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AN INVESTIGATION OF METAL SPINNING

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Summary Report on Mechanically