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PART 3

INVESTIGATION OF ALLOYS OF MAGNESIUM AND THEIR PROPERTIES

Part 3. The Origin of the Double Peak in the Texture of Certain Rolled Magnesium Alloys

THE DOW CHEMICAL COMPANY

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FOREWORD

This report was prepared by The Dow Chemical Company, under Government Contract No. AF 33(616)-2337. The contract was initiated Project No. 7351, "Metallic Materials" Task No. 73514," Improved Magnesium Alloys. RDO 615-15, "Improved Magnesium Alloys" and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Lt. J. D. Wood acting as project engineer and editor of the report.

This report covers work conducted from February 1954 to February 1955.

ABSTRACT

Inhomogeneous deformation has been studied in high-purity magnesium and magnesium-calcium alloys. Metallographic examination of cold-rolled sheet disclosed that narrow bands of preferential recrystallization had occurred in the alloys containing less than 0.055 percent calcium. These bands rotated toward the rolling plane with increasing reduction while newly formed bands subtended an angle of 30°. Room temperature compression tests on hot-rolled material showed that the magnesium showed banding whereas a Mg-0.5 Ca alloy did not, in agreement with the observations on sheet. The homogeneity of deformation also showed anisotropy in the compression tests. In both compression and rolling the bands became eventual crack loci.

A large amount of information on preferred orientation of flat magnesium alloy extrusions has been obtained. As in the case of rolled magnesium alloy sheet, various deviations from the ideal orientation occur. These deviations are primarily rotations of the maximum basal pole density about the transverse direction as an axis. In addition, marked variation of preferred orientation with depth below the surface has been found. Profile plots of the rotation as a function of depth fall into two broad groups: (1) those which show a double orientation at the center and (2) those which show a single orientation at the center. A theory is outlined in an attempt to explain these general categories of sheet and flat extrusions. Basal slip and twinning are assumed of primary importance. Compressive strains are modified by shear strain in such a way as to explain many of the experimental observations in a consistent manner.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
TECHNICAL DIRECTOR
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INTRODUCTION

The ideal orientation for magnesium alloy sheet and flat extrusions is defined as that of parallelism between the surface and the basal plane. This is manifested in the corresponding (0001) pole figure by a single density maximum at the center. Textures representing a spread about this ideal have been reported for magnesium and its alloys since about 1930.(1-4) A few years later investigators began to recognize a significantly different (0001) texture, one which displayed two maxima placed in the normal direction - rolling direction plane symmetrically about the center of the pole figure.(4-14,23) An important way to facilitate production of this texture was thought to be the addition of calcium to magnesium. The published material as well as that which remains unpublished contains various attempts to explain the double texture. Most of the explanations have involved the entrance of a new twinning system $\{10\bar{1}1\}$ or the influence of non-basal slip systems.

This research was undertaken as the most recent attempt to understand the double maximum texture. The experimental approach has been threefold. First, the microstructural characteristics of a cold-rolled series of Mg-Ca alloys were examined in connection with a determination of the preferred orientation. Second, a study of the compression of cylinders of magnesium and a Mg-Ca alloy has been conducted to obtain equivalent microstructural evidence under conditions where the strain is an important simplification of the flow in rolling. Finally, a large amount of evidence has been obtained on the preferred orientation of flat recrystallized magnesium alloy extrusions. Since the double texture is also important in flat extrusions, it was hoped that some generality would be added to the picture. A theoretical explanation of the preferred orientation observations in magnesium alloys is outlined in the final section of this report.

Rolling of Mg-Ca Alloys

Experimental.

A series of alloys of pure magnesium plus calcium was prepared with the compositions shown in Table I. The 2 x 4 x 8 inch ingots were rough machined on the rolling surfaces, homogenized and hot rolled at 650F to 0.066 inch. The cold-rolling was performed at room temperature and 80 ft/min on an 8 inch mill. Each alloy was cold rolled to gages of 0.059, 0.048, 0.038, 0.028 and 0.018 inch with intermediate anneals between each level.

The preferred orientation was obtained with a Norelco x-ray spectrometer modified for the Schultz surface reflection technique.(15) Metallographic examination was made on each cold rolled specimen.

Previous studies have shown the variation in preferred orientation through the thickness of rolled magnesium alloy sheet to be significant.(14)(16) In this phase of the work, the orientation was determined on surfaces which were obtained after etching away one quarter of the sheet thickness in all cases. The pole density (x-ray intensity) data in the plane containing the rolling direction and the normal direction are summarized in Table II. The numbers 30-0-30 at the top of the columns refer to the angle between the normals to the reflecting (002) planes and the rolling plane normal. The vertical axis represents the intensity of x-ray reflections. Orientation changes for a given alloy do not undergo any marked variations with increasing reduction. The curves may be classified by shape into two broad categories: (1) rather irregular but fully developed peaks below 0.055 Ca and (2) markedly flattened orientations, tending toward a plateau rather than a peak above this calcium level. A slight double peak may be resolvable at higher reductions in the 0.18 Ca alloy.

Metallographic examination of sheet specimens disclosed that the lower calcium bearing alloys exhibited numerous bands of preferentially recrystallized grains lying at an angle to the rolling plane, Figures 1-5. The density of these bands increased with increasing reduction although the individual band widths did not change. The metallographic specimens were mounted in metal clamps rather than in hot plastic. Thus, the recrystallization must have occurred during or immediately after rolling. Similar microstructures were seen for calcium contents up to 0.055%, Figures 6-10. Above this level, the sheet showed no evidence of these lamellar regions of preferential recrystallization, Figures 11-15.

Measurement of the angles between the rolling plane and the bands showed that the angle was approximately 30° and that it remained essentially constant regardless of the percent reduction. Since the sheet was annealed between each reduction and the bands showed no progressive increase in angle, it must be concluded that they were generated anew during each rolling cycle. This would mean that the preferentially recrystallized bands are obliterated by general recrystallization and grain growth during each annealing treatment. Examination of specimens after annealing between 15 and 20 hours at 400F revealed there was no evidence of any bands.

It was noted without exception that incipient cracking during rolling occurred within the bands containing fine recrystallized grains, Figures 1-10. At calcium contents above 0.055%, no bands were seen and no evidence of cracking was observed.

An additional study was performed on the 0.017 Ca alloy without the use of intermediate anneals between stages of the cold rolling. The purpose of this work was to obtain information on the rotation of the early-formed bands during later deformation.

Metallographic examination showed that the bands formed initially at an angle of 30° to the rolling plane and their inclination remained approximately constant for reductions up to 15%. However, the number of bands was observed to increase with increasing reduction. Apparently it is easier to form new bands between the relatively widely spaced bands at these levels of reduction rather than to promote rotation of the bands. New bands which form during each increment of reduction above 15% subtend an angle of 30° to the rolling plane while the first-formed bands undergo rotation. Figure 16 is a low magnification photograph of the cross section of the sheet specimens. The bands subtend a decreasing angle to the rolling plane as the reduction increases. Several well developed cracks may also be seen parallel to the bands.

If the bands which subtend an angle of 30° are omitted and the mean angle of the bands is plotted as a function of the percent reduction, Figure 17 is obtained. The calculated amount of rotation was determined by the relationship: $\frac{t_o}{t_1} = \frac{\sin \alpha_o}{\sin \alpha_1}$. The agreement between calculated and observed values would probably be even closer if the band started to rotate with the initial reduction.

Discussion

The pronounced tendency at the low calcium contents to form lamellar regions which are intimately associated with incipient cracking implies localized regions of high strain. In other words, these alloys appear to deform heterogeneously. On the other hand, alloys containing more than 0.055 Ca show no evidence of banding or cracking and appear to deform homogeneously. Additions of calcium promote more uniform deformation. It may be that the recrystallization temperature is raised sufficiently that the bands are not able to relieve the high strain by spontaneous recrystallization.

The observed band rotation with increased deformation is in reasonable agreement with the analogous situation of slip plane rotation during single crystal deformation. The bands are relatively stable during deformation and undergo rotation as a unit. It is clear that although localized deformation produced the bands, the structure between the bands must also undergo simultaneous deformation in order to accomplish the band rotation in its entirety.

It is interesting to note that the cracks in Figure 16 lie at an angle of 30° to the rolling plane although the greatest number of bands subtend a smaller angle at the higher reductions. Since the shearing stresses decrease and the normal stresses increase in the band as rotation occurs, this may be the explanation of the occasionally observed healing of cracks with increased rolling.

Such phenomena as these have been reported in the literature. Adcock(17) described some extensive studies on the deformation of cupronickel in which similar bands were removed by recrystallization. Grogan(18) reported observations on band formation in a Mg-Al-Mn alloy in which recrystallization occurred first within the bands upon annealing so that eventually the bands disappeared. He also expressed the opinion that the position of the bands was not simply due to orientation, since the bands crossed many grain boundaries.

Bands similar to those reported here have also been observed in the following rolled magnesium-base alloys. Mg + 1.8 Mn, ME20, AZ61A and AZ80A.(19)

Compression of Mg and Mg-Ca Alloy Cylinders.

Experimental.

As a result of the striking effect of the addition of >0.055 Ca on the homogeneity of deformation during the cold-rolling of magnesium, this study was planned to simplify the strain pattern. The influence of the compressive component of rolling was studied here.

Cylinders approximately 1/2 inch in diameter and 1/2 inch high were prepared from hot-rolled (700F) plate of (1) sublimed magnesium and (2) sublimed magnesium + 0.5 percent calcium. The initial grain size of the magnesium was about 10 thousandths of an inch and that of the alloy about 1 thousandth. A treatment of 15 hours at 1000F was used to bring the alloy grain size to about 10 thousandths of an inch. The specimens were electropolished on the cylindrical surface before the final compression. They were compressed at room temperature between smooth steel anvils on a hydraulic testing machine. A specimen of each material was compressed to fracture. A series of cylinders for each alloy was compressed to successively greater steps using intermediate annealing (700F-2 hours) at intervals of 4-5 percent strain. Complete recrystallization was obtained in these anneals. The deformed cylindrical surfaces were examined optically at low magnification. Transverse sections of selected cylinders were electropolished, etched and examined.

The specimens which were compressed directly to fracture are shown in Figure 18. The magnesium is on the left and the Mg-Ca alloy on the right. Two opposite sides are shown in (a) and (b). The marked difference in homogeneity of deformation is apparent and in agreement with the previous observations on rolled Mg-Ca alloy sheet. The magnesium fractured at 12.6 percent compressive plastic strain and the alloy fractured at 18.1 percent. Recrystallization followed the bands of localized deformation and fracture finally occurred along them in the magnesium. Deformation within the bands was of the same kind as outside them except that it was more intensive. Slip, low angle boundary formation (kinking and folding) and a very little twinning were the principal mechanisms observed.

The Mg-0.5 Ca alloy deforms uniformly until fracture occurs on a high shear stress plane. However, no bands of deformation or recrystallization were detectable. The cracks broke cleanly through the specimen, showing little or no preference for either grain boundaries or crystallographic planes. These results are further illustrated in the transverse sections, Figures 18c and 18d. The bands in the magnesium are inclined between 15 and 35° to the compression surface. Although electropolishing has cavitated the cracks greatly, the recrystallized zones between crack segments are visible.

Figure 19 presents the series which were given intermediate anneals. The electropolish was used just before the final compression for each cylinder. The difference in homogeneity of deformation was reaffirmed by these series. Although intermediate annealing recrystallized the specimen, the tendency for banding on further deformation remained. This also agrees with previously reported observations on rolled sheet.

It was decided to test the influence of another variable, hot-rolled preferred orientation, on the homogeneity of deformation before the observed differences were attributed solely to the presence of calcium. Cylinders were taken from the 1/2 inch hot-rolled magnesium plate so that compression axes were (a) parallel to the rolling direction (b) 45° to the normal direction and in the normal direction - rolling direction plane and (c) 45° to the normal direction and in the normal direction - transverse direction plane. Cylinders were also taken from a 1/2 inch round extrusion of sublimed magnesium. The extrusion was produced in the recrystallized condition at 600F. The compression and extrusion axes were parallel in one specimen and perpendicular in the other. All these cylinders were prepared, polished and compressed directly to fracture under the conditions described above. The results can be summarized briefly:

(1) The specimen with compression axis parallel to the rolling plane deformed quite homogeneously until cracking began on planes of high shear stress, Figure 20a. The surface appearance resembled more closely the Mg-Ca alloy behavior than that of the magnesium under compression perpendicular to the rolling plane.

(2) The specimens with compression axes at 45° to the normal direction showed a homogeneity intermediate to the perpendicular and parallel cases, Figure 20b. They deformed into elliptical rather than circular cylinders.

(3) The extrusion cylinder with compression and extrusion axes parallel behaved much as did (1) but showed more strain before cracking began, Figure 20c.

(4) The extrusion cylinder with compression and extrusion axes perpendicular, Figure 20d, show an intermediate appearance which was closer to the inhomogeneous extreme (hot-rolled plate compressed perpendicular to the rolling plane).

A brief check was made on the possible rate dependence of the inhomogeneous deformation characteristic of magnesium compressed perpendicular to the rolling plane. Tests were carried to fracture in the two extreme times of about 10 seconds and about two hours. There were no apparent differences from the behavior at normal rates (2-5 minutes).

Discussion.

The present results reinforce the viewpoint that the cold-rolling behavior of magnesium alloys must be explained with the assistance of the general knowledge of inhomogeneous deformation of metals. A marked change in compressive deformation characteristics over a narrow elevated temperature range has been reported for several commercial extruded magnesium alloys.(21) For example, a Mg-1 Mn alloy showed a clean shear failure in cylinders after a small amount of deformation at temperatures up to and including 515F. At 525F and above, the deformation was practically unlimited resulting in pancakes. The work was interrupted before any general conclusions could be drawn.

The observation of banding in the compression of cylinders is general for paraffin, marble and steel.(22) The effort to relate these observations and those of Luders band formation, occurrence of the yield point and step-stair stress-strain curves has only started in recent years. The compression study of variously oriented cylinders has shown that the homogeneity of deformation is dependent on the previous orientation to a degree which cannot be considered secondary. It is hoped that future work will reveal whether any part of the effect of Ca is tied to such orientation dependence.

Preferred Orientation of Magnesium Alloy Extrusions.

A number of preferred orientation determinations have been made on flat extrusions (1-1/4 x 1/8 inch) which were prepared for the purposes of another research. There appears to be enough such information at present to attempt a systematization and explanation. Two experimental techniques have been used. The majority of the data were obtained with a photographic forward x-ray diffraction method. The x-ray beam, extrusion normal and transverse directions are coplanar. The (0002) ring produced in the pattern shows an angular intensity variation corresponding to the reflection circle which passes through the center of the (0001) pole figure. The maxima are located by visual examination. The corresponding angular rotation toward (+) or away from (-) the extrusion direction is plotted as a function of depth below the surface. This "profile" plot gives to a very close approximation the maximum density positions along the north-south axis of the pole figure.

In some cases, pole figures were developed at successive levels below the surface using the modified Schulz technique(15) and a Norelco x-ray goniometer. The two methods agreed quite well. The spectrometer technique was the more sensitive. It is good to know that the abbreviated photographic method gives an accurate representation of the pole density maximum positions along what is almost invariably the most important axis of the pole figure.

The first thing that one realizes from examining a group of profile plots is that in general a remarkable variation in preferred orientation with depth below the extruded surface exists. It appears that from either a theoretical or practical viewpoint a pole figure at the surface of a magnesium alloy extrusion gives an incomplete story of the texture. Both the maximum positions and the densities at the maxima vary markedly through the extrusion.

The textures fall into two broad categories, those which show a double orientation at some level below the surface and those which do not. The latter group by symmetry must exhibit either the ideal or a random texture at the center. Those which show a double orientation are plotted in Figures 21 and 22. This group includes electrolytic magnesium and binary alloys containing 0.06 Ce, 0.7 Ce, 6.0 Ce, 3.1 Th, 3.4 Th and 5.2 Th. The group which does not show the double texture, Figure 23, includes alloys of electrolytic magnesium with 2.0 Al, 6.2 Al and 10.3 Al.

Especially interesting orientation variations near the surface are seen in the double texture group. These are comparable to those surface variations observed in rolled magnesium alloy sheet by Hargreaves(16) and later in this laboratory.(14) However, in extrusions the percent of volume so affected is somewhat greater. This surface effect appears in electrolytic magnesium and the cerium alloys at positive rotation and the minor element is negative. In the thorium alloys the negative element is the major one and it shows the surface variation in the 3.4 and 5.2 Th compositions. The 3.1 Th alloy, which received a somewhat different treatment in extrusion shows no surface variations. In these alloys the angular deviation from the ideal of the maxima of the elements has reached ± 35-40°. In other words, the angular difference between the maxima has reached the surprisingly high figure of about 80°.

