NMI-1174

METALLURGY AND CERAMICS

UNITED STATES ATOMIC ENERGY COMMISSION

DUCTILITY IN BERYLLIUM RELATED TO GRAIN ORIENTATION AND GRAIN SIZE

By
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August 9, 1957

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Cambridge, Massachusetts

Technical Information Service Extension, Oak Ridge, Tenn.

Printed in USA. Price $1.25. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

AEC Technical Information Service Extension
Oak Ridge, Tennessee

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Ductility in Beryllium Related to Grain Orientation and Grain Size

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Contract AT(30-1)-1565

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ABSTRACT

The anisotropy of fracture and slip, that is, the brittleness and ductility of the beryllium single crystal, is characteristic also of polycrystalline beryllium in which the grains are oriented in a preferred manner. Beryllium with grain orientations resulting from hot working either uni-directionally or bi-directionally is ductile or brittle in directions given by the anisotropy and orientation of the grains. Textures developed from various hot-working sequences are given, and tensile results are correlated with textures.

Not only texture, but fine grain size is necessary for obtaining high tensile elongation. Ultimate tensile strength and elongation are both correlated with grain diameter. Of particular interest is the case in which unusually high tensile elongations of 30% to 40% are obtained when basal planes are oriented to carry little or no tensile stress.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

INTRODUCTION

The beryllium crystal (of nominal purity) is probably unique among metals with respect to its unusually acute anisotropy of slip and fracture. While extensive slip can occur on the system $(10\bar{1}0)$ $[11\bar{2}0]$ starting at about 19,000 psi, the (0001) plane is particularly vulnerable to fracture at 4500 psi or less. Fracture occurs also on the $(11\bar{2}0)$ plane at about 26,000 psi.[1,2,3] Further, there seems to be no other slip system which contributes significantly to room-temperature ductility. It is clear, then, that ductility and strength in polycrystalline beryllium should be dependent upon grain orientation and stress direction.

In fact, from many other investigations concerning mechanical properties of polycrystalline beryllium, both strength and ductility have been reported to be apparently sensitive to texture and microstructure. Some of the literature relevant in this regard is by Smegelskas and Barret,[4] Kaufmann, Gordon, and Lillie,[5] Beaver and Wikle,[6] Winchell,[7] Macres,[8] Klein, et al,[9] Greenspan,[10,11] and others. The following contributes further by giving quantitative studies of grain orientations as a function of several different fabrication sequences. A definite relationship is established between tensile properties and grain orientation when grain size is fine and uniform. Then with data from another group of samples where texture is relatively uniform, quantitative relationships are shown between tensile properties and grain size. One interesting result is the case of high tensile elongation in two dimensions only.

PART I

I. PROCEDURES

A. Fabrication

All fine-grained stock was formed from Brush QMV-200 mesh beryllium powder compacts by hot extrusion, hot pressing, hot rolling, and combinations of these processes. Essentially, beryllium with the following five general fabrication histories was studied: (1) extruded,

(2) extruded and cross rolled, (3) hot pressed, (4) hot pressed and hot rolled uni-directionally, and (5) hot pressed and hot rolled bi-directionally. Beryllium was jacketed in steel for all hot-working operations.

B. Tensile Testing

Samples (Fig. 7) of known direction in the sheet surface, equipped with double SR-4 strain gages were tested in uniaxial tension at room temperature. Average strain rate was approximately 1%/min. Large strains were measured with an Ames dial arrangement, and total elongations were checked by means of fiducial markings on the sample. Reductions in width and thickness were measured with a pointed micrometer.

C. Pole Figures

A Geiger counter spectrometer with filtered Cr$K\alpha$ radiation was used with samples 2 inches x 2 inches x 0.040 inch. A special goniometer[12] was employed which allowed complete pole figure determination without unmounting the sample. The central portion of the pole figure, to 60°, was determined by reflection, and the peripheral portion by transmission.[13,14] Intensity determinations were made at 10° vertical and 15° radial intervals, but near maxima and other points of interest were checked at 5° or smaller intervals. A random sample of pressed beryllium powder, having a μt value equivalent to that of the x-ray sample, was taken as a standard for comparison. All intensity contours are expressed as multiples of random. The polar net grid is included as background to pole figures to permit ready location of peaks, fringes, and other points of interest.

II. RESULTS

A. Texture

1. Uni-Directional Hot Rolling at 1900°F (1038°C)

Figure 1 is arranged to show texture as a function of reduction by a multi-pass, multi-heat rolling schedule. Basal pole scatter decreases in the working direction and increases in the transverse direction as rolling reduction proceeds. Peaks form on the transverse axis and apparently migrate outward with increasing rolling reduction. Prism poles become oriented in the working direction, with scatter decreasing as reduction increases. In Fig. 2(a) the texture of an extruded flat 2-1/2 inches x 5/8 inch is of the same pattern as the texture of the uni-directionally rolled sheet in Fig.1(b), but it is carried to a greater degree of completeness. Total reductions in samples represented by Fig. 1(b)(b') (uni-directionally rolled) and Fig. 2(a)(a') (extruded flat) are equal, and in this respect the differences in textures are of interest.

2. Bi-Directional Working, Extrusion and Cross Rolling at 1900°F (1038°C)

It is clear from the results of the preceding section that the texture pattern should be variable to a considerable extent by working the metal in more than one direction. Particularly interesting is the case of extrusion and cross rolling, in which rolling is performed in the transverse direction of an extruded flat. Figure 2 is arranged to show the effect of cross-rolling reduction on texture when rolling was performed at 1900°F (1038°C) using a multi-pass, multi-heat rolling schedule.

A reduction of 6:1, part b, Fig. 2, shifts the basal pole peak from the periphery of the pole figure, part a, to near 10° of the surface normal, and scatter is reduced to about 38°. On increasing reduction to 80:1, part c, the uni-directional texture pattern appears to take shape in the rolling direction. Prism poles, intensely fibered in the extrusion direction, part a, decrease in intensity as cross rolling proceeds, part b, and finally migrate toward the rolling direction, part c.

The basal plane distribution in part b, Fig. 2, is one where most basal planes are nearly parallel to the sample surface. For convenience in this report, this is subsequently called the "basal plane layer" texture. In this notation, prism pole positions are not specified.

3. Effect of Rolling Temperature in Cross Rolling

Basal plane textures of samples with equivalent rolling history except for rolling temperature are given in Fig. 3. According to this illustration, the basal plane layer texture is maintained through a greater range of rolling reductions when rolling is performed at 1900°F(1038°C) than when it is done at 1600°F (871°C). The reason for this is not clear, though among the many complexities involved in hot rolling, a relevant factor may be temperature changes in the crystallographic deformation mechanisms, if they occur. In any case, the behavior illustrated in Fig. 3 is of practical value to the fabricator who desires to form basal plane layered beryllium by the extrusion, cross-rolling technique.

4. Bi-Directional Rolling of Hot-Pressed Stock

The texture resulting from rolling a hot-pressed block with random grain orientation in two right angular directions is given in Fig. 4(b). The basal pole figure differs from that of the extruded and cross-rolled sample [Fig. 4(a)], chiefly by the absence of peaks and their characteristic contours. Instead, there is a randomness in radial or azimuthal directions, with a ridge occurring at an angle near 20° from the surface normal. As discussed later, it appears that the most significant factor associated with two-dimensional ductility is the vertical angle between surface normal and basal poles. In this regard, the two types of pole figure in Fig. 4 can be roughly resolved for comparison by averaging basal pole intensity along lines of latitude of the polar net, and plotting this value against its angle with the surface normal. When this is done as in Fig. 5, the two basal pole distributions appear nearly alike. It is later shown that tensile properties with respect to two-dimensional ductility also are nearly alike. It is interesting to compare the working reductions involved: that of Fig. 4(a) is 108:1 (18:1 extrusion with 6:1 cross rolling), while that of Fig. 4(b) is 14:1 (3.75:1 rolling in each direction).

The prism pole distribution also, Fig. 4(b'), is characterized by a randomness in radial directions, though there are traces of peaks in the two rolling directions. Prism pole distribution of the extruded and cross-rolled sample, Fig. 4(a'), shows hexagonal symmetry, chiefly because the strong $(10\bar{1}0)$ fiber texture of extrusion [Fig. 2(a')] still prevails. In this respect the grain orientation in Fig. 4(a') is more ordered than that of Fig. 4(b'), and the former approximates a quasi single crystal.

B. Tensile Tests

1. Extruded and Cross Rolled at 1900°F (1038°C)

a. Tensile Elongation

Tensile elongation as a function of cross-rolling reduction, in Fig. 6, is given separately for directions longitudinal and transverse to rolling. Extruded stock, represented by the initial point of each of the curves, has about 12% elongation in the extrusion direction, but virtually none transverse to this (i.e., the direction in which rolling is to take place). When cross rolled to reductions of approximately 5:1 to 15:1, which is the range identified with the basal plane layer texture, ductility is increased in both directions to 30% to 40% tensile elongation. At greater rolling reductions, ductility declines steadily in both directions, as the uni-directional texture becomes more prominent.

The unusually high tensile elongation and exceptionally good bending ability in samples with optimum ductility is illustrated in Fig. 7.

b. Tensile Strength

Ultimate strength, calculated on the basis of ultimate load and initial cross-sectional area, is plotted as a function of cross-rolling reduction in Fig. 8. The anisotropy in strength of the extruded flat is clearly shown by comparing the initial points of both curves where strength in the extrusion direction is about 85,000 psi, but that in the cross direction is only about one-third this value.

Cross rolling to reductions of approximately 3:1 to 10:1 results in beryllium with strength of about 65,000 psi in both directions, thereby moderating this strength anisotropy. When rolling reductions are further increased, strength declines moderately. It is notable that this loss of strength is coincident with loss of ductility (Fig. 6).

Ultimate strength calculated on the basis of ultimate load and minimum cross-sectional area at time of fracture, that is, the true strength, is usually greatest in the most ductile beryllium. Here, true strength values are of the order of 90,000 to 100,000 psi.

c. Plastic Deformation, Reduction in Area, and Fracture

In Fig. 7, the tensile sample has, in addition to unusually high elongation, a moderate neck. This is characteristic of beryllium with tensile elongations in the 30% to 40% range. That for the sample shown is 41% as calculated from $\Delta \ell / \ell$ derived from fiducial markings at the gage length limits of the sample. However, the tensile elongation, calculated to be equivalent to the reduction in area at the neck, is about 72%. This fact is noted to illustrate the remarkably good degree of workability in the operating slip system (assumed to be $(10\bar{1}0)$ $[11\bar{2}0]$) of this polycrystalline aggregate.

