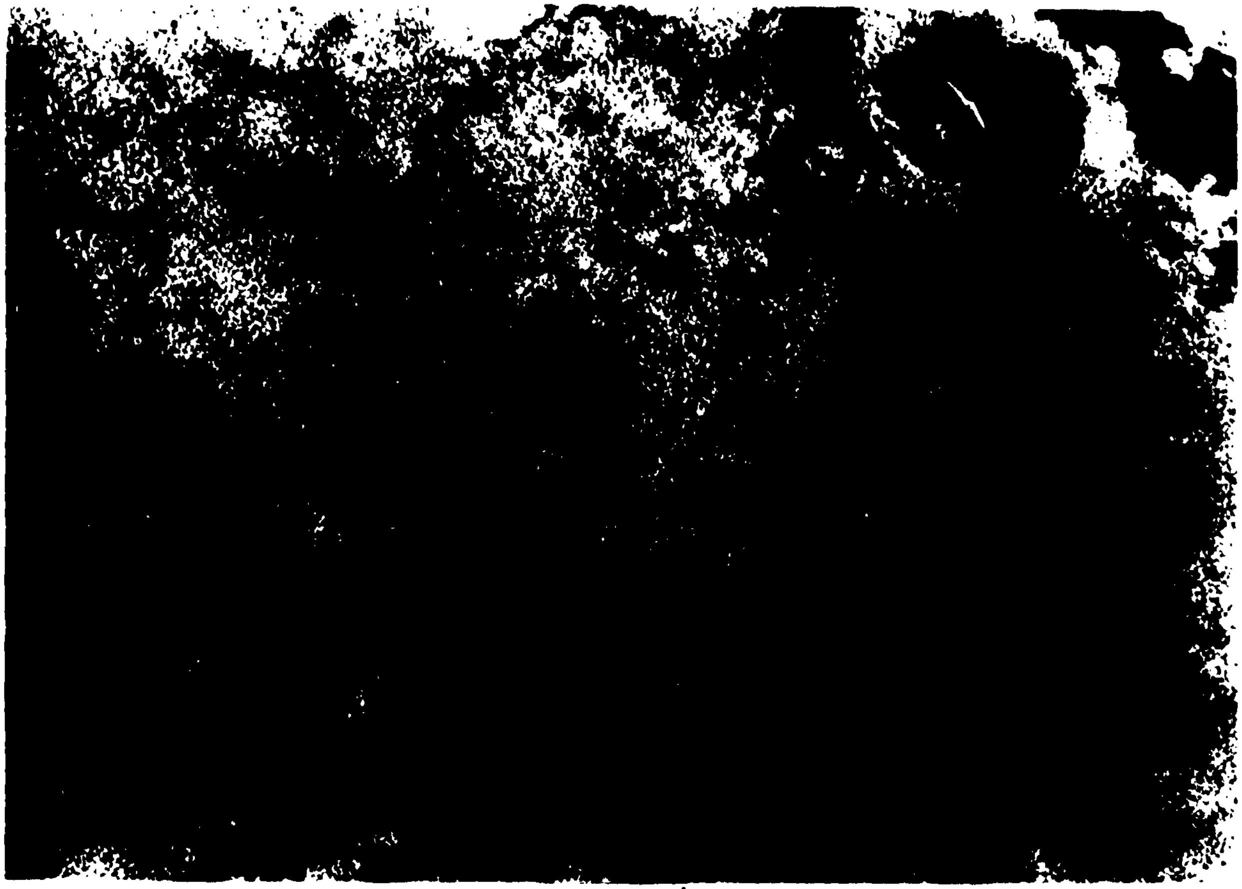


Figure 24

Figure 25