Essentially complete extrusion surface (0001) pole figures have been developed for the 0.7 Ce, 3.1 Th, 3.4 Th and 5.2 Th alloys, Figures 24-27. A series of (0001) pole figures at increasing depths below the extruded surface of the 5.2 Th alloy appear in Figures 27-34. The x-ray intensity levels shown on the figures should be proportional to (0001) pole density. The pole figures are complete only out to about 60° from the center.

This represents the limit of utility of the reflection technique. Fortunately in magnesium alloys, there is good reason to believe that no major density maxima lie in the outer 30° of the figure. However, as will be seen later in this report, certain important points in the theory of preferred orientation development may hinge on the minor details of pole density in this region. A transmission technique to cover this region would be desirable and should utilize thin specimens in order to avoid averaging the orientation over a depth variation.

The pole figures agree quite well with the profile plots. The growth of the minor element and the decrease of the major element as the depth below the surface increases is illustrated in a way that cannot be shown in the profile plots. The latter can communicate no quantitative information on density or sharpness of maxima. The only place where the profile plots fail to give the complete story on location of maxima is in the case of Figures 26 and 29. In these figures the major (negative rotation) elements really have two subsidiary maxima on each side of the normal direction - rolling direction plane.

The extrusions studied here were all recrystallized during the extrusion process, that is these are so-called hot-extruded textures. The alloys containing 0.7 Ce, 6.0 Ce, 3.1 Th, 3.4 Th, 5.2 Th, 6.2 Al and 10.3 Al were two-phase. The profile plots for the series of cerium alloys, Figure 21, indicate that the effects of solid solution preferred orientation which we are interested in studying are not significantly influenced by the presence of a small amount of second phase.

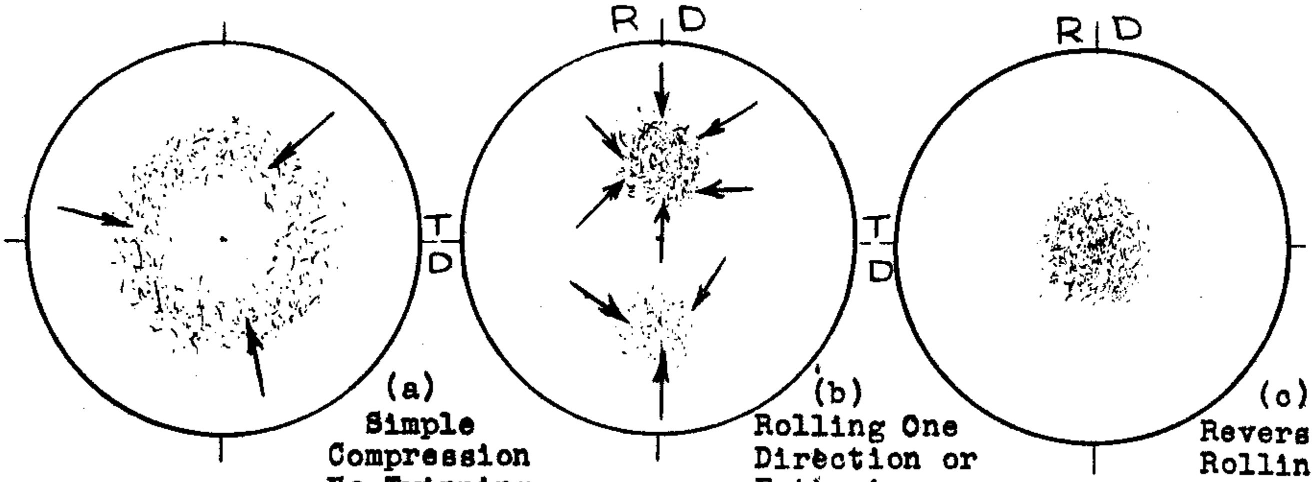
Outline of the Theory

A comparison of the preferred orientation data for rolled magnesium alloy sheet and flat extrusions has shown that both may be categorized broadly into single and double textures. It appears that one could not always be sure into which category an alloy sheet or flat extrusion fell from a determination made on the surface only. If the texture is double at the surface, it can be expected to be double throughout, but if it is single at the surface the evidence is uncertain.(14)(16) The center of the thickness would be the best place to make a single determination. Of course, the very best picture of the preferred orientation is in a series of determinations at different levels from surface to center.

All of these observations suggest that a general theory of preferred orientation generation, applicable to both rolling and flat extrusion, is possible and desirable. Let us assume that basal slip and mechanical twinning are the most important deformation mechanisms involved in the generation of preferred orientation in magnesium alloys. On this simple basis let us predict what will happen in single compression of a randomly oriented aggregate of magnesium grains. An application of the ideas of Calnan and Clews(20) predicts that grains within 68° of the compression axis would rotate toward the center of the projection forming a broad ring as in (a) below. Grains outside the 68° ring prefer to twin and reorientation occurs thereby into the center of the projection. A reorientation of ~86° occurs as a result of a strain of only ~6%.

In passing to the case of rolling, we effectively superimpose a shear strain on the primary compression component. Many studies of the flow of artificially located lines or bands initially perpendicular to the rolling direction have shown that a shear strain gradient generally exists at the end of the rolling deformation. Although the strain analysis in extrusion is more complex, similar experiments have shown the existence of a shear strain gradient and an effective compression component there also. In general the shear strain is maximum at the surface after rolling or extrusion is complete. It seems reasonable that this shear strain will alter the preferred orientation from that of simple compression in a different way at the surface than at the center. With rolling in one direction only or extrusion schematic surface pole figure (b), the alteration from (a) involves the reduction of slip-produced orientations to two maxima and the favoring of one maximum over the other. When reversed rolling is used, the favored surface maximum may come to the ideal position under the influence of reversing shear strain, as in (c). The pole figures in Figures 24, 25 and 27 show the case of (b) for extrusions. The observations of (b) and (c) for AZ31B and AZ31A (calcium-bearing) sheet have been made for non-reversed and reversed rolling, respectively.(14) Hargreaves(16) found (c) apparently using reversed rolling with Mg-1.5 Mn alloy sheet.

SCHEMATIC SURFACE POLE FIGURES

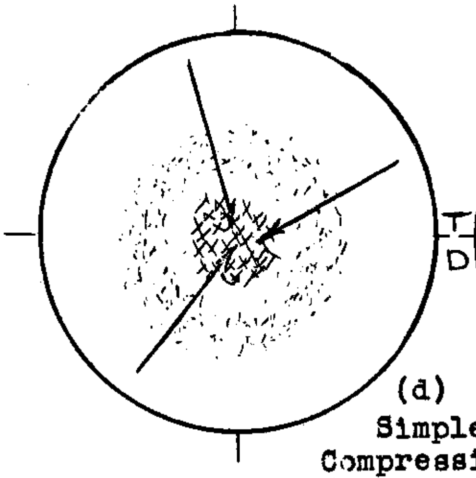


(a) Simple Compression No Twinning

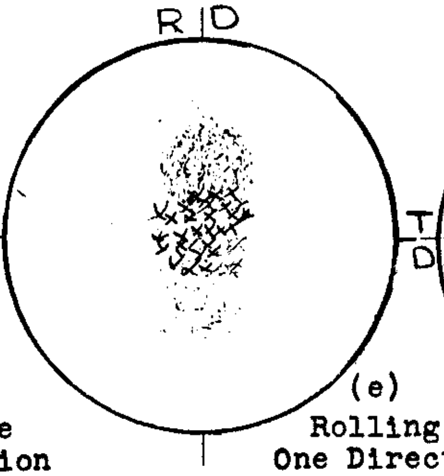
(b) Rolling One Direction or Extrusion No Twinning

(c) Reversed Rolling No Twinning

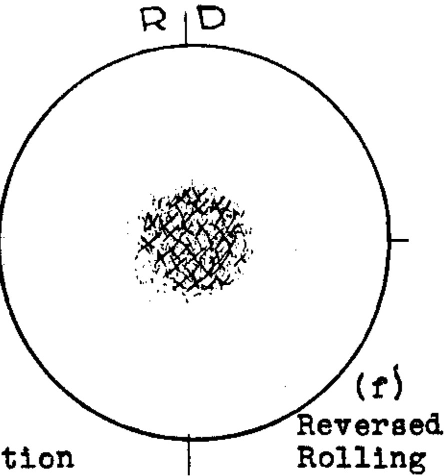
If twinning becomes appreciable, a fill-in of orientation at the pole figure center is predicted and the schematic surface pole figures would modify to (d) (e) and (f).



(d)
Simple
Compression
Twinning

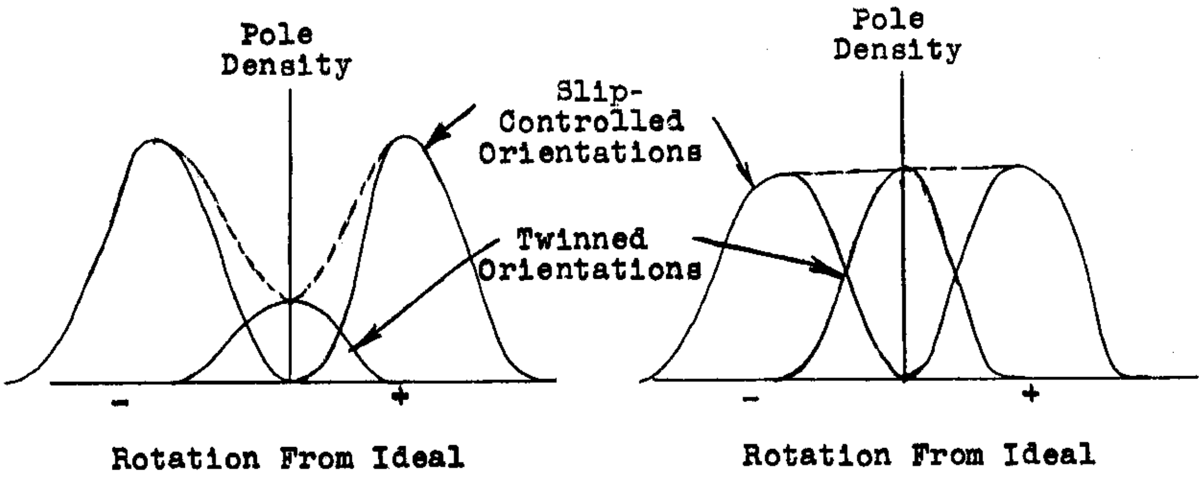


(e)
Rolling
One Direction
or Extrusion
Twinning



(f)
Reversed
Rolling
Twinning

The preferred orientation at the center of the sheet will show either the double texture with equal density peaks or the single texture, depending on the amount of twinning. The pole density variations in the rolling direction - normal direction plane for two levels of twinning are shown schematically:



In intermediate cases and when curve shapes are proper, a plateau curve may develop. Thus, it is possible to explain any of the curve shapes seen in Table II, for example. An examination of the density per area data developed from double maximum pole figures by Bakarian(4) indicates that 15-30% twinning by volume might be expected to convert to a single maximum. The higher figure would be more realistic if only 50% of the twinning was from the peripheral orientations required by the model. Such amounts of twinning are often observed in cold-rolled magnesium alloys.

If this theory is correct, anything which reduces twinning will favor the double orientation and anything which increases it will favor the single maximum. The factors which control the amount of twinning in magnesium are not known well enough at present. However, they may be separated into (a) probably the most important and best studied variable, orientation and magnitude of the stress and (b) other suspected variables, prominent among which are temperature, alloy content and strain rate. Thus, in principle one could decrease twinning and favor the double texture (a) by initially excluding grains from the peripheral orientations or (b) by increasing temperature, alloying or decreasing the strain rate. Since the influence of calcium on the stress necessary for twinning in magnesium is not known, it is uncertain in which way this element might have more effect. At least, the results of the compressed cylinder study harmonize with the present model in that the magnesium specimen showed twinning whereas the Mg-Ca specimen did not, Figure 18. If we are trying to predict a cold-rolled texture the pole density of the hot-rolled texture in the outer regions should be an important criterion. Similarly, the orientation of an extrusion should be dependent on whether the starting material was cast-equiaxial grained or pellet (random orientation), cast columnar or pre-extruded (preferred orientation).

It has been found that recrystallization first favors removal of twins to the parent orientation in magnesium. On the basis of the present model, when the single texture is observed in a cold-worked structure, it might be resolved into the double texture because of twin removal. One such occurrence has been observed for a Mg-0.6 Th alloy which was cold-rolled 30% and then annealed 1 hour at 400F.(13)

Since this model ignores deformation mechanisms which are known to occur, such as non-basal slip, it cannot be completely correct in detail. It should be judged on its ability to explain most of the observations of magnesium alloy preferred orientation in a consistent way. Further effort is needed to extend the aspects of the theory involving the gross rheology to the stage where the surface variations of the double and the general variation of the single texture with depth are explainable.

CONCLUSIONS

1. The addition of 0.055 percent calcium to high purity magnesium engenders homogeneous deformation during rolling by suppressing the formation of preferentially recrystallized bands.

2. The constancy of the angle of the recrystallized bands to the rolling plane indicates that they are a geometrical result of the forces operative during the rolling process.

3. The angle, α, between the bands and the rolling plane decreases with increasing reductions according to the

relationship

$$\frac{t_0}{t_1} = \frac{\sin \alpha_0}{\sin \alpha_1}$$

where t is the sheet thickness.

4. The compressive component in rolling is the primary cause of the banding in unalloyed magnesium.

5. Hot-rolled magnesium plate showed an anisotropy of homogeneity during cold deformation which cannot be considered secondary.

6. The preferred orientations of magnesium alloy sheet and flat extrusions can be grouped into two broad categories which show single or double (0001) maxima in the center of the section.

7. The categorization of sheet or flat extrusions on the basis of surface orientation alone can be misleading.

8. Since the double orientation is observed in unalloyed magnesium as well as many different alloys, any theory of it should be expressed in fairly general terms.

9. The assumption of the primary importance of basal slip and twinning in rolling or extrusion allows an explanation of the major features of the surface and center preferred orientations of magnesium alloy sheet and flat extrusions.

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TABLE I

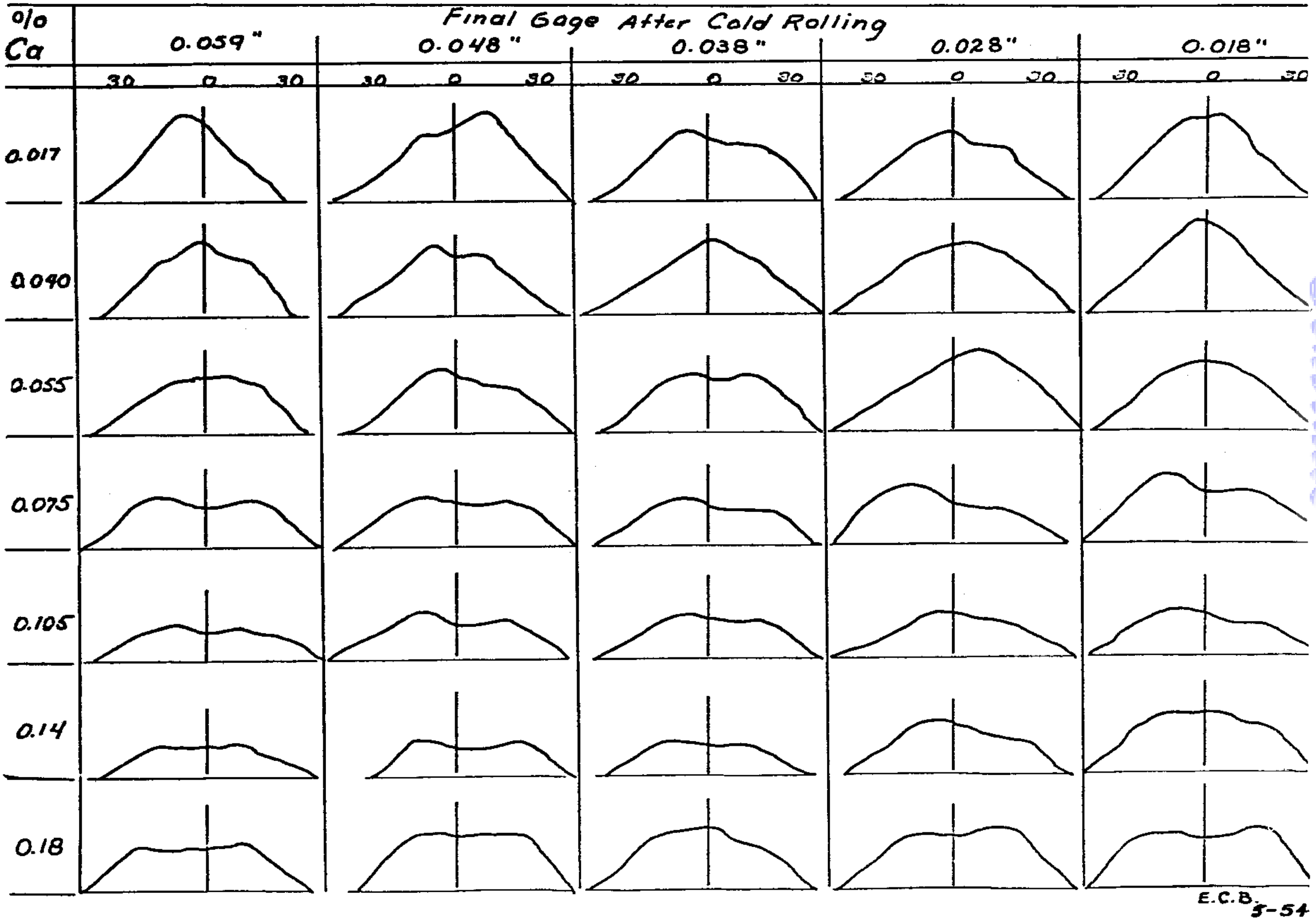
ANALYSES OF Mg-Ca ALLOYS

Alloy No.	% Al	% Ca*	% Ca**	% Cu	% Fe	% Mn	% Ni	% Pb	% Si	% Sn	% Zn
1	.0001	.015	.017	.0001	.0011	.0007	.0001	<.0004	.0035	<.001	<.02
2	<.0001	.047	.040	<.0001	.0006	.0004	.0001	<.0004	.0023	<.001	<.02
3	<.0001	.083	.075	.0002	.0007	.0004	.0001	<.0004	<.001	<.001	<.02
4	<.0001	.063	.055	<.0001	.0007	.0005	.0001	<.0004	.0012	<.001	<.02
5	<.0001	.118	.105	<.0001	.0008	.0005	.0001	<.0004	<.001	<.001	<.02
6	<.0001	--	.14	.0002	.0006	.0004	.0001	<.0004	.001	<.001	<.02
7	.0001	.14	.18	.0002	.0006	.0004	.0001	<.0004	.0021	<.001	<.02