Fracture in such a case is always wedge-like, and by conventional terms can be described as "brittle". The fracture area consists mostly of $(11\bar{2}0)$ planes as indicated by x-ray scan. The $(11\bar{2}0)$ plane is known to be a fracture plane in the beryllium single crystal.

In high ductility samples, reduction in area takes place almost exclusively by a reduction in width, as indicated by physical measurement of the sample before and after the tensile test. Since thickness remains virtually unchanged, it is assumed that ductility is absent in the third dimension. In view of this fact, and the curves of Fig. 6, the term "two-dimensional ductility" adequately describes the plastic deformation behavior of this case. (It has been confirmed[10] that testing in only longitudinal and transverse directions is sufficient to detect two-dimensional ductility.)

It is interesting that some of the above-mentioned characteristics are different when ductility is lower. For example, when the beryllium is incapable of approximately 20% or less tensile elongation, there is no necking. Also, instead of the wedge-type fracture, the fracture area is usually at right angles to the tensile axis. In such cases, the average strength is lower, as discussed in more detail in Part II.

2. Extruded and Cross Rolled at 1600°F (871°C)

Figure 3 has shown differences in texture attributed to rolling temperature. It is therefore significant that there are also differences in tensile properties. The counterparts of Figs. 6 and 8, giving tensile elongation and tensile strength, related to the 1900°F (1038°C) rolling temperature, are given in Figs. 9 and 10, respectively, for the 1600°F (871°C) rolling temperature.

a. Tensile Elongation

The data, on the average, are characterized by a greater spread in results, so that a trend is less accurately expressed. Nevertheless, they are best represented by the curves of Fig. 9 which show a pattern similar to that of Fig. 6, but with peaks lower and narrower. The ductility peaks are associated with the basal plane texture.

b. Tensile Strength

The plot in Fig. 10 is of the same pattern as that in Fig. 8. However, peak strength is slightly higher (about 70,000 psi as compared to 65,000 psi) and occurs at lower rolling reductions (2:1 to 5:1 as compared to 3:1 to 10:1). Further, the rate of decline in strength with respect to rolling reduction, after the maximum, is somewhat greater here than in Fig. 8.

3. Hot Pressed and Bi-Directionally Rolled, 1600°F - 1850°F (871°C - 1010°C)

Figure 5 has illustrated a likeness in basal pole distribution of the two types of beryllium under consideration. It is therefore of interest to compare tensile properties.

Provided that reductions in each of the two directions are equal and at the same temperature, data show that tensile strength and elongation are not appreciably changed by changing rolling temperature within the range 1600°F - 1850°F (871°C - 1010°C). Furthermore, tensile properties in both rolling directions are nearly alike. For this reason, two-dimensional ductility and two-dimensional strength are each best represented by a single curve which combines data from both directions, and which represents rolling temperatures of 1600°F - 1850°F (871°C - 1010°C).

a. Tensile Elongation

Two-dimensional ductility as a function of total rolling reduction is given in Fig. 11 where the upper limit of reduction is 14:1 (3.75:1 in each direction). Hot-pressed stock has tensile elongation of the order of 0.5% to 3% (presumably in all directions).[6] When bi-directionally rolled to reductions of 8:1 to 14:1, two-dimensional tensile elongation becomes about 25%. Bi-directional rolling of hot-pressed beryllium therefore increases two-dimensional ductility.

b. Tensile Strength

Ultimate strength calculated on the basis of ultimate load and initial cross-sectional area is plotted as a function of total rolling reduction in Fig. 12. Hot-pressed stock has strength of the order of 40,000 psi. When bi-directionally hot rolled as previously described, strength in each of the two rolling directions becomes approximately 65,000 to 70,000 psi. The true strengths corresponding to the latter are 85,000 to 95,000 psi. Bi-directional rolling of hot-pressed beryllium therefore increases its two-dimensional strength.

c. Plastic Deformation, Reduction in Area, and Fracture

These three characteristics are nearly analogous to those of basal plane layered sheet fabricated by extrusion and cross rolling.

C. Microstructure

Figure 13(a) is representative of the microstructure of all stock associated with the results of the preceding sections. Grain size is nearly uniform and of the order of 10^{-3} inches. The effect of grain size on tensile properties is unusually significant and is given in more detail in Part II of this report.

III. DISCUSSION

A. Ductility and Fracture

When grains are oriented in a regular fashion, as in Fig. 4, the anisotropy of deformation and fracture seems to be similar to that of the beryllium single crystal. That is, the mechanisms of $(10\bar{1}0)$ $[11\bar{2}0]$ slip, $(11\bar{2}0)$ fracture, and (0001) fracture seem to prevail, and the polycrystalline mass behaves nearly as a single crystal with the same directional relationship between stress and crystallographic poles. In the single crystal, the (0001) plane is the most vulnerable to fracture, while the only significant source for plastic deformation is the $(10\bar{1}0)$ $[11\bar{2}0]$ slip system.[1] When in basal plane layered beryllium stress is applied perpendicular to the surface normal, the $(10\bar{1}0)$ $[11\bar{2}0]$ slip system is favorably oriented for slip, while large stresses are avoided on most basal planes. (Figure 14 is a simplified version, that is, purely uniaxial, of stress distribution on various cross sections of the tensile sample which is related to relevant features of the pole figure.) This apparently permits considerable plastic deformation to take place before fracture occurs. Fracture seems to be primarily on the $(11\bar{2}0)$ plane, the secondary fracture plane, of the crystallites. However, the possibility of basal fracture is also present because of the extent of the fringe area of the basal pole figure (Figs. 2(b) and 14).

B. Engineering Limitations of Two-Dimensional Ductility

Lack of ductility in the third dimension imposes far reaching limitations on the material in an engineering sense. When the metal undergoes a uniaxial tensile strain, it cannot adjust in thickness but only in width; a transverse contraction must be permitted to allow a longitudinal elongation. Any attempt to perform simultaneous positive biaxial strains should and does result in immediate fracture. The property of two-dimensional ductility, then, is not expected to accommodate complex strains of this type. The realization of beryllium as a truly "ductile" metal in the conventional sense is not attained by two-dimensional ductility.

It is expected, however, that there is a general improvement in engineering properties in the following ways: (1) the accommodation of simple strains, (2) better uniaxial strength, and (3) better uniformity in tensile properties, that is, less spread in tensile results, than is usual in beryllium.

IV. SUMMARY (PART I)

A. Basal plane orientation resulting from hot rolling is a function of rolling direction, rolling reduction, and rolling temperature, and can be controlled to a significant extent by controlled hot working.

B. Basal plane layer textures can be formed by extrusion and cross rolling, or by hot pressing and bi-directional rolling.

C. Beryllium with grain size of the order of 10^{-3} inches, and carefully controlled basal plane layer texture resulting from extrusion and cross rolling, has two-dimensional ductility of the order of 30% to 40% tensile elongation. Beryllium (with approximately the same grain size) and with basal plane layer texture resulting from hot pressing and bi-directional rolling of the order of 14:1 reduction has two-dimensional ductility of about 25% tensile elongation.

D. Because basal plane layered beryllium does not reduce in thickness when plastically deformed in tension, it is assumed there is no ductility in the third dimension.

E. The capacity for tensile elongation, provided grain size is fine, corresponds in a quantitative way to the amount of stress carried by basal planes. The same is true of tensile strength. The view is taken that, in general, adequate strength is necessary to permit high ductility.

F. Two-dimensional ductility is a ductility of a limited nature. It probably does not provide resistance to fracture induced by many types of complex stress. However, good resistance to fracture is demonstrated under simple stresses such as uniaxial tension or bend.

G. The attainment of two-dimensional ductility has: (1) established a link between tensile properties of the single crystal and a polycrystalline mass, (2) confirmed single crystal studies which indicated that the brittleness problem in polycrystalline beryllium must be associated with single crystal properties, and (3) provided a material for study by design engineers which may lead to better beryllium "hardware".

For future studies of many types, the large pseudo crystal of Fig. 2(b) may replace the more difficult single crystal.

PART II

I. GENERAL

It is perhaps fortuitous that in hot-worked beryllium of -200 mesh powder (Brush QMV) the grain size remains relatively fine and uniform. This makes possible the sort of study given in Part I, in which the grain size remains reasonably constant. However, it is fairly well established that tensile properties are also sensitive to grain size. It is the object of Part II to show as nearly as possible a quantitative relationship between tensile strength and grain size, when the texture is reasonably uniform. The basal plane layer texture was adopted for this study.

II. PROCEDURES

A. Fabrication, Tensile Testing, and X-Ray

Stock was fabricated, tensile tested, and x-rayed for pole figures by methods described in Part I.

B. Microstructure

The usual method for obtaining a variety of grain sizes was by controlled grain growth of beryllium in which extensive grain growth occurs. For this, the starting material was either cast or powder (the reason for inadvertent grain growth in the latter is not clearly known) which was bi-directionally hot rolled at a variety of temperatures. A variety of grain sizes is attained apparently by the influence of rolling temperature on nucleation and growth rates. The stock of fine grain size was that described in Part I.

C. Grain Size Measurement

Samples were mounted, polished by standard procedure,[15] and photographed in polarized light. Grain sizes, as resolved in this way, were measured from photomicrographs of known magnification.

III. RESULTS

A. Microstructure

Figure 13 shows the range of grain sizes encountered, and very briefly, the fabrication history believed to be relevant to grain size. In relating grain size to tensile properties, a "most critical possible" condition was adopted, and where grain size departed considerably from uniformity in a given sample, the largest detectable grain dimension was taken.

B. Texture

The texture of fine-grained, bi-directionally rolled material is given in Fig. 4(b)(b') of Part I. However, as grain size increases, it is known that basal pole spread increases.[11] Further, when grain size is very coarse, texture is unknown because the statistical distribution of grains is not sufficient for pole figure determination. Direct relationship of tensile properties to grain size alone is therefore somewhat clouded in this respect, though it is expected that the importance of texture would decrease as grain size increases.

C. Tensile Strength and Grain Diameter

When data from a relatively large number (about 65) of tensile samples are collated to show true tensile strength as a function of square root of grain diameter, the empirical result is as given in Fig. 15. The data are best represented by a straight, sloping line, showing that strength increases with decreasing grain diameter.

D. True Strength and Maximum Strain Per Sample

When data from all samples, excepting extruded stock, of Parts I and II (that is, both texture and grain size variables) are collated to show, for each tensile sample, the strain equivalent to that at the neck as a function of true strength, the empirical result is as given in Fig. 16. The data are best represented by a straight, sloping line showing, in general, the dependence of ductility on strength.

IV. DISCUSSION AND SUMMARY (PART II)

A. The empirical relationship (Fig. 15), square root of grain diameter vs true strength (texture constant as nearly as possible) shows quantitatively the importance of grain size with respect to tensile properties. From this it appears that attainment of still finer grain sizes would be valuable.

B. Figure 15 has interesting associations with crack theory of the type described in reference 16, in spite of the anisotropy involved. Gross fracture may be viewed as transgranular propagation of cracks initially equivalent in size to the grain diameter.

C. The general empirical relationship, maximum ductility vs true strength (Fig. 16), shows quantitatively the dependence of ductility on strength. No simple theoretical basis for the straight-line relationship is obvious at this time. It is interesting to note that the behavior here is opposite that of steel, for example,[17,18] where strength, ductility relationships depend on other fundamentals.

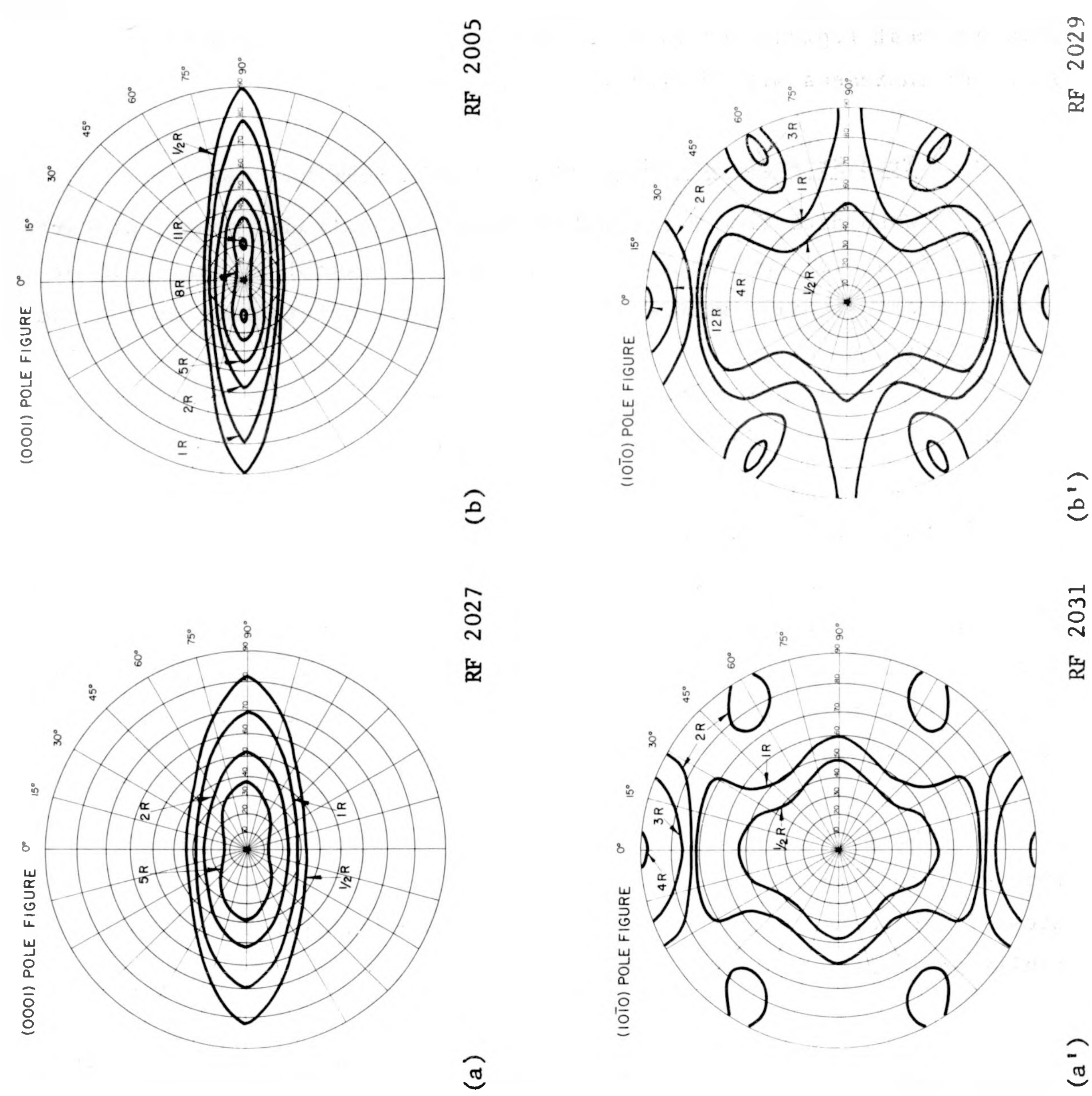
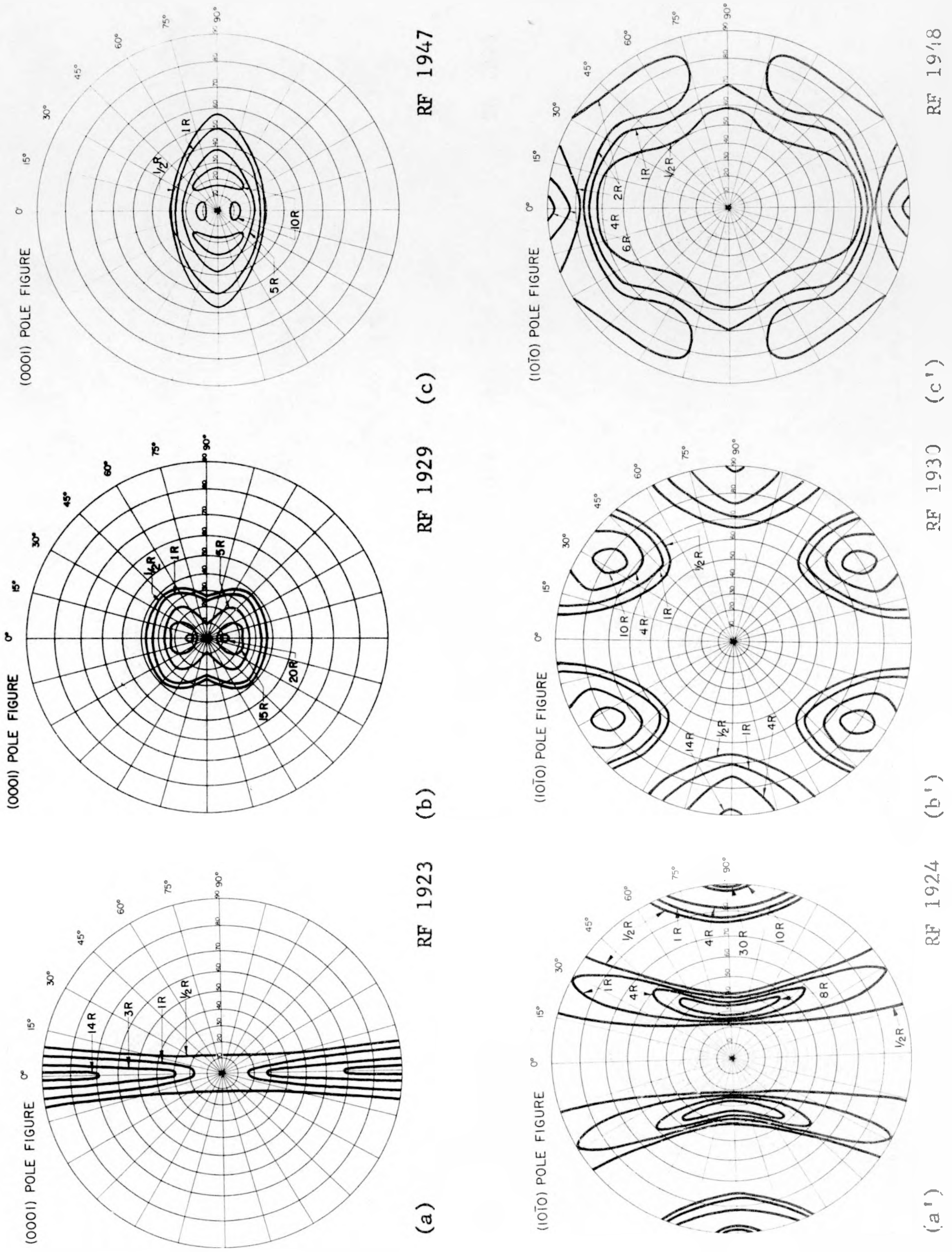


Fig. 1 - Texture study of beryllium unidirectionally hot rolled. Basal and prism orientations for reduction of 5:1 in a, a' and 18:1 in b, b'.



<u>Fig. 2</u> - Texture study of beryllium, extruded and cross rolled at 1900°F (1038°C). Basal and prism orientations for as-extruded flat 2-1/2 inches x 5/8 inch (starting material for cross rolling), extrusion reduction 18:1 in a, a', cross rolling reduction 6:1 in b, b', and 80:1 in c, c'.