*Spectrographic Analysis

**Flame Spectrophotometer

Table II Preferred Orientation of (002) Planes in Plane Containing the Rolling Plane Normal and the Rolling Direction



BANDS OF PREFERENTIAL RECRYSTALLIZATION IN COLD ROLLED MAGNESIUM-CALCIUM ALLOYS

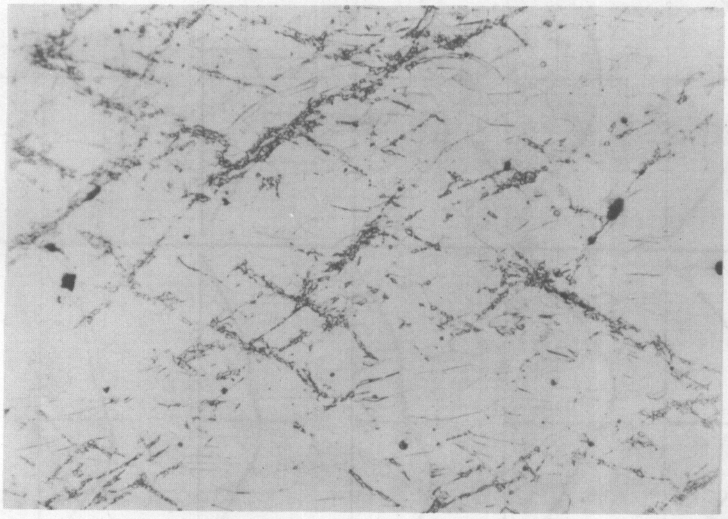


FIGURE 1
Neg. No. 34565 100X
Electro Polished
Acetic glycol etch
Alloy No. 75775 - Cold rolled to 0.059"

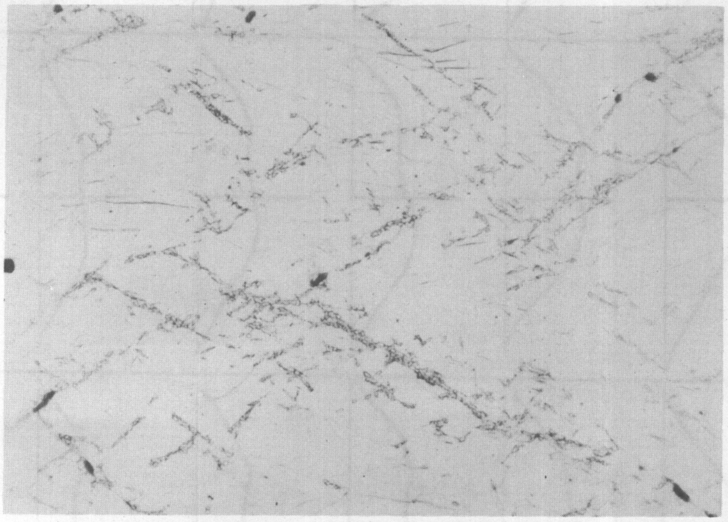


FIGURE 2
Neg. No. 34566 100X
Electro polished
Acetic glycol etch
Alloy No. 75775 - Cold rolled to 0.048"

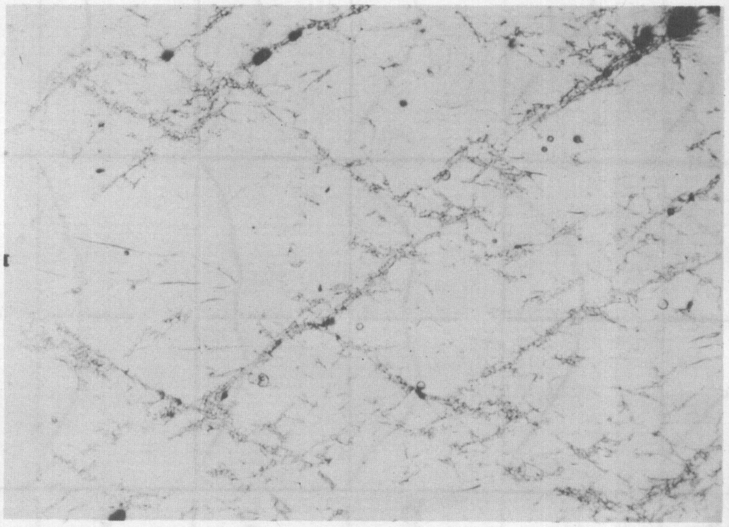


FIGURE 3
Neg. No. 34566 100X
Electro polished
Acetic glycol etch
Alloy No. 75775 - Cold rolled to 0.038"

FIGURE 4
Neg. No. 34568 100X
Electro polished
Acetic glycol etch
Alloy No. 75775 - Cold rolled to 0.028"

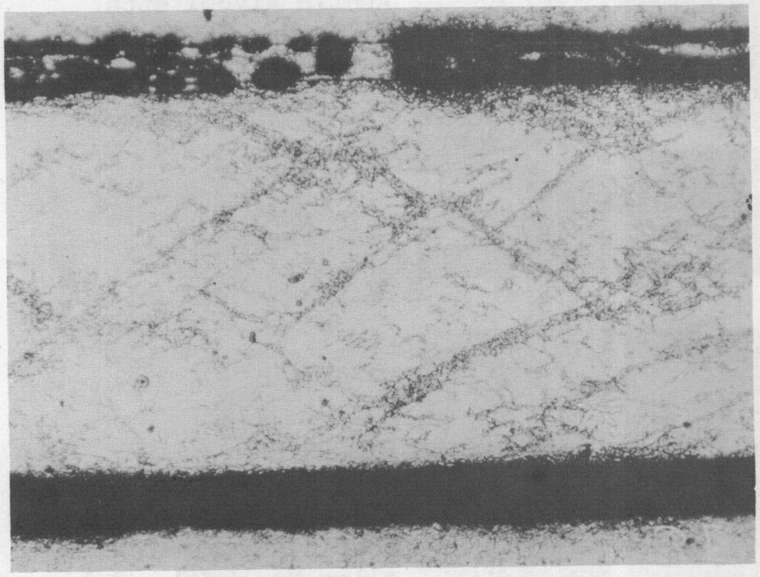


FIGURE 5
Neg. No. 34569 100X
Electro polished
Acetic glycol etch
Alloy No. 75775 - Cold rolled to 0.018"

BANDS OF PREFERENTIAL RECRYSTALLIZATION IN COLD ROLLED MAGNESIUM-CALCIUM ALLOYS

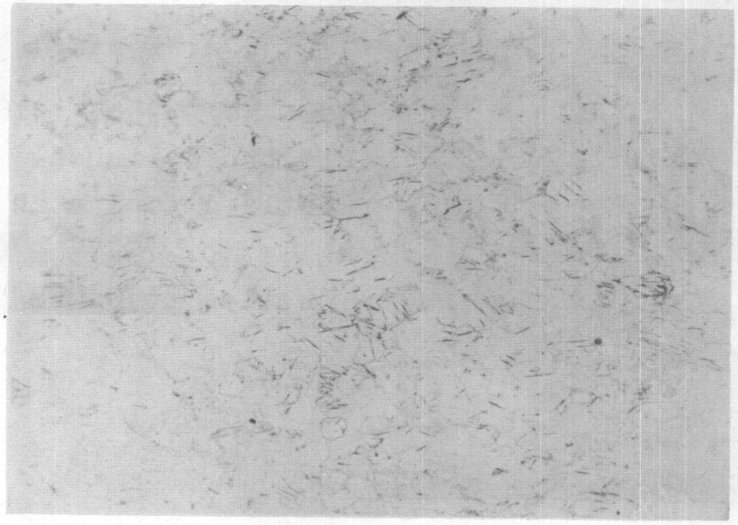


FIGURE 6
Neg. No. 34606 100X
Electro polished
Acetic glycol etch
Alloy No. 75778 - Cold
rolled to 0.059"

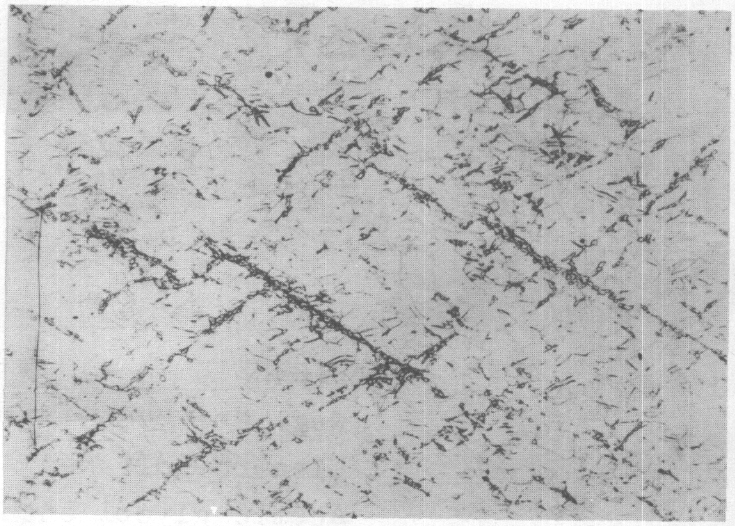


FIGURE 7
Neg. No. 34607 100X
Electro polished
Acetic glycol etch
Alloy No. 75778 - Cold
rolled to 0.048"

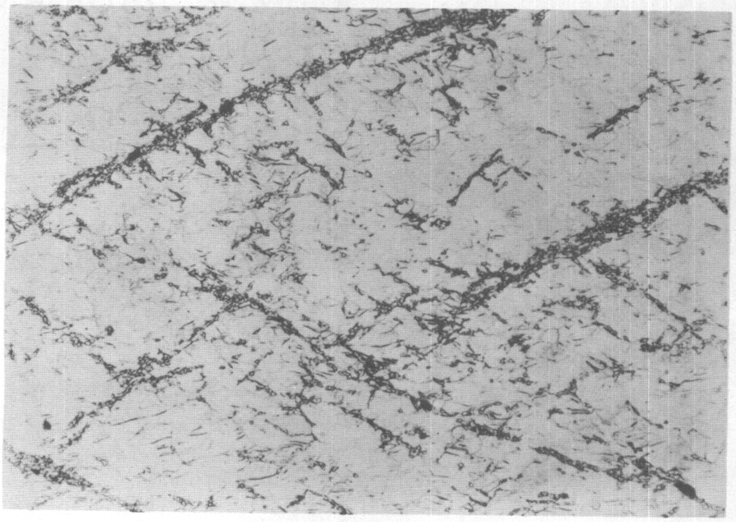


FIGURE 8
Neg. No. 34608 100X
Electro polished
Acetic glycol etch
Alloy No. 5778 - Cold
rolled to 0.038"

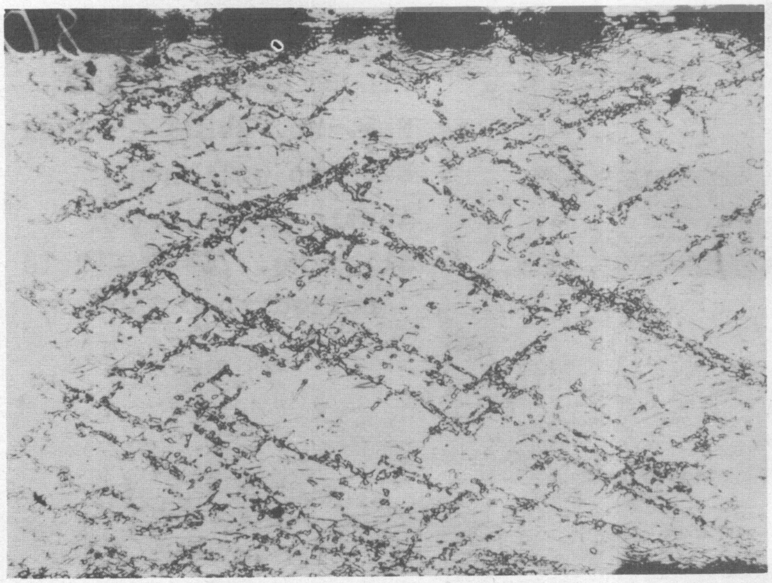


FIGURE 9
Neg. No. 34609   100X
Electro polished
Acetic glycol etch
Alloy No. 75778 - Cold
  rolled to 0.028"

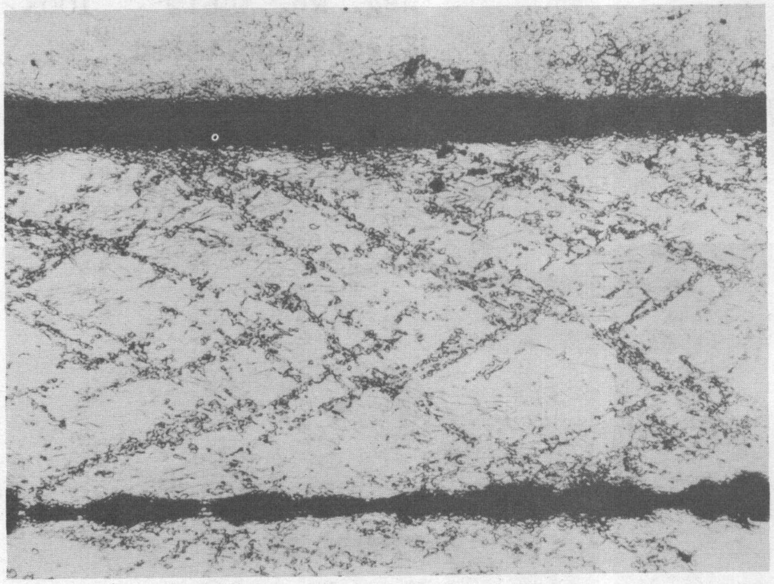


FIGURE 10
Neg. No. 34610   100X
Electro polished
Acetic glycol etch
Alloy No. 75778 - Cold
  rolled to 0.018"

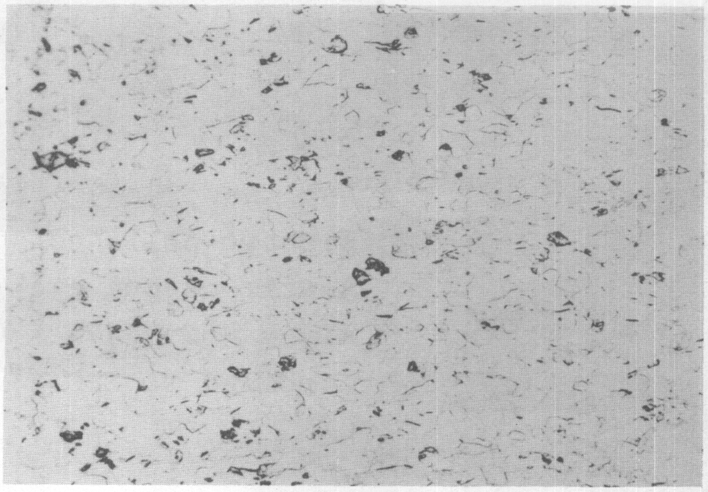


FIGURE 11
Neg. No. 34611 100X
Electro polished
Acetic glycol etch
Alloy No. 76432 - Cold
rolled to 0.059"