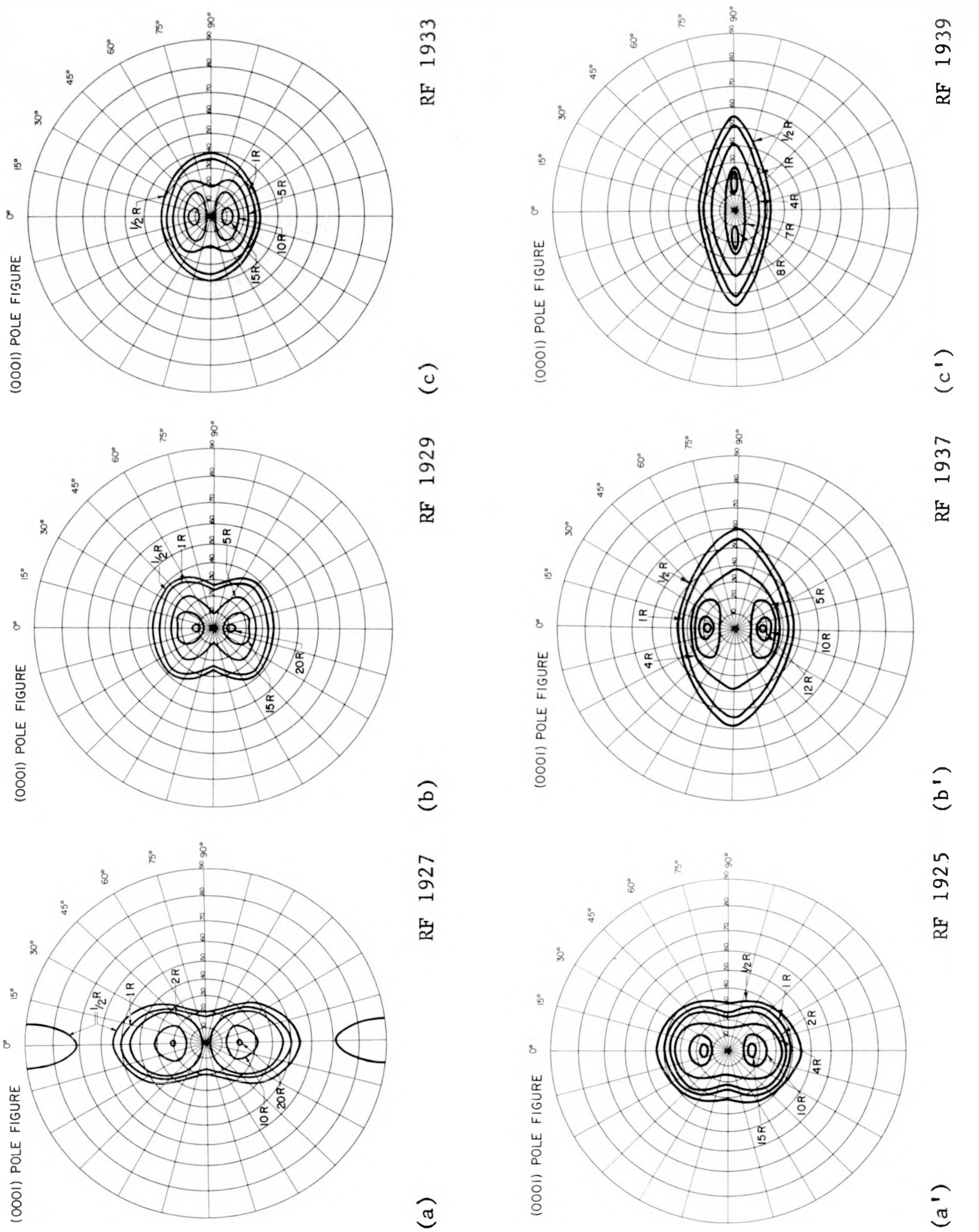
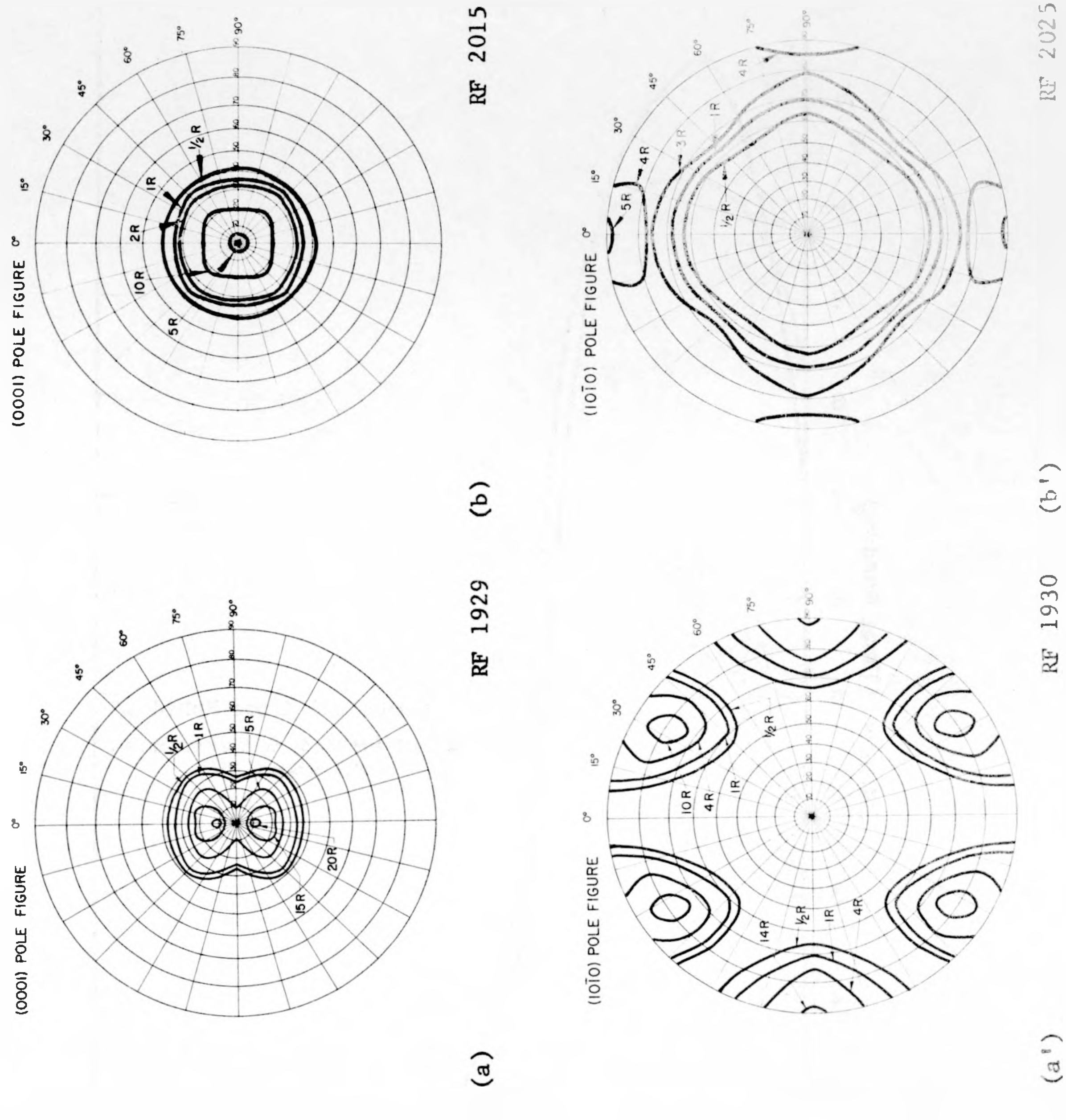


Fig. 3 - Basal texture study of beryllium, extruded and cross rolled, related to cross rolling temperature. Cross rolling temperature 1900°F (1038°C) for a, b, c, and 1600°F (871°C) for a', b', c'. Cross rolling reduction 3:1 for a, a', 6:1 for b, b', and 30:1 for c, c'.



<u>Fig. 4</u> - **Textures in beryllium related to two-dimensional ductility.** Basal **and prism orientations for extrusion and cross rolling in a, a', and for hot pressing and bi-directional rolling in b, b'.**

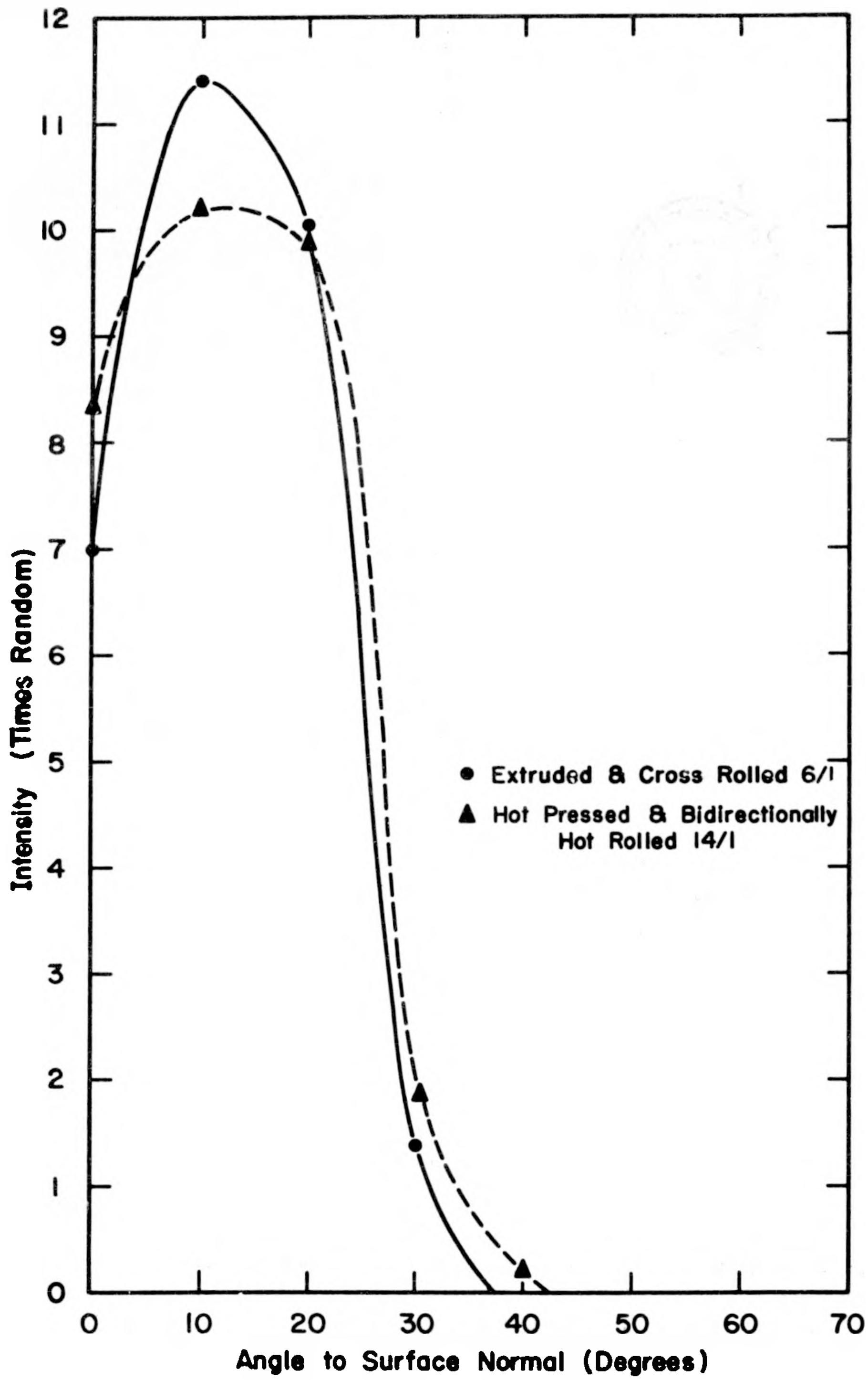


Fig. 5 - Basal pole distribution with respect to surface normal for comparison of textures by extrusion, cross rolling, and hot press, bi-directional rolling. Average intensity (times random) vs angle to surface normal.

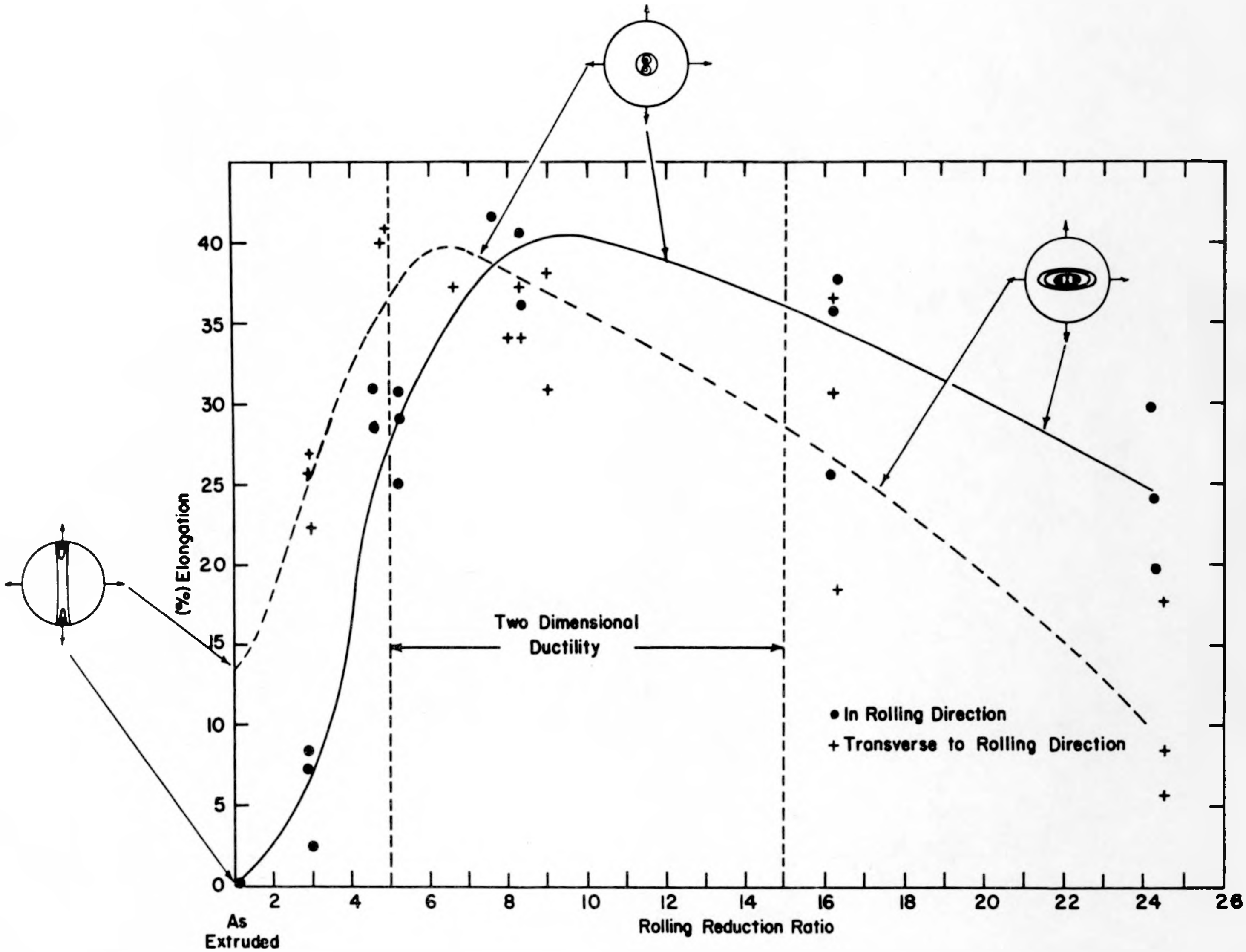
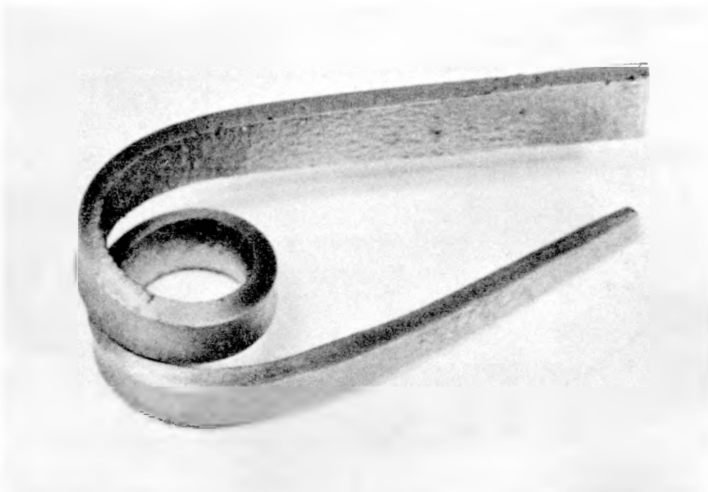


Fig. 6 - Tensile elongation (room temperature) in beryllium extruded and cross rolled at 1900°F (1038°C), related to cross rolling reduction and texture. Percent elongation vs rolling reduction ratio.

(a) RF 1492



(b) RF 1986

<u>Fig. 7</u> - High ductility beryllium (two dimensional) in tension, part a, and bend, part b.

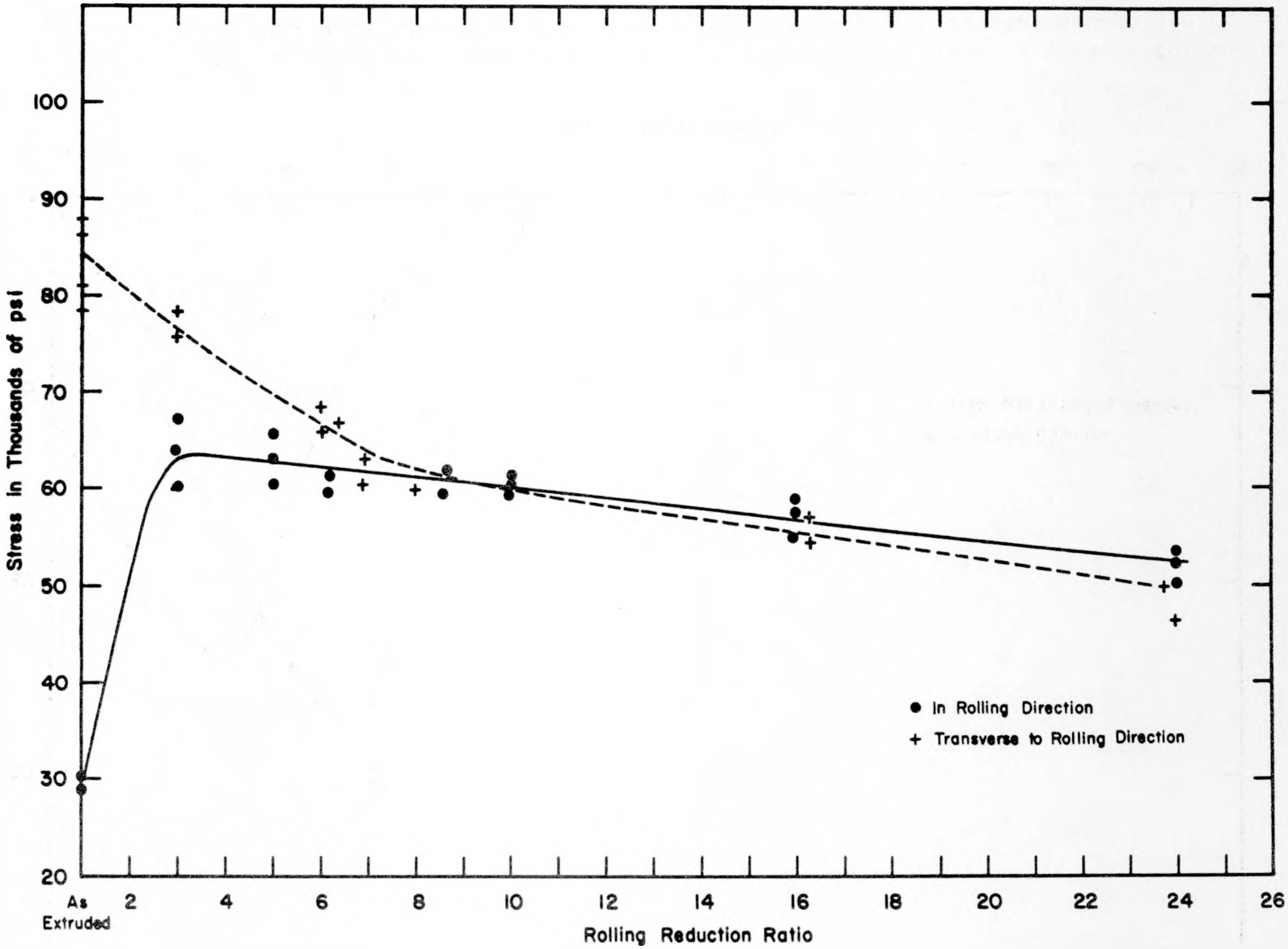


Fig 8 - Tensile strength (room temperature) in beryllium extruded and cross rolled at 1900°F (1038°C), related to cross rolling reduction Conventional strength vs cross rolling reduction.