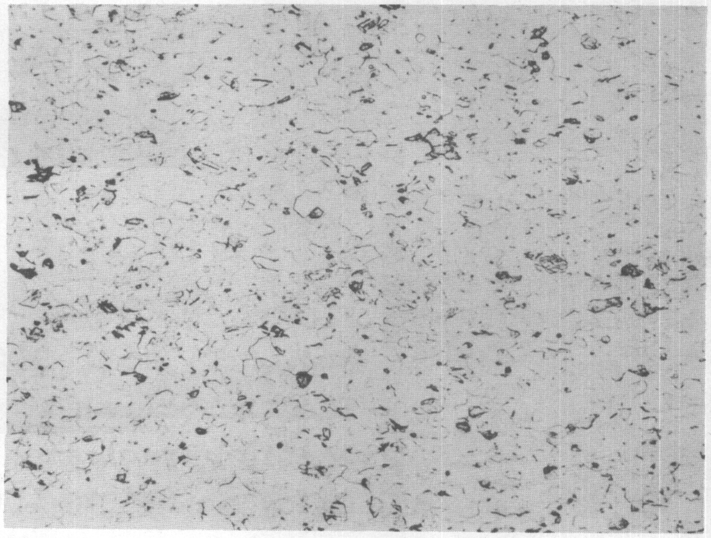


FIGURE 12
Neg. No. 34612 100X
Electro polished
Acetic glycol etch
Alloy No. 76432 - Cold
rolled to 0.048"

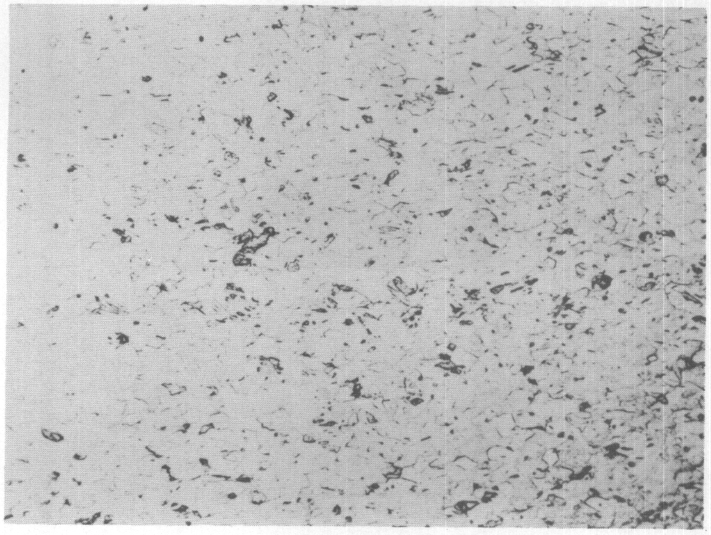


FIGURE 13
Neg. No. 34613 100X
Electro polished
Acetic glycol etch
Alloy No. 76432 - Cold
rolled to 0.038"

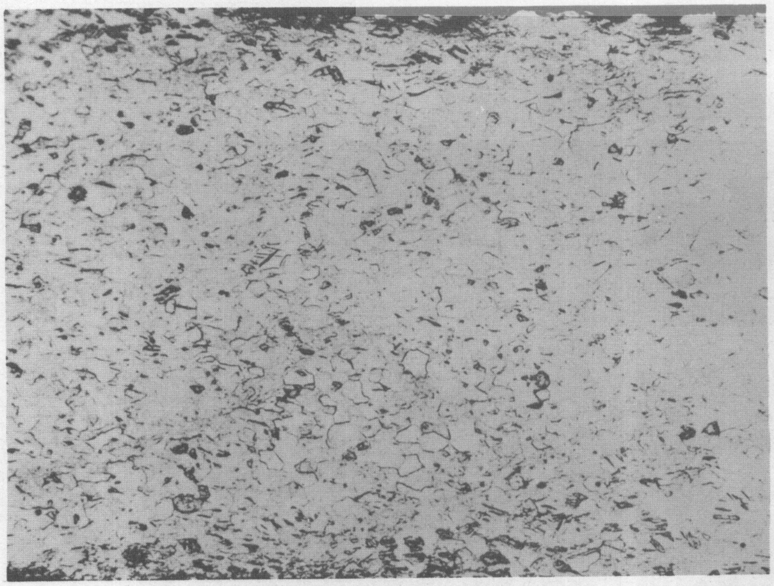


FIGURE 14
Neg. No. 34614 100X
Electro polished
Acetic glycol etch
Alloy No. 76432 - Cold
rolled to 0.028"

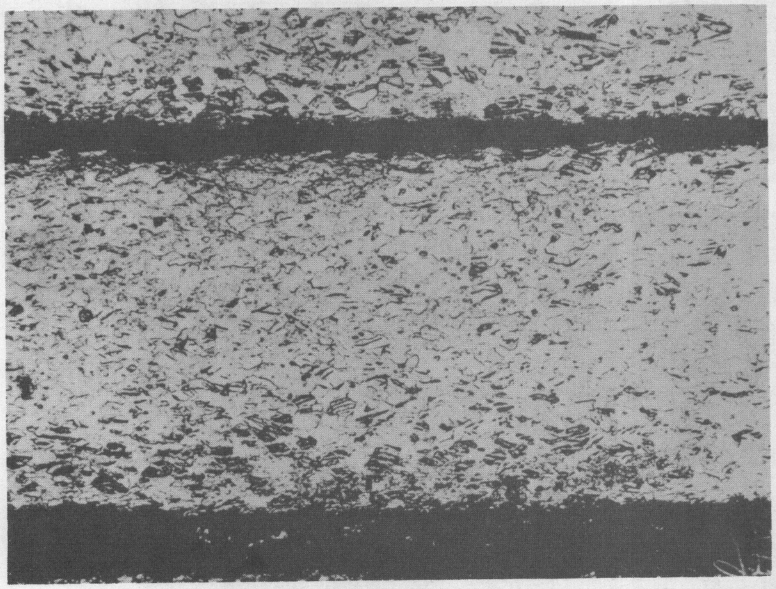


FIGURE 15
Neg. No. 34615 100X
Electro polished
Acetic glycol etch
Alloy No. 76432 - Cold
rolled to 0.018"

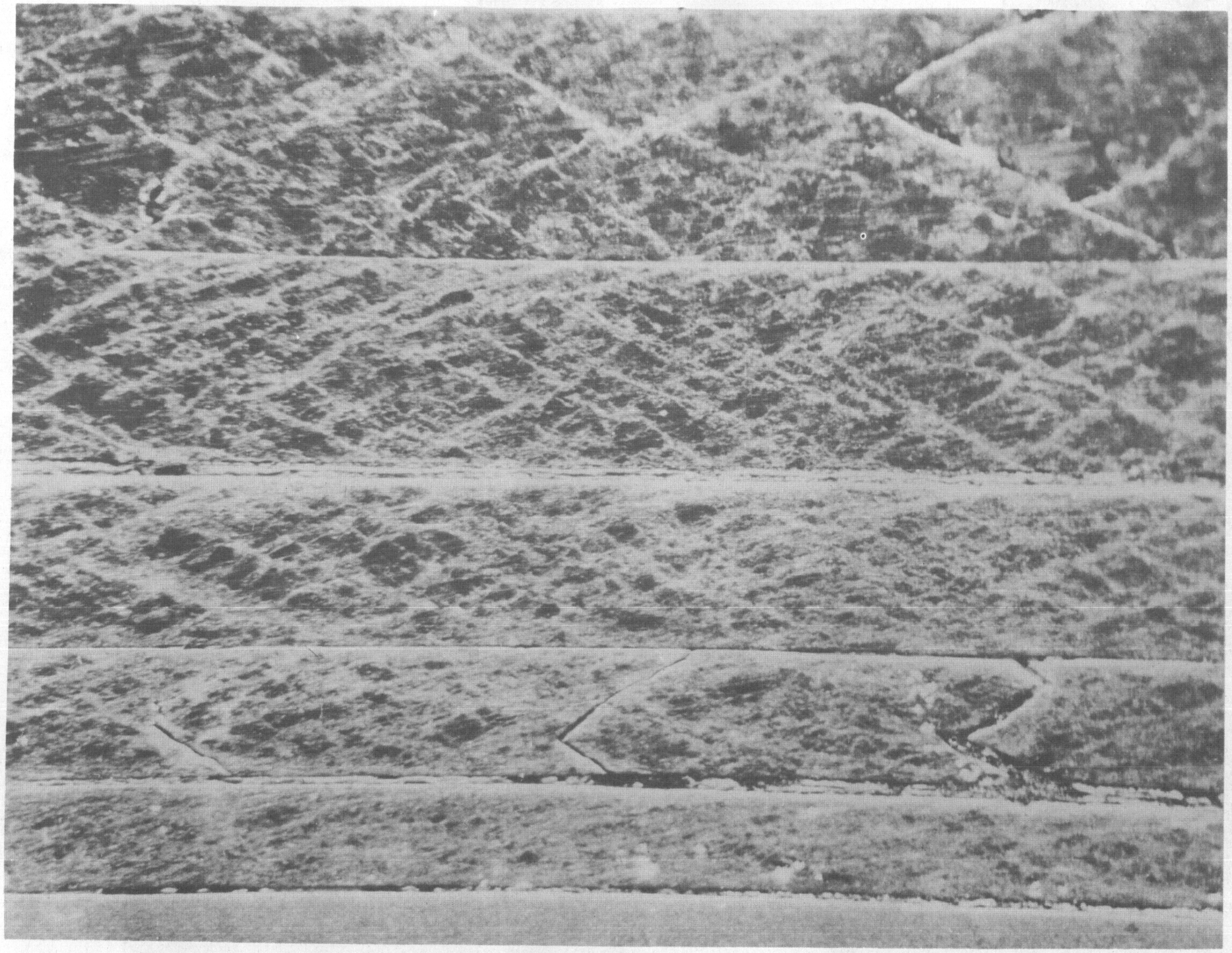


FIGURE 16 - CROSS SECTION OF Mg + 0.017% Ca SHEET TAKEN PARALLEL TO R.D. SHOWS DECREASING ANGLE BETWEEN BANDS AND R.P. WITH INCREASING REDUCTION.

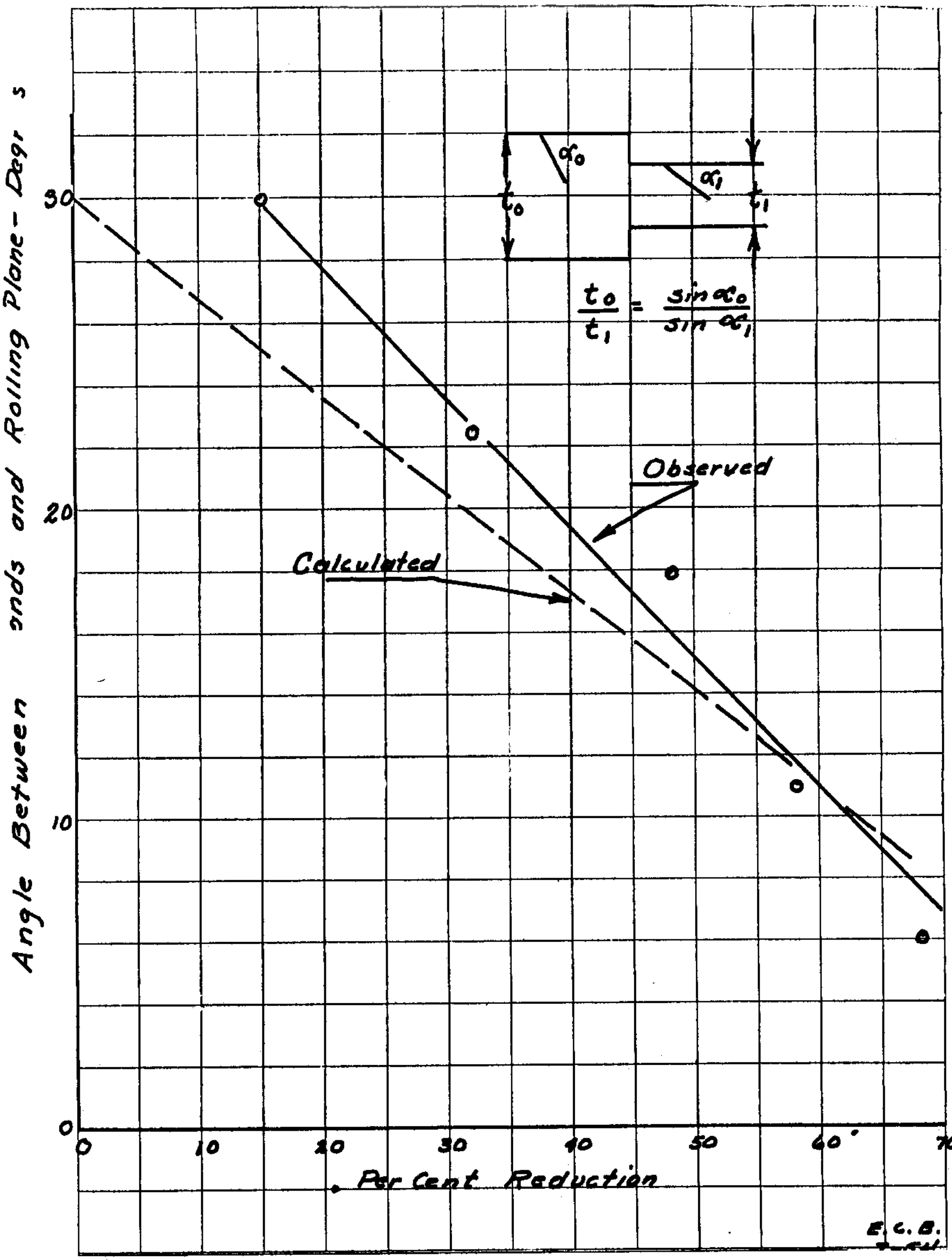
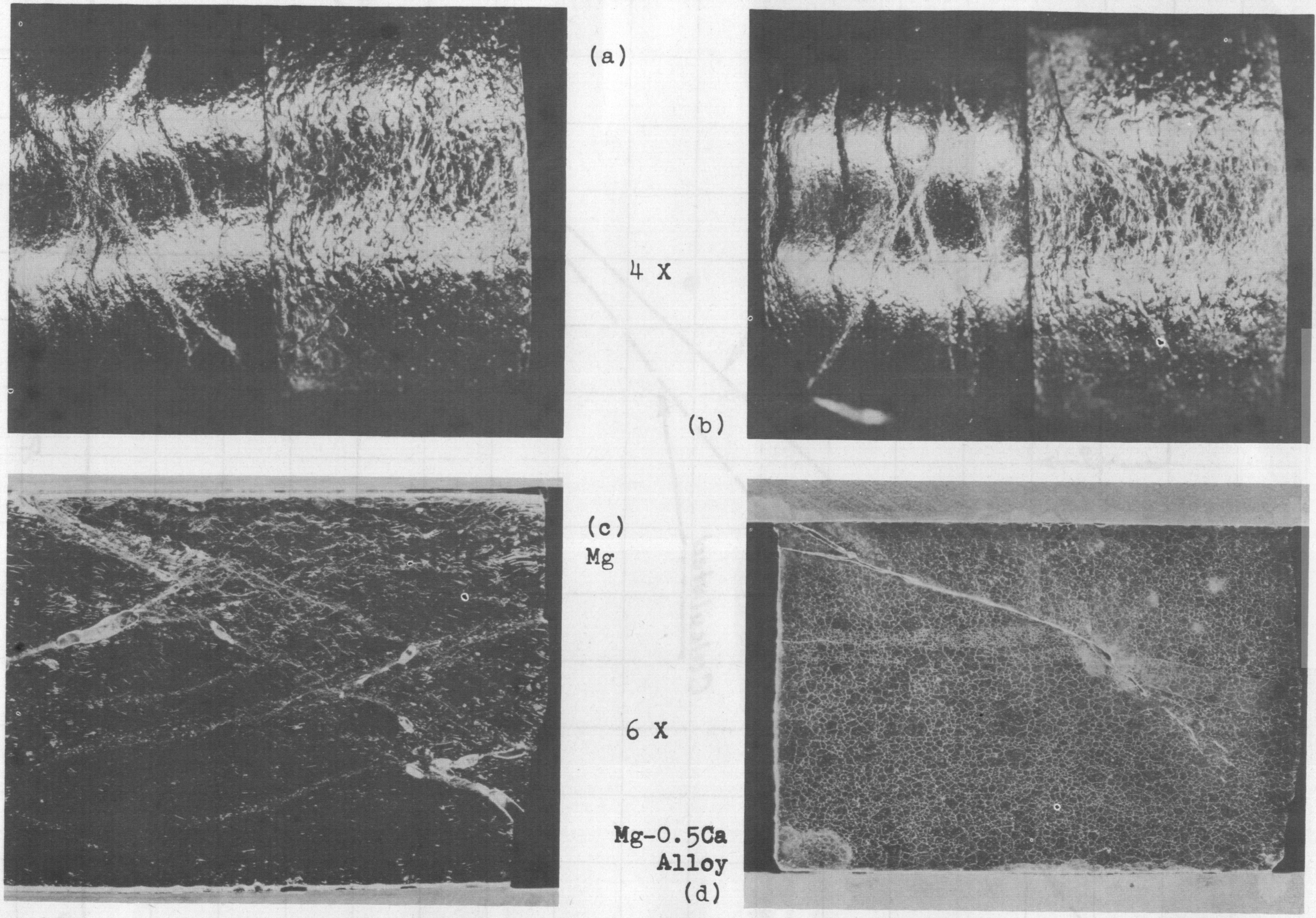