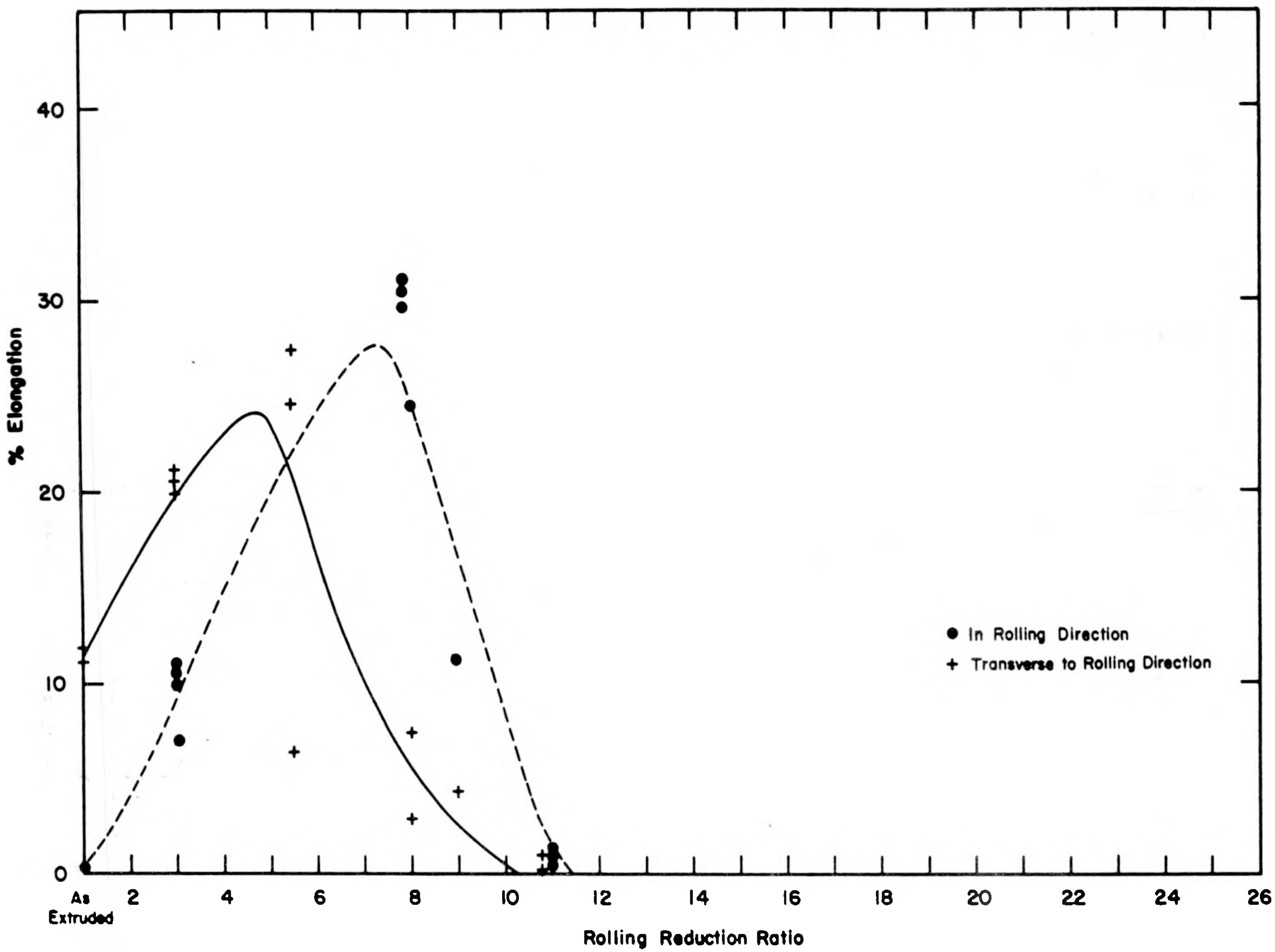


Fig. 9 - Tensile elongation (room temperature) in beryllium, extruded and cross rolled at 1600°F (871°C), related to cross rolling reduction. Percent elongation vs cross rolling reduction.

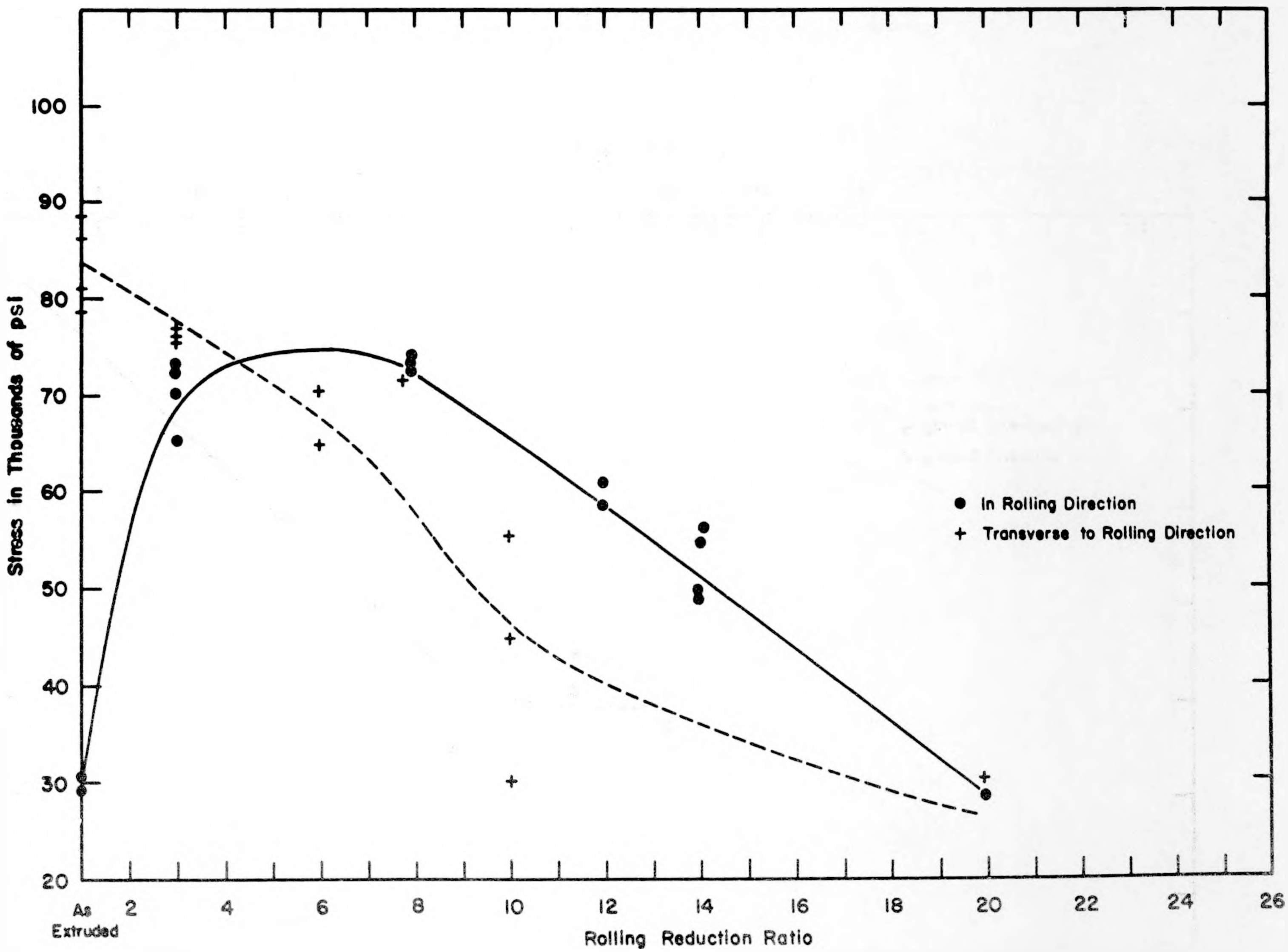


Fig 10 - Tensile strength (room temperature) in beryllium extruded and cross rolled at 1600°F (871°C), related to cross rolling reduction. Conventional strength vs cross rolling reduction.

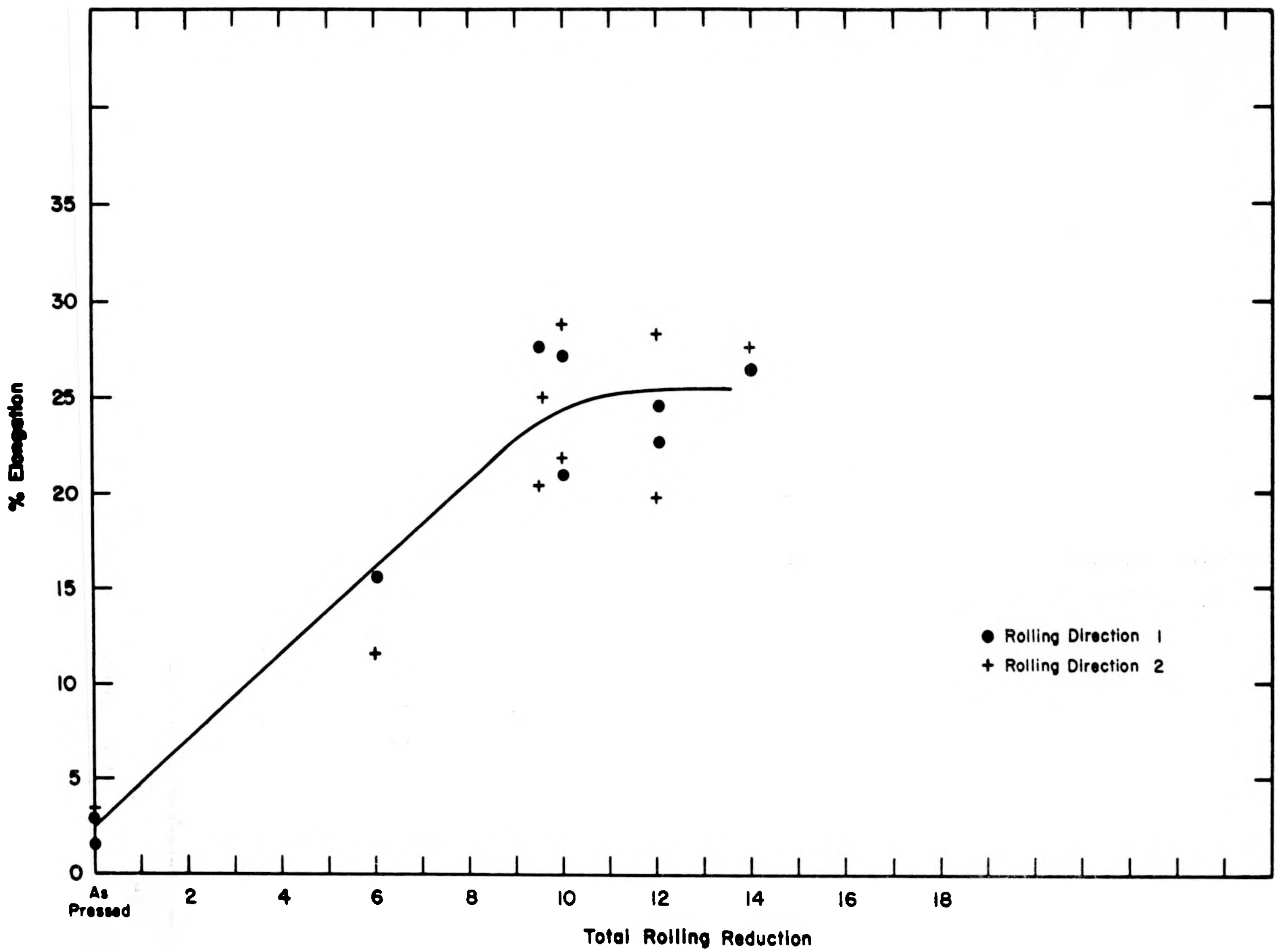


Fig. 11 - Tensile elongation (room temperature) in beryllium, hot pressed and bi-directionally hot rolled, related to total rolling reduction. Data represents rolling temperatures 1600°F - 1850°F (871°C - 1010°C).

Percent elongation vs total rolling reduction.

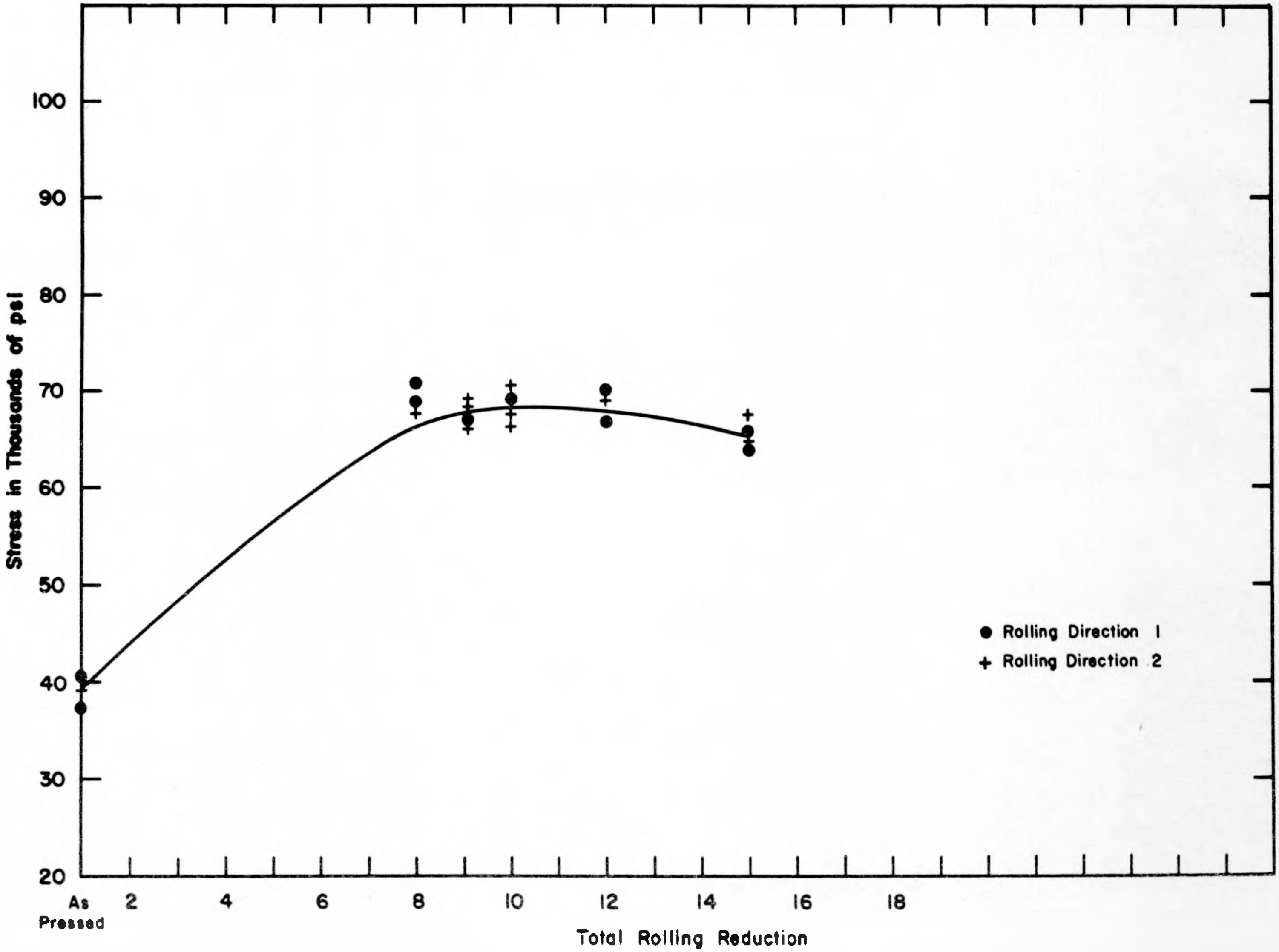
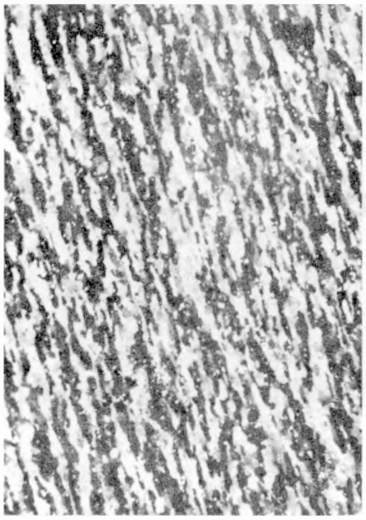
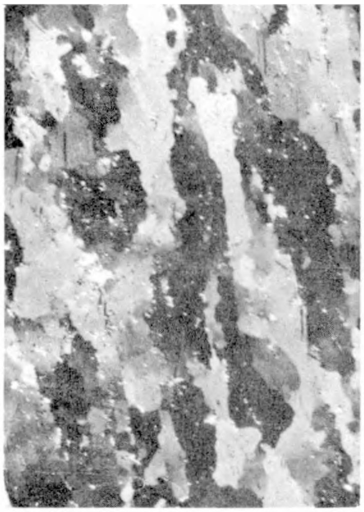


Fig. 12 - Tensile strength (room temperature) in beryllium, hot pressed and bi-directionally hot rolled, related to total rolling reduction. Data represents rolling temperatures 1600°F - 1850°F (871°C - 1010°C).
Conventional strength vs total rolling reduction



(a) 150X Pd.Lt B-260-2a

(b) 150X Pd.Lt B-260-15



(c) 150X Pd.Lt. B-262-1a

(d) 150X Pd.Lt. B-260-10

Fig. 13 - Microstructures of beryllium representative of data in Part II, this report. Beryllium was bi-directionally worked for basal plane layer texture.

(a) Extruded and cross rolled at 1900°F (1038°C) Brush -200 mesh QMV powder
(b) Cast and bi-directionally rolled at 1475°F (802°C).
(c) Extruded and cross rolled at 1600°F (871°C) Brush -200 mesh QMV powder, inadvertent grain growth.
(d) Cast and bi-directionally rolled at 1800°F (982°C).