FIGURE 17 COMPARISON OF OBSERVED AND CALCULATED ROTATION OF BANDS DURING COLD ROLLING


(a)

(b)

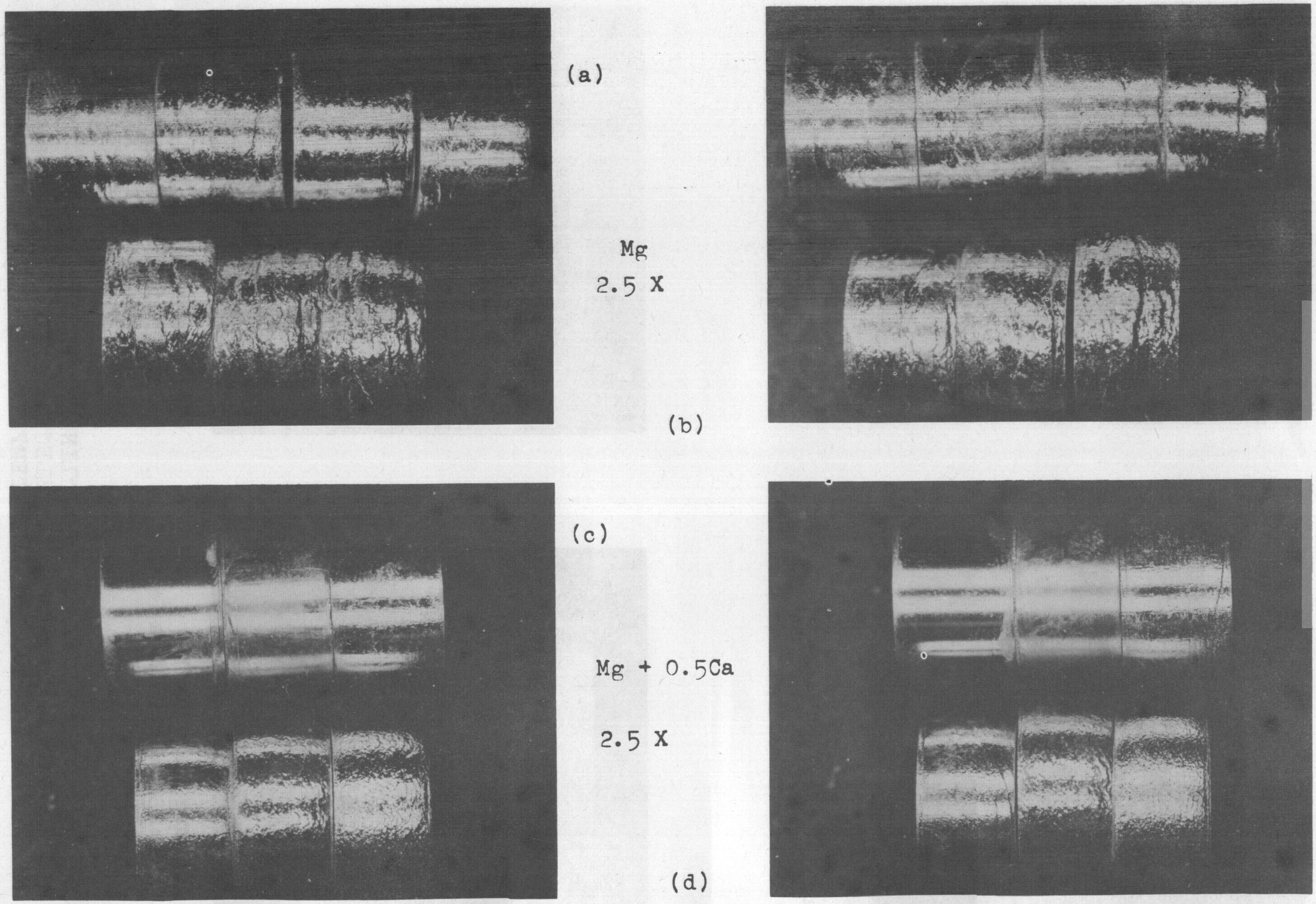
4 X

(c) Mg

(d) Mg-0.5Ca Alloy

6 X

FIGURE 18. MAGNESIUM AND MAGNESIUM-0.5 PERCENT CALCIUM ALLOY CYLINDERS COMPRESSED AT ROOM TEMPERATURE. Electropolished Before Compression.



(a)

Mg

2.5 X

(b)

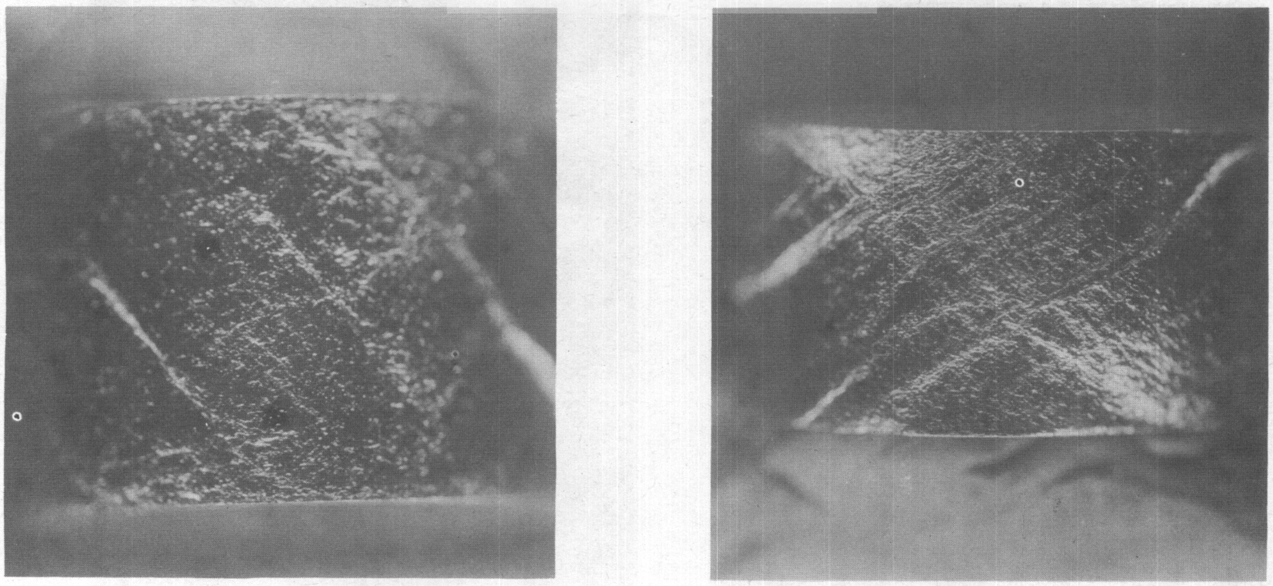
(c)

Mg + 0.5Ca

2.5 X

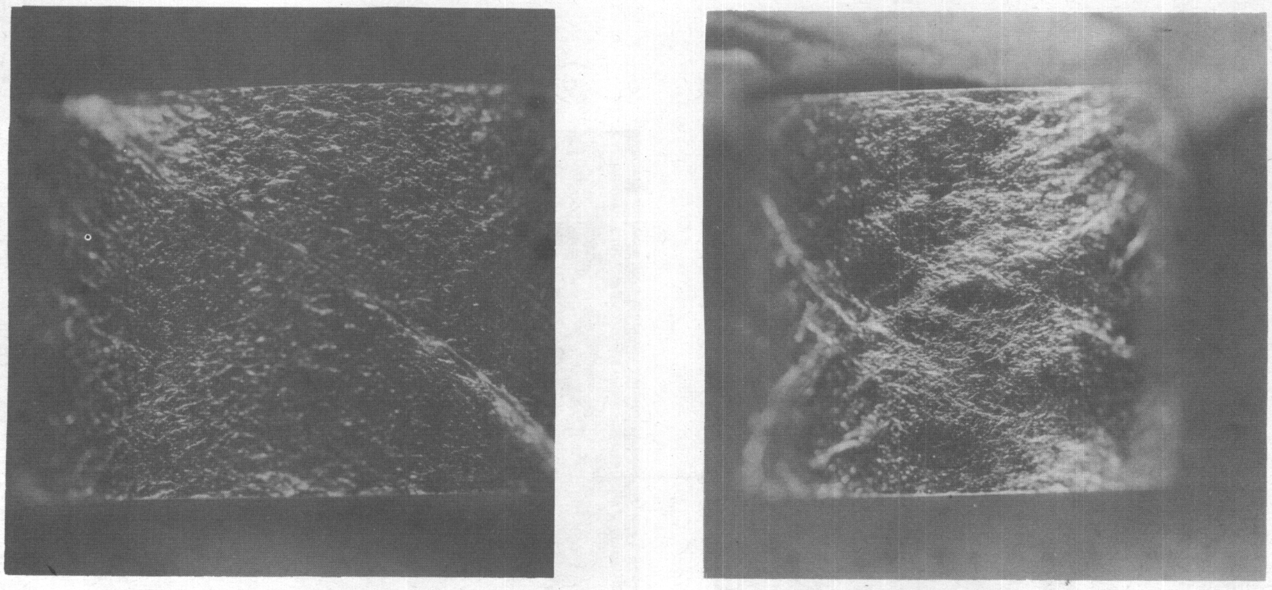
(d)

FIGURE 19. MAGNESIUM AND MAGNESIUM-0.5 PERCENT CALCIUM ALLOY CYLINDERS COMPRESSED AT ROOM TEMPERATURE. Electropolished Before Final Compression.



(a) Compression Axis Parallel to Rolling Plane of Plate

(b) Compression Axis 45° to Transverse Direction of Plate



(c) Compression Axis Parallel to Extrusion Direction

(d) Compression Axis Perpendicular to Extrusion Direction

FIGURE 20. SUBLIMED MAGNESIUM CYLINDER FROM HOT-ROLLED PLATE AND EXTRUSION AFTER ELECTROPOLISHING AND COMPRESSING TO FRACTURE AT ROOM TEMPERATURE. 5X

FIGURE 21

PREFERRED ORIENTATION PROFILES FOR MAGNESIUM ALLOY EXTRUSIONS

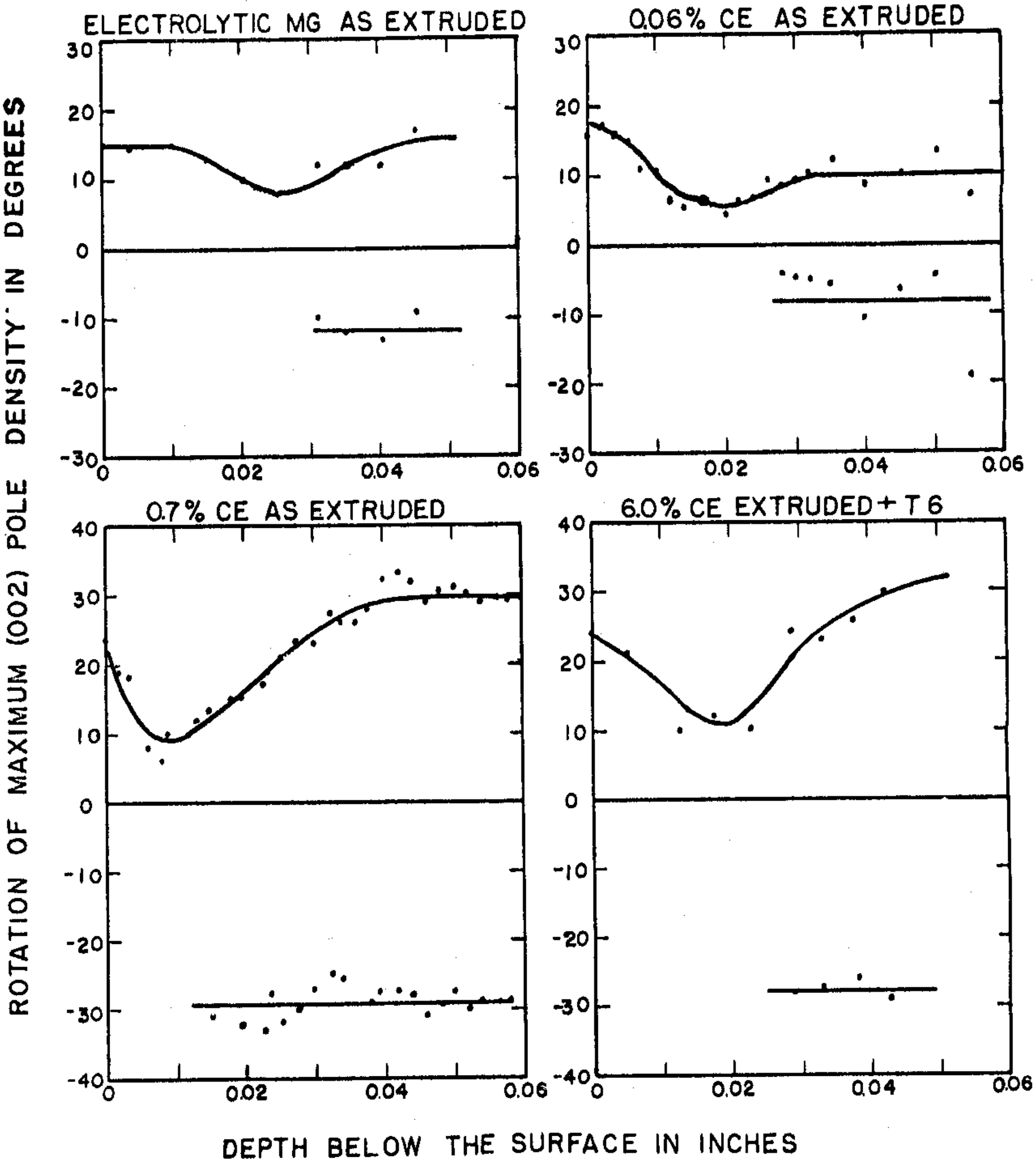


FIGURE 22

PREFERRED ORIENTATION PROFILES FOR MAGNESIUM ALLOY EXTRUSIONS

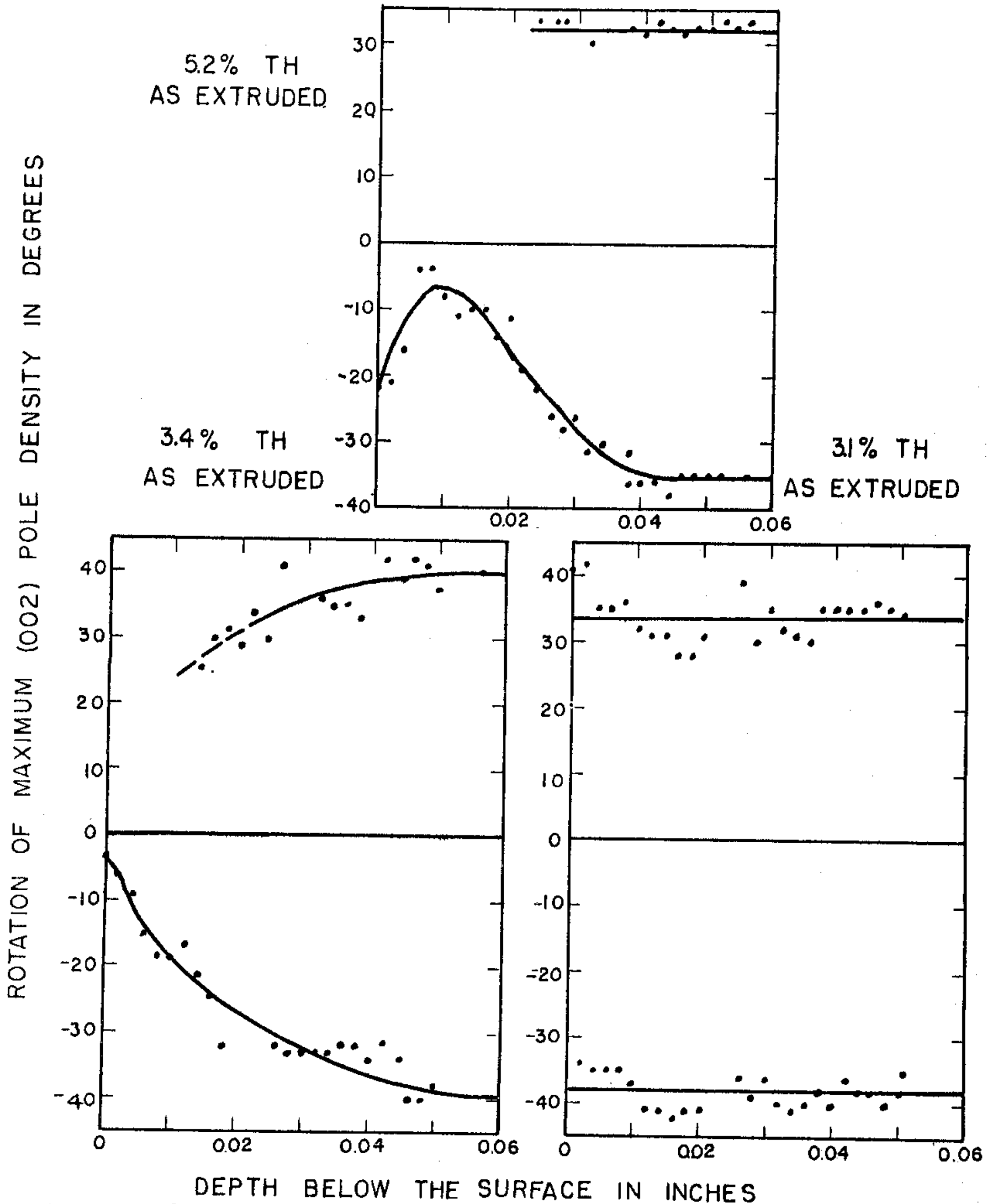
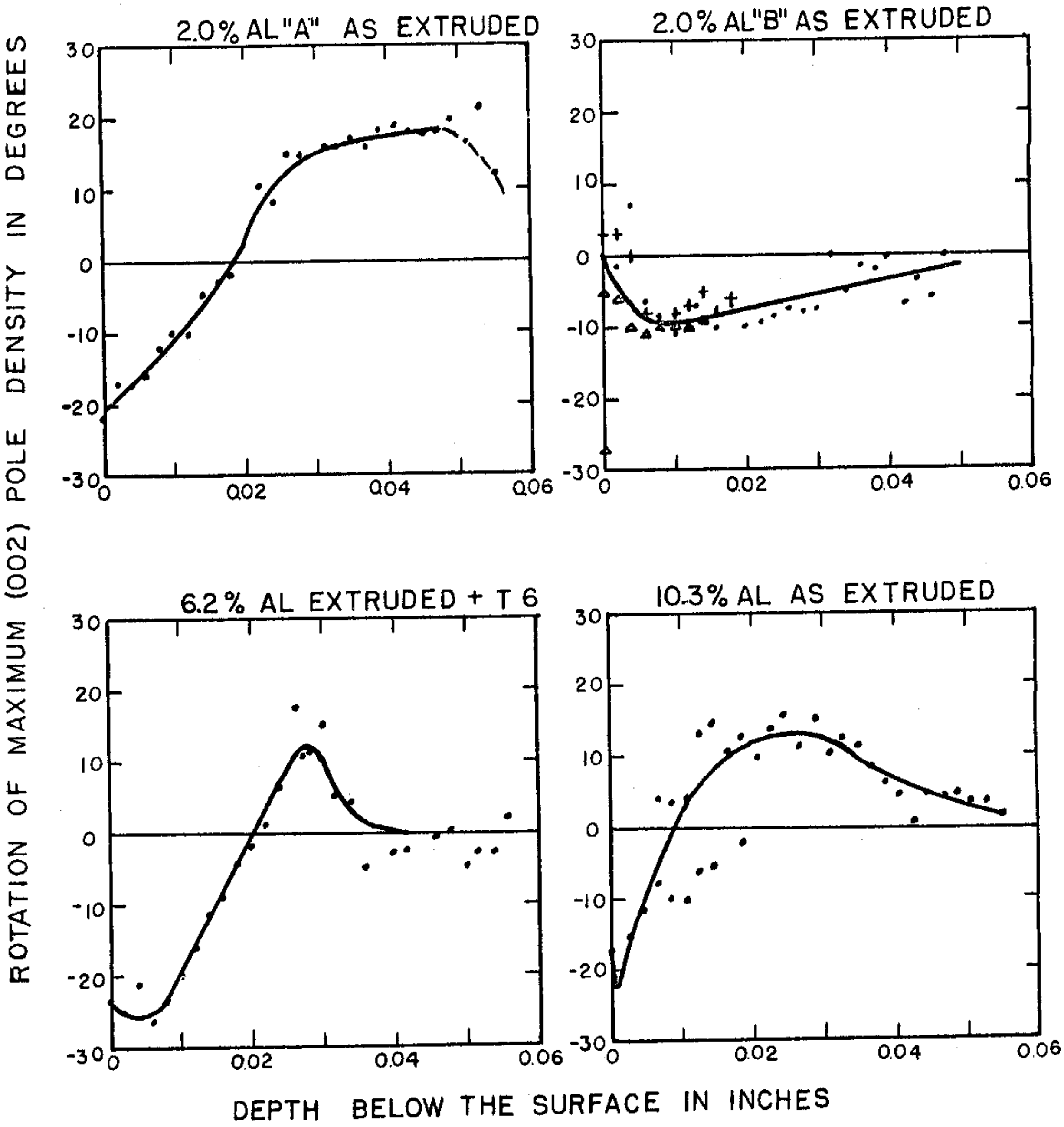


FIGURE 23

PREFERRED ORIENTATION PROFILES FOR MAGNESIUM ALLOY EXTRUSIONS



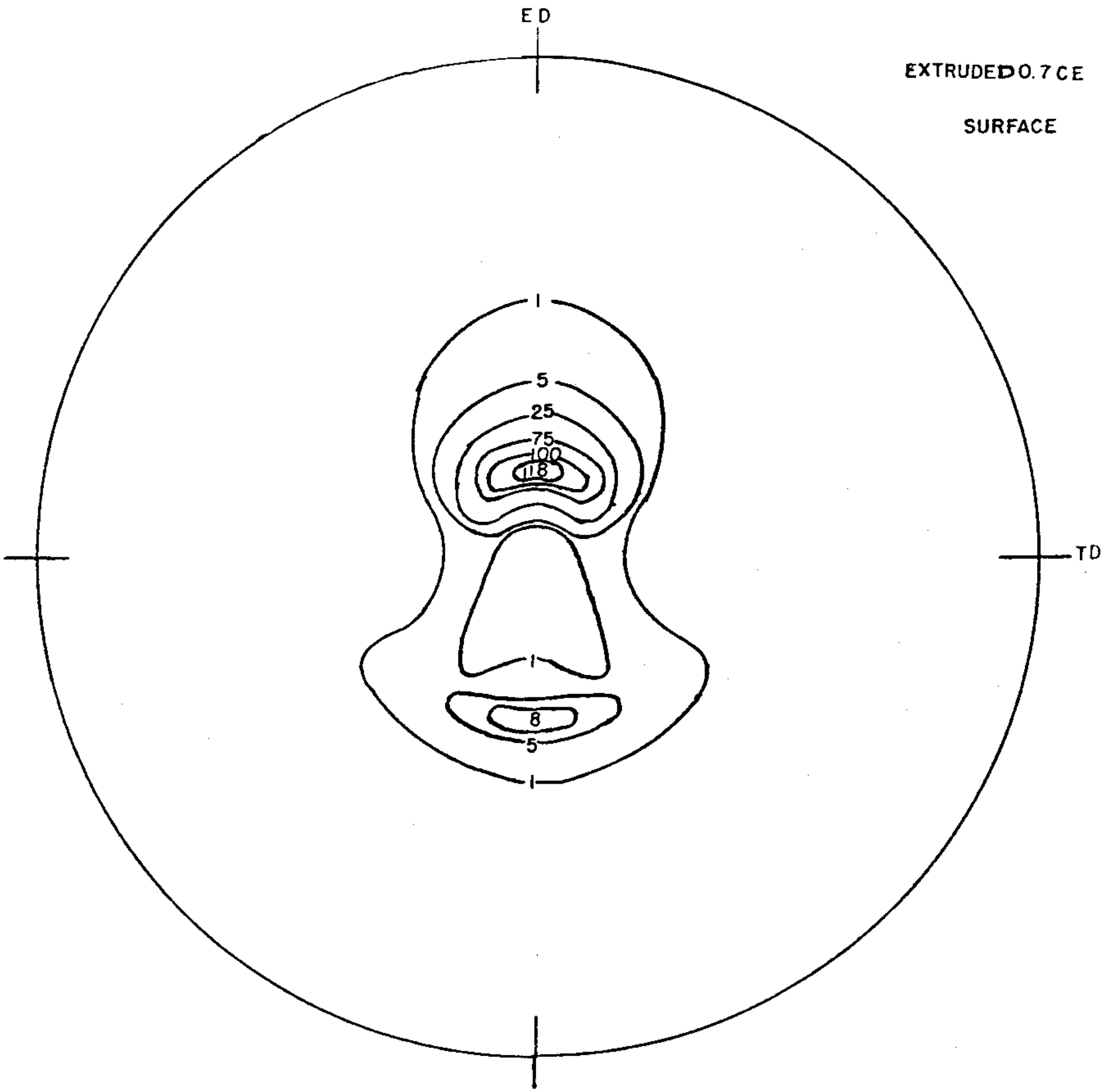


FIGURE 2 4 (002) POLE FIGURE FOR MG-0.7CE ALLOY

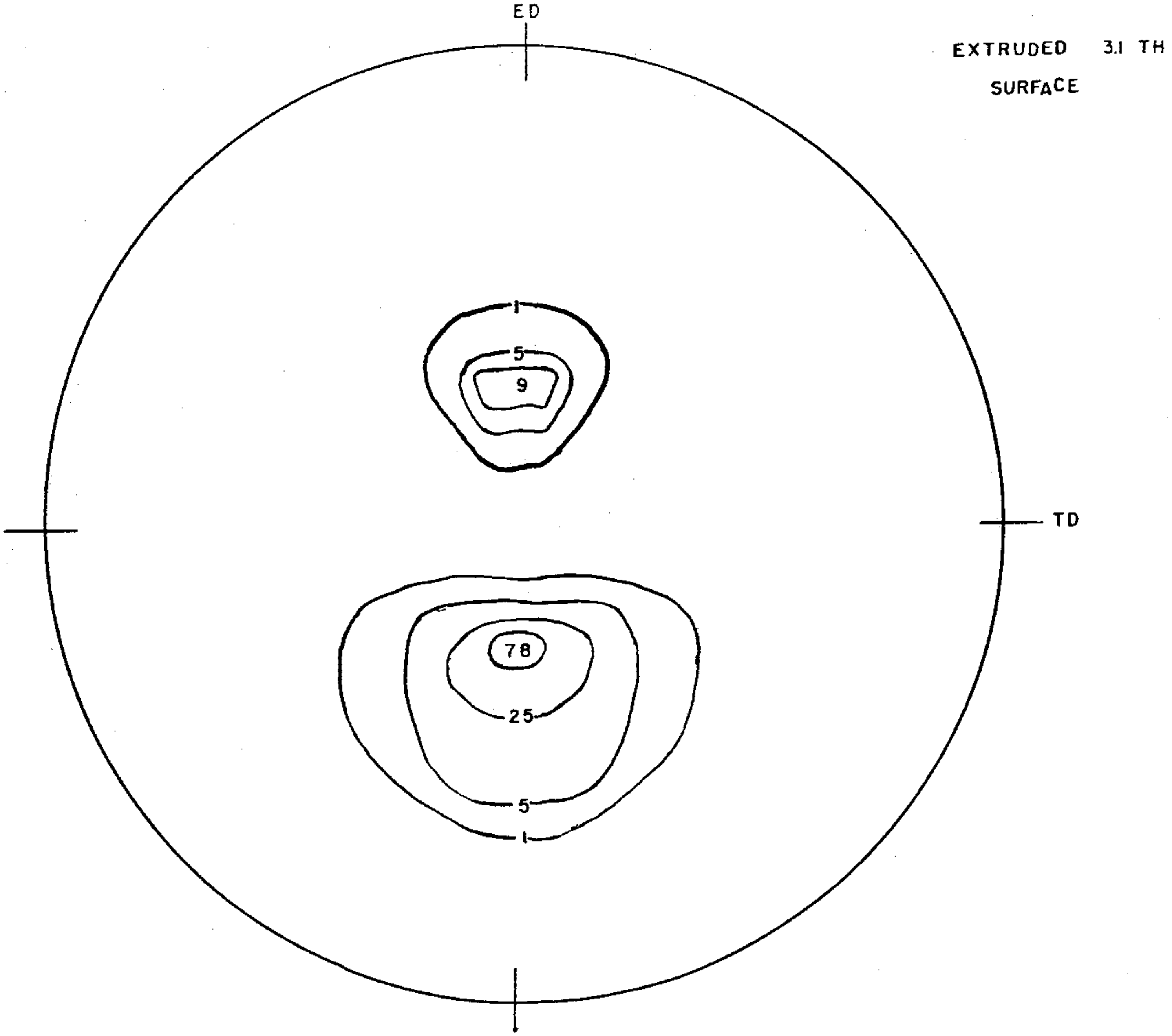


FIGURE 25 (002) POLE FIGURE FOR MG-3I TH ALLOY

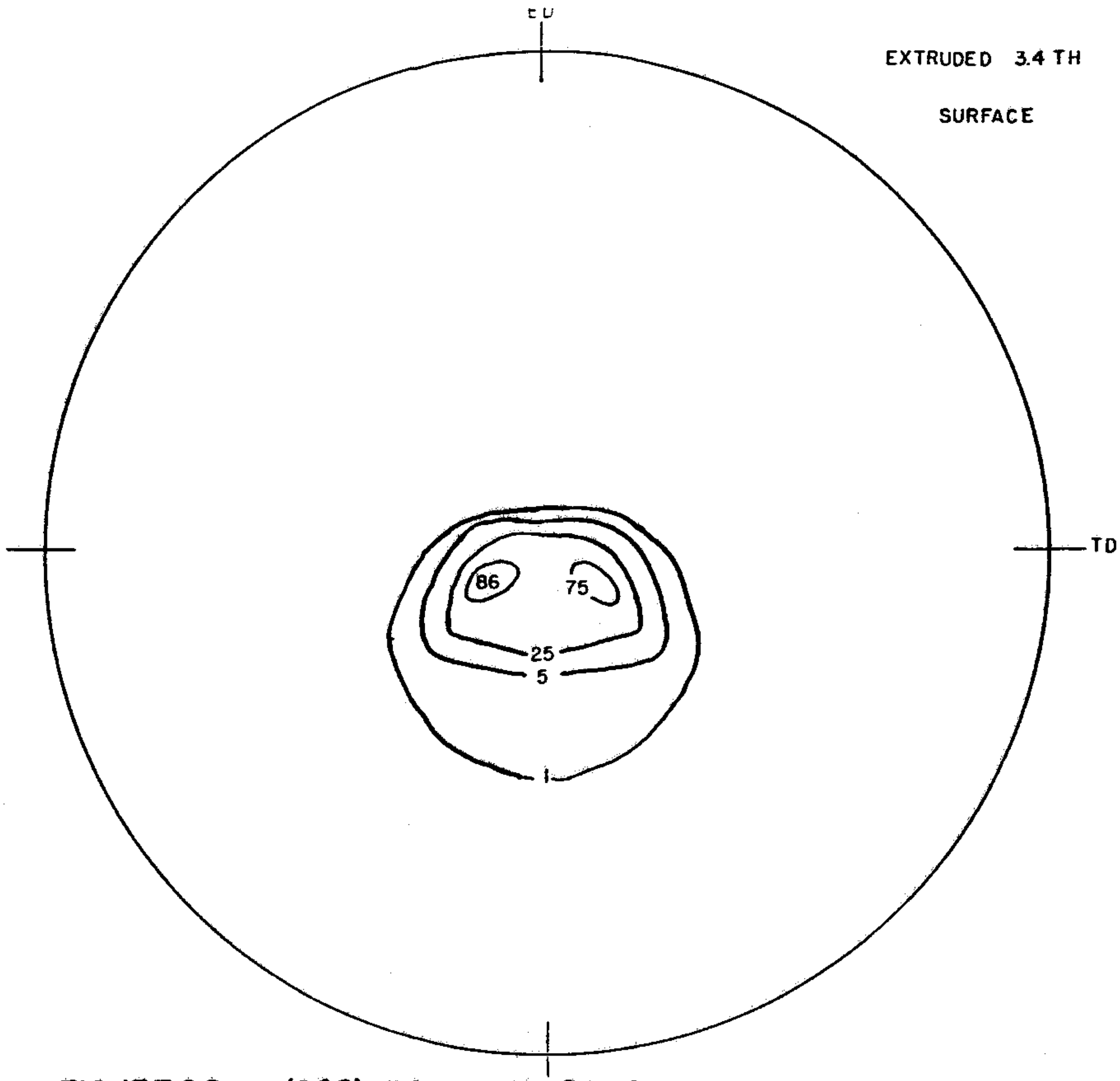


FIGURE 26 (002) POLE FIGURE FOR MG-3.4 TH ALLOY

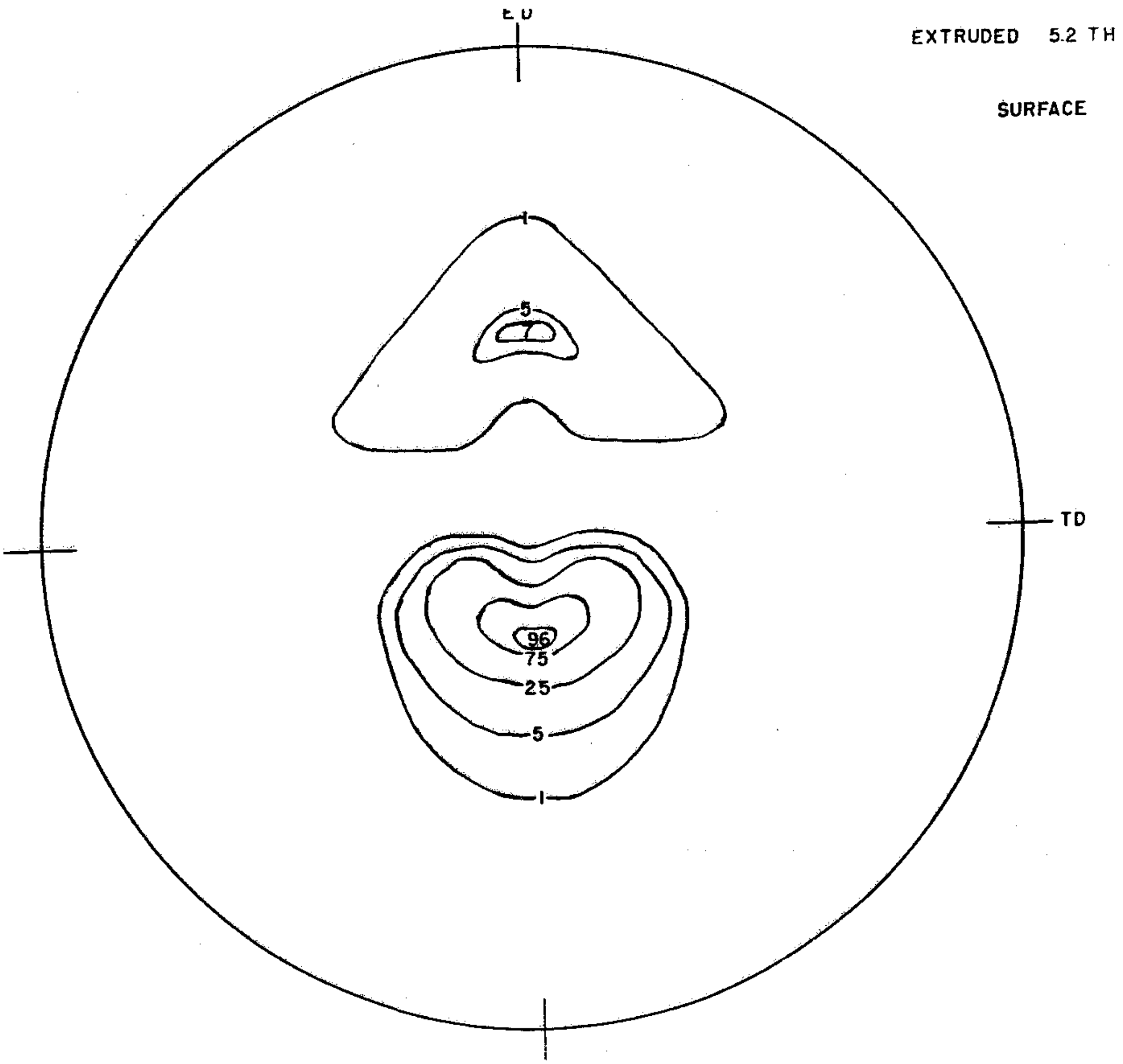


FIGURE 27 (002) POLE FIGURE FOR MG-5.2 TH ALLOY

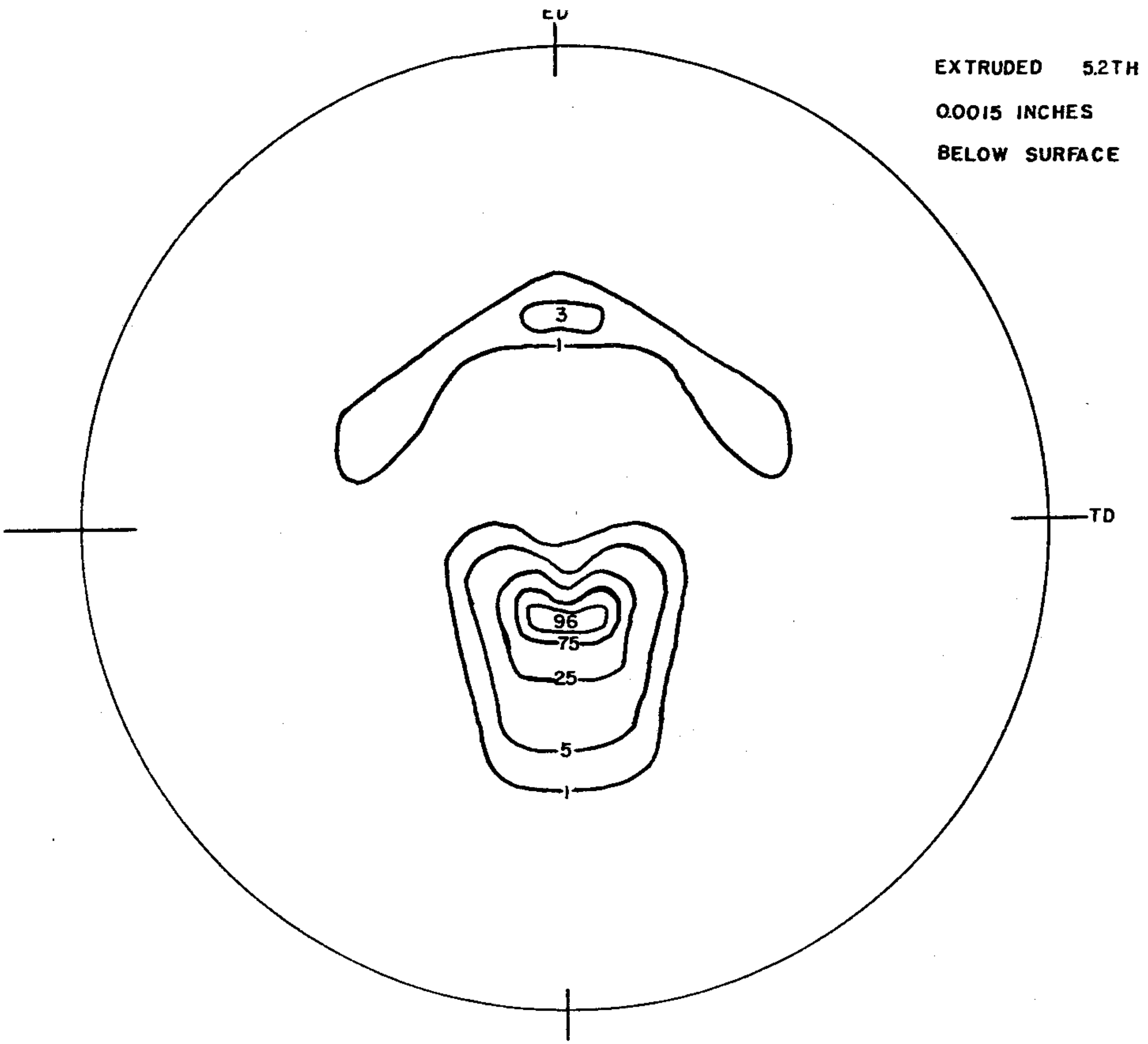
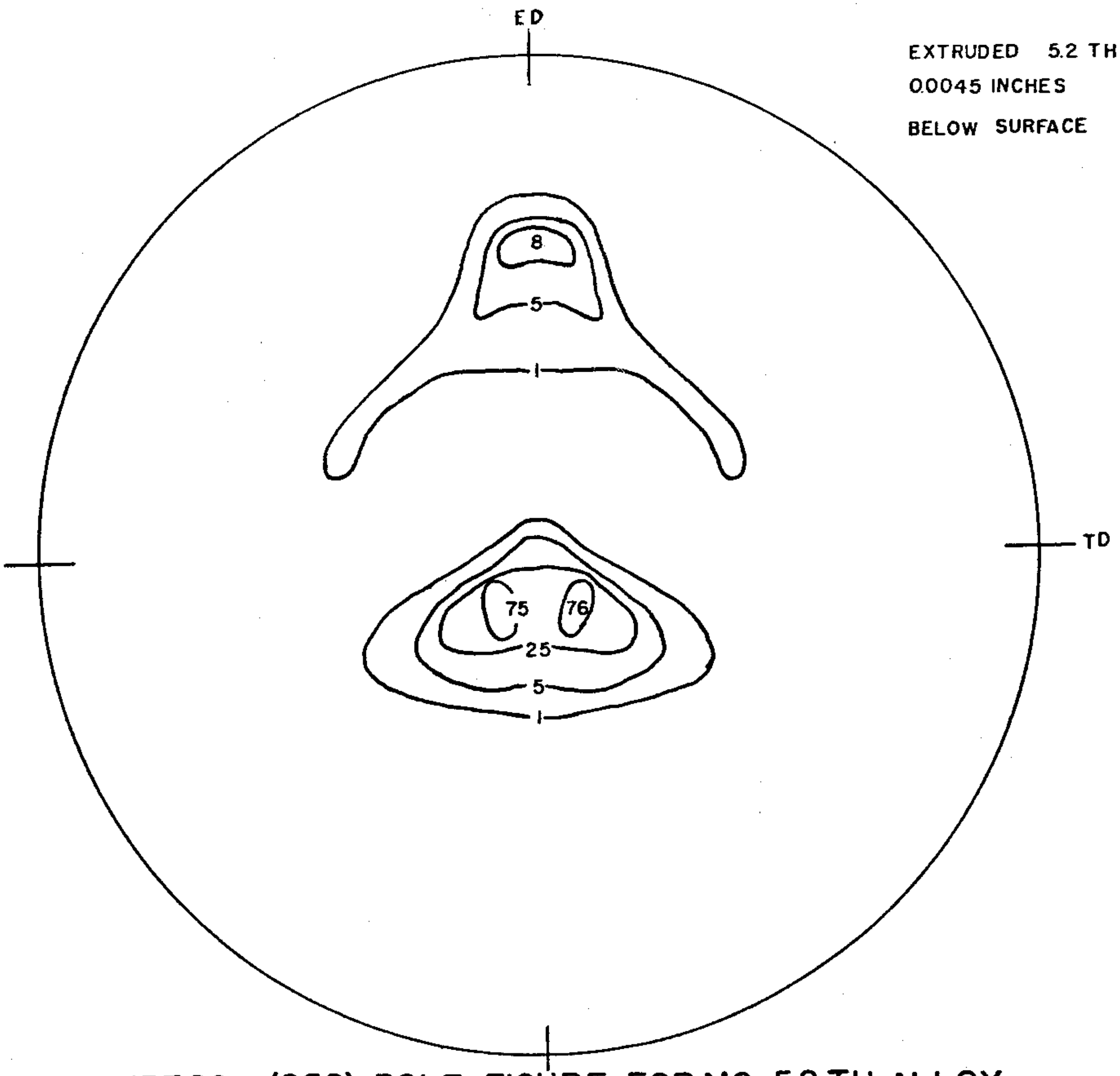
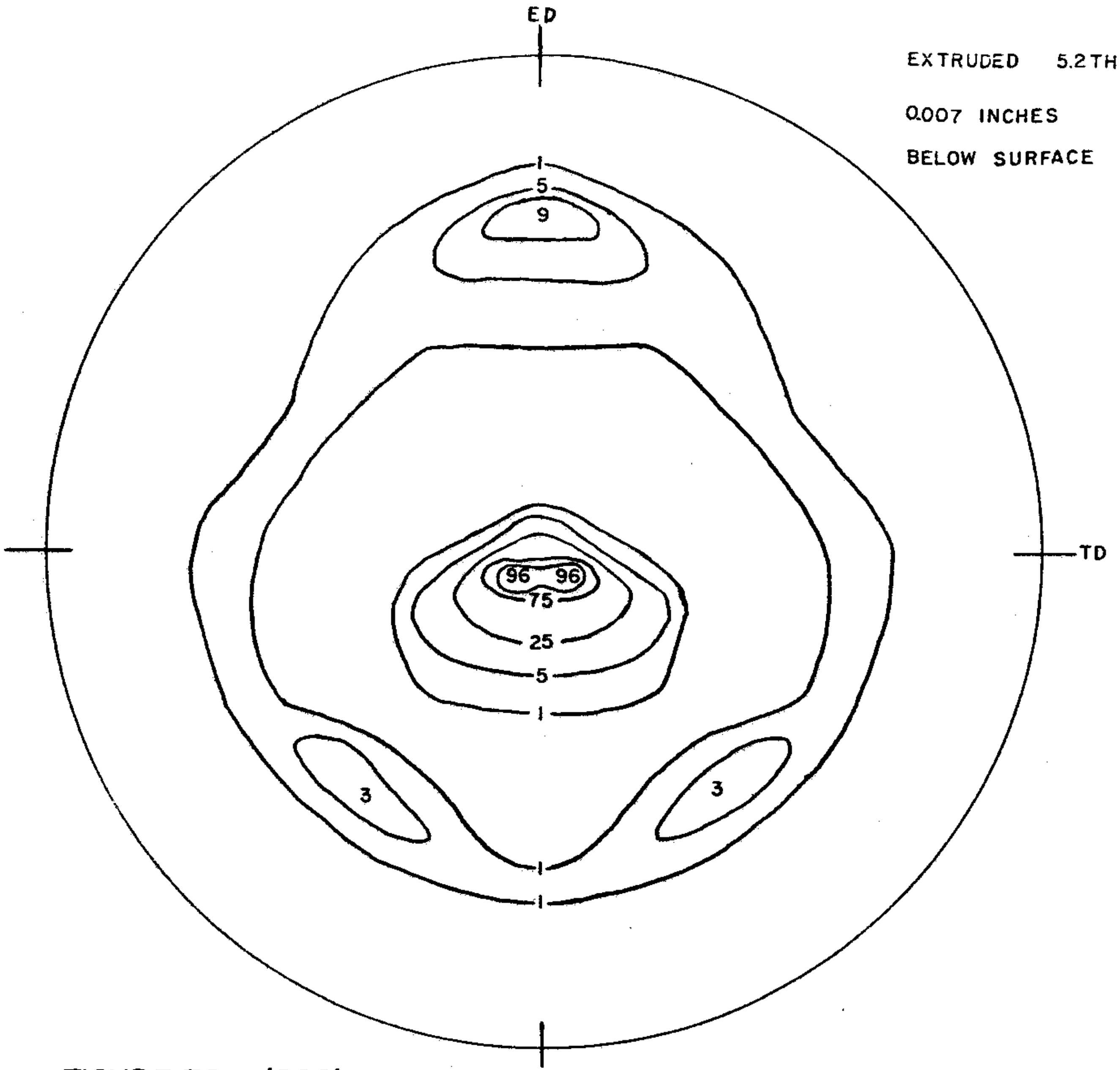


FIGURE 28 (002) POLE FIGURE FOR MG-5.2 TH ALLOY



EXTRUDED 5.2 TH
0.0045 INCHES
BELOW SURFACE

FIGURE 29 (002) POLE FIGURE FOR MG-5.2 TH ALLOY
0.0045 INCHES BELOW SURFACE



EXTRUDED 5.2 TH
0.007 INCHES
BELOW SURFACE

FIGURE 30 (002) POLE FIGURE FOR MG-5.2 TH ALLOY
0.007 INCHES BELOW SURFACE

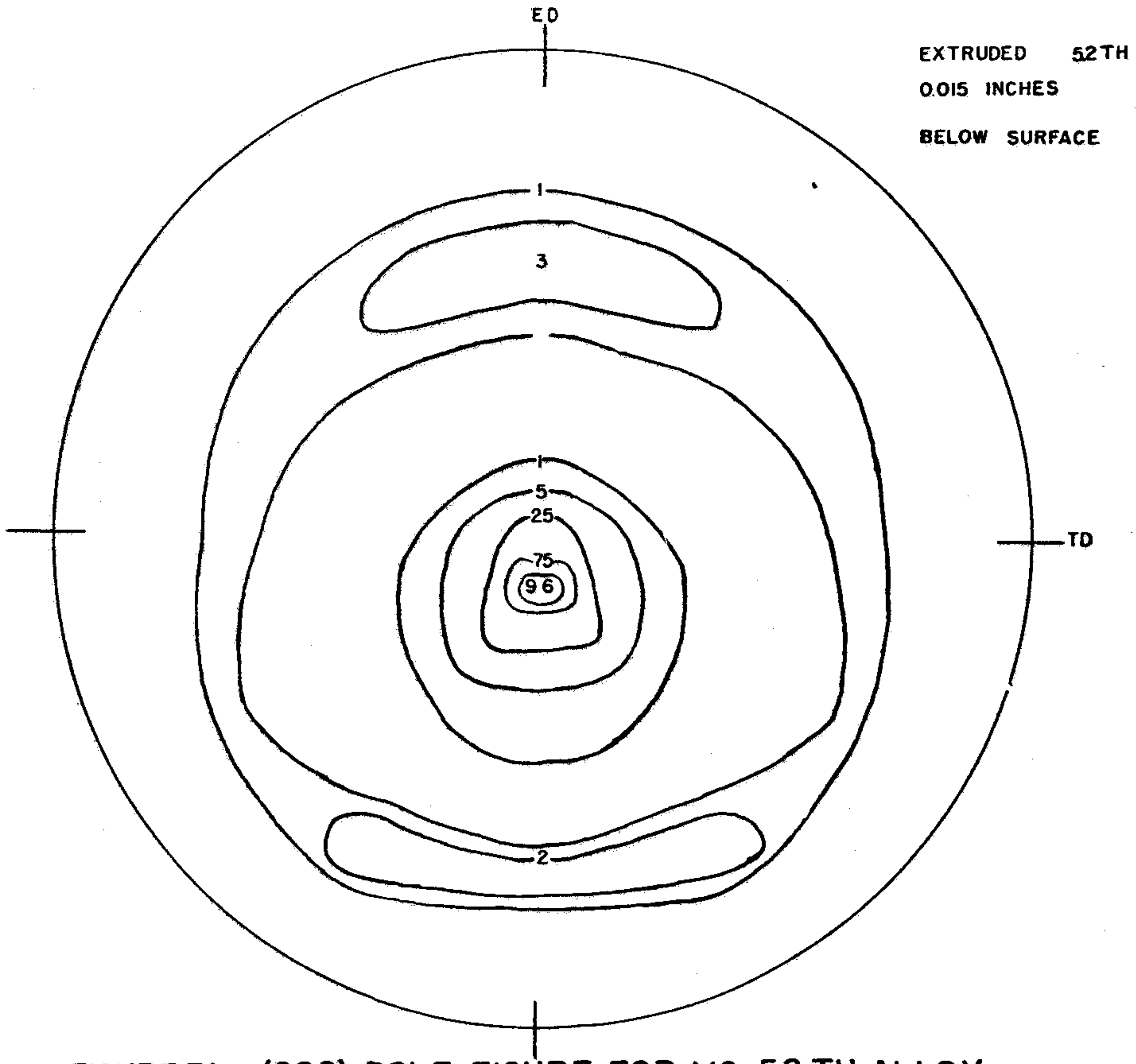
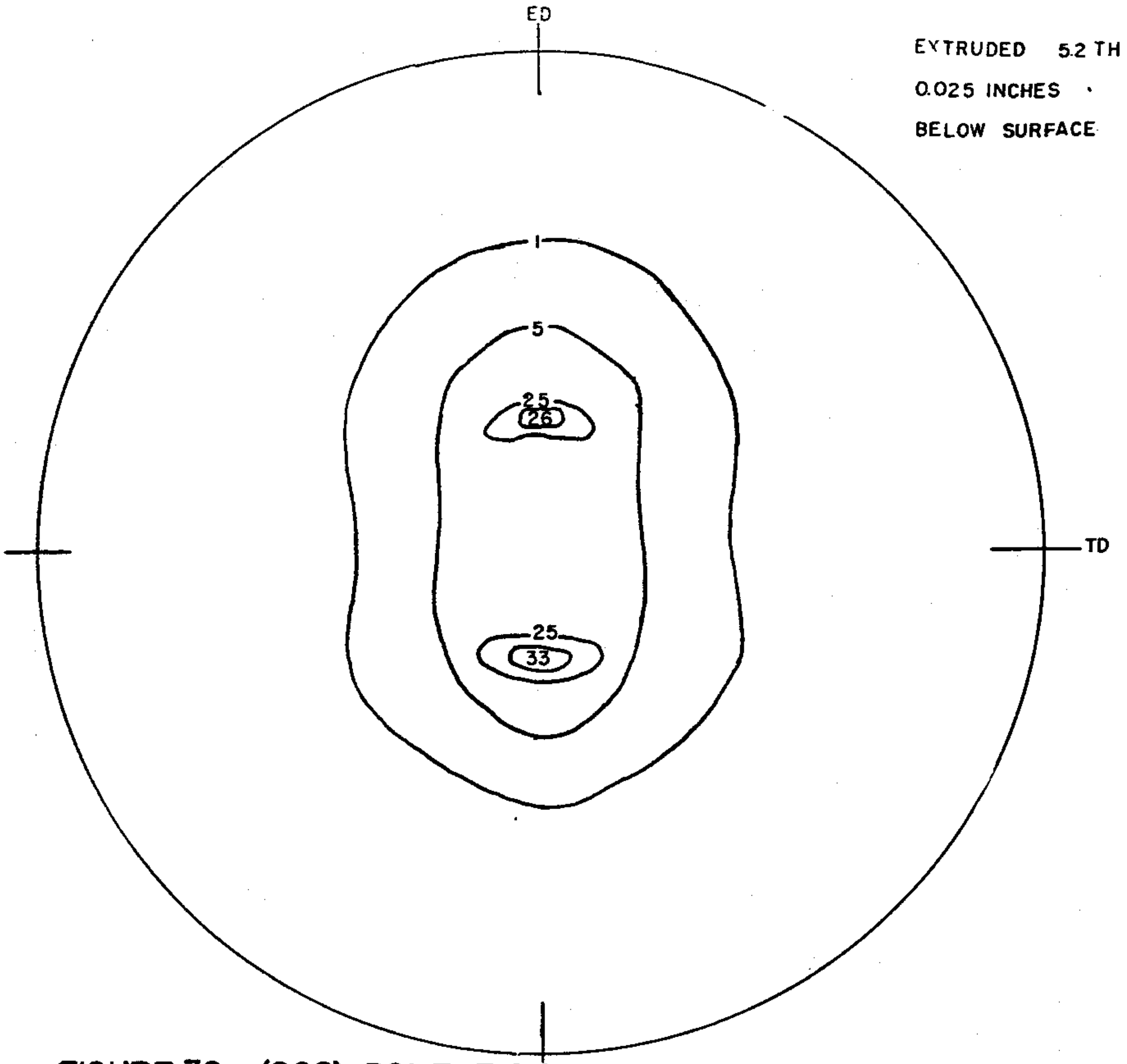


FIGURE 31 (002) POLE FIGURE FOR MG-5.2 TH ALLOY
0.015 INCHES BELOW SURFACE



EXTRUDED 5.2 TH
0.025 INCHES
BELOW SURFACE

FIGURE 32 (002) POLE FIGURE FOR MG-5.2 TH ALLOY
0.025 INCHES BELOW SURFACE

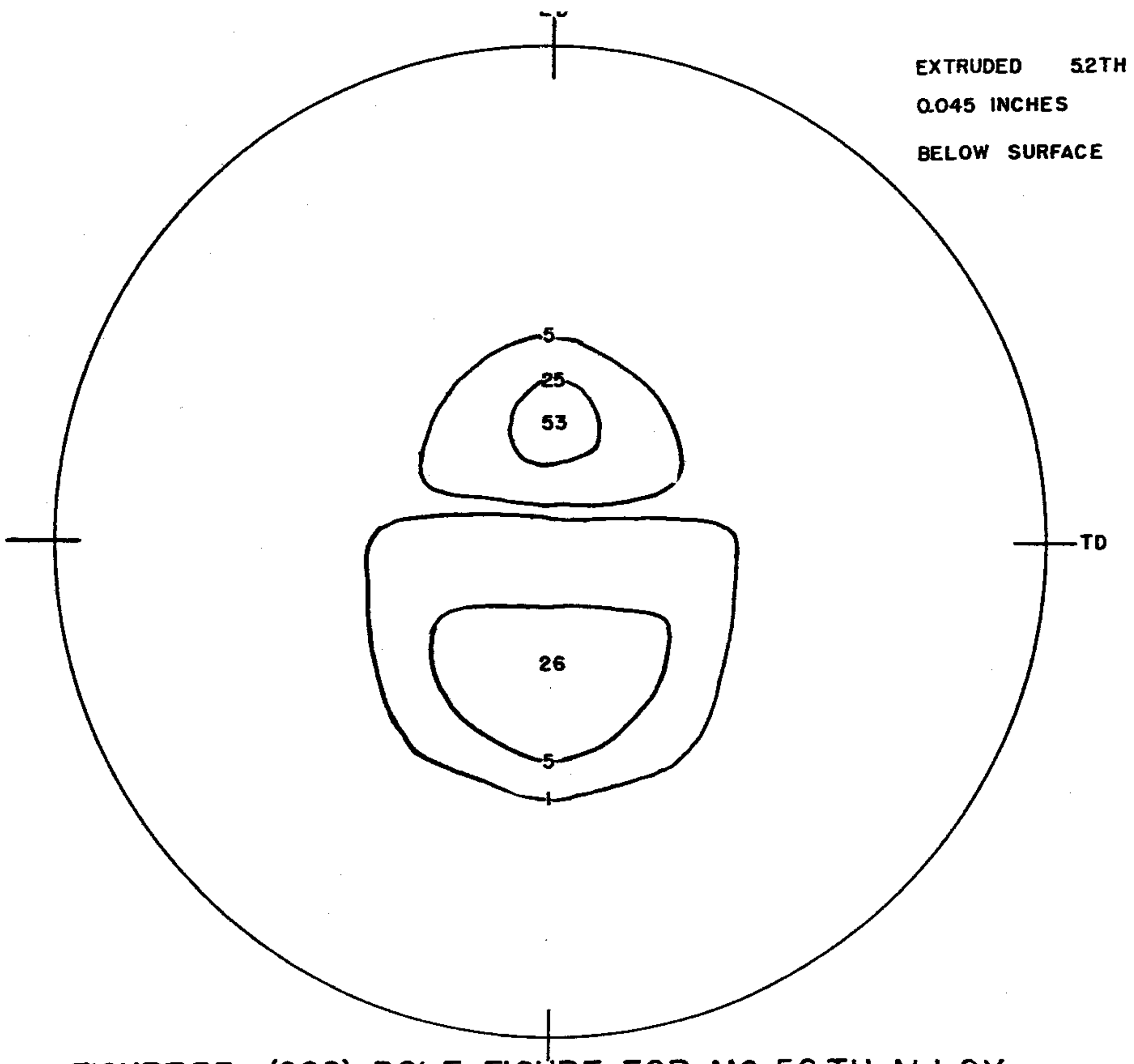


FIGURE 33 (002) POLE FIGURE FOR MG-5.2 TH ALLOY 0.045 INCHES BELOW SURFACE

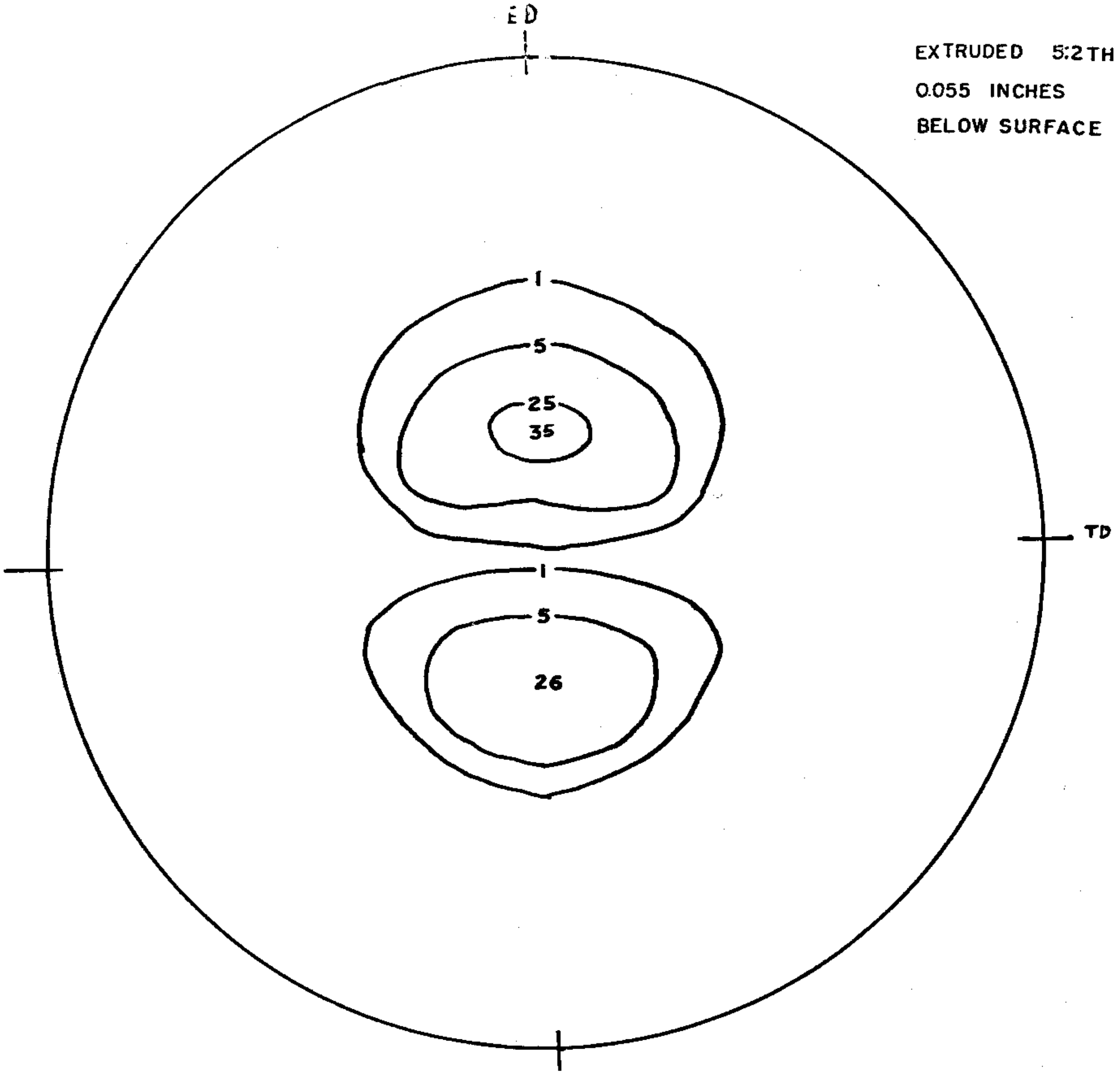


FIGURE 34 (002) POLE FIGURE FOR MG-5.2 TH ALLOY 0.055 INCHES BELOW SURFACE