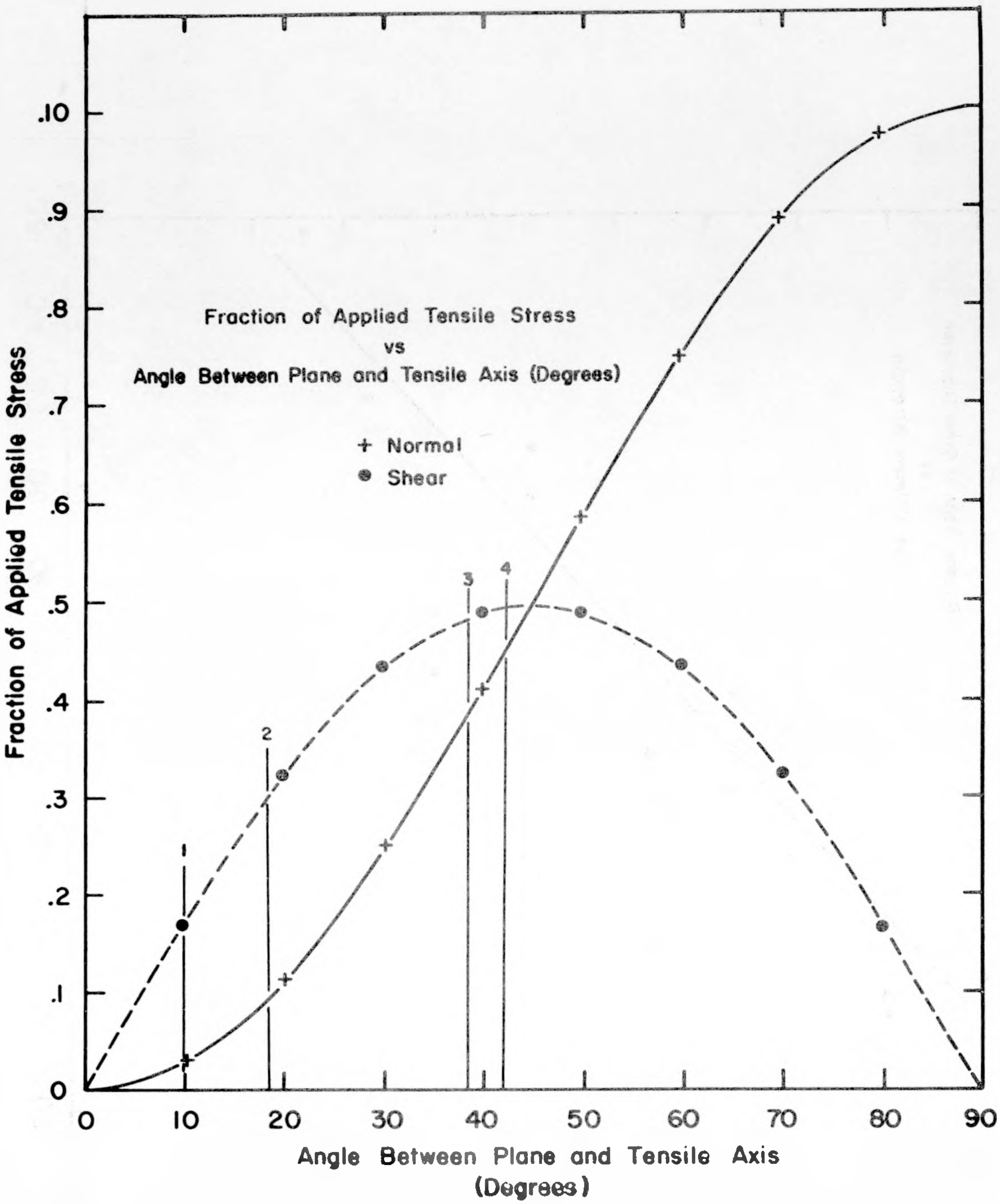


Fig. 14 - Stress distribution in tensile sample related to angle between tensile axis and various cross-sectional planes (simplified). Fraction of applied tensile stress vs angle between plane and tensile axis.

(1) Peak of basal plane layer texture, extruded and cross rolled.
(2) Peak of basal plane layer texture, hot pressed and bi-directionally rolled.
(3) Spread of basal plane layer texture, extruded and cross rolled.
(4) Spread of basal plane layer texture, hot pressed and bi-directionally rolled.

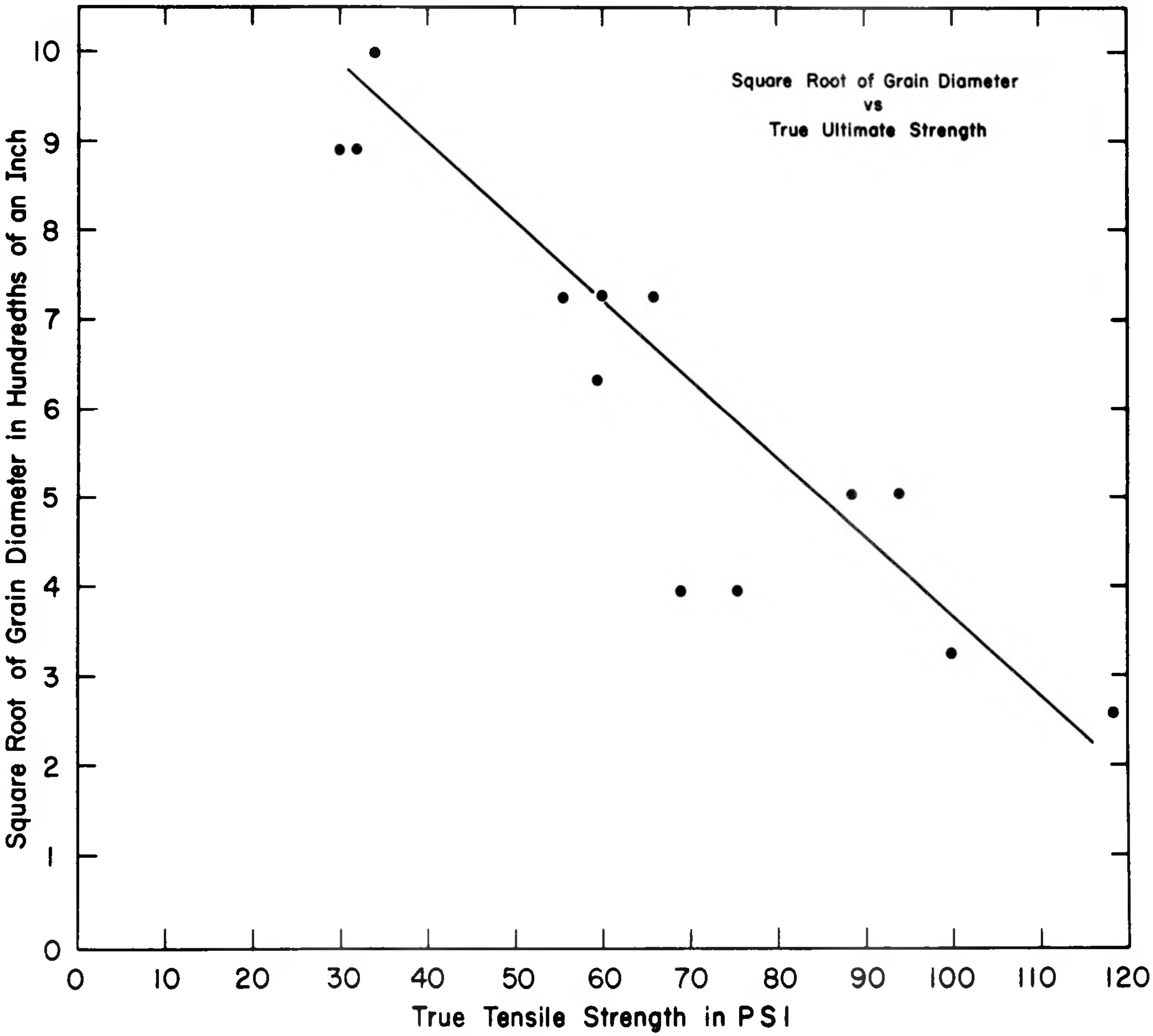


Fig. 15 - True tensile strength in basal plane layered beryllium related to grain diameter. Square root of grain diameter vs true ultimate strength.

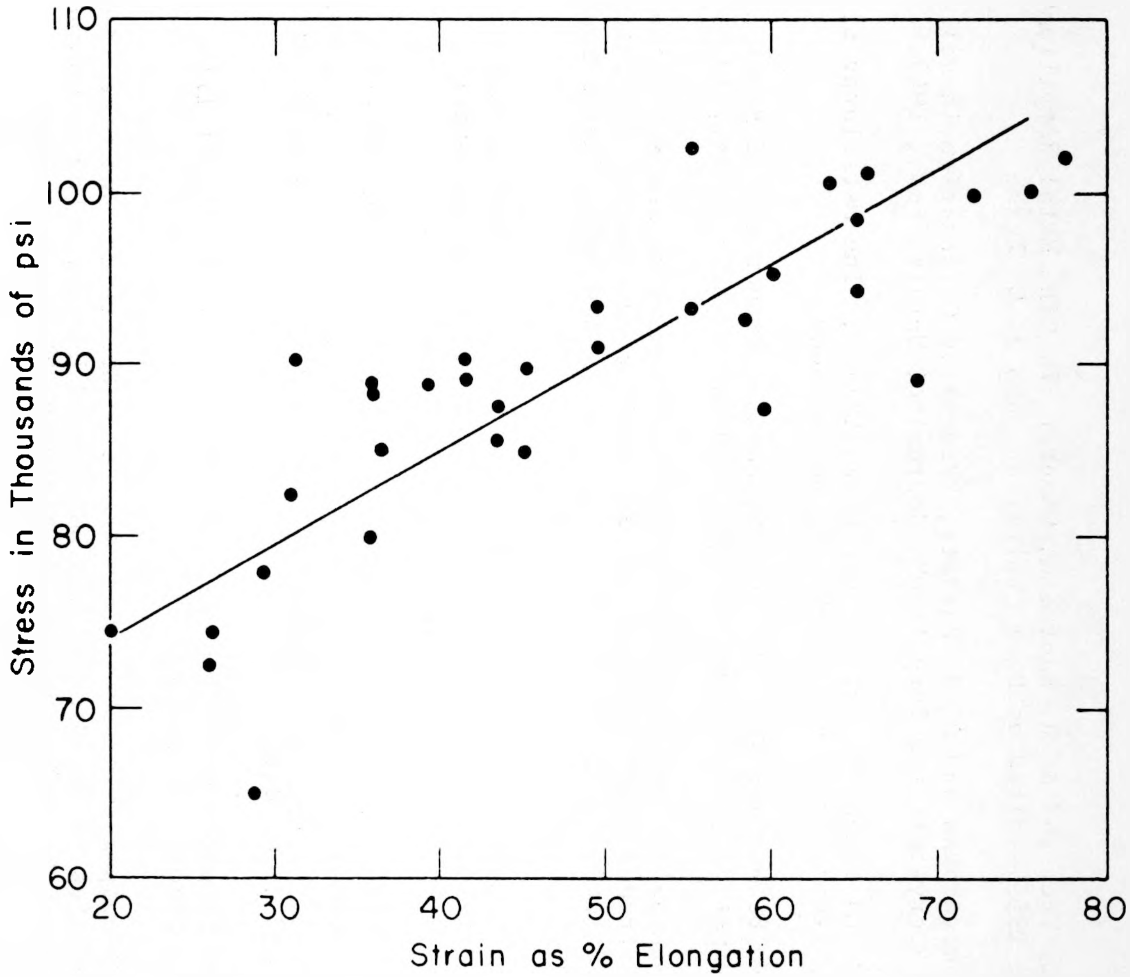


Fig. 16 - True ultimate strength in basal plane layered beryllium related to maximum strain at neck. True strength vs maximum strain.

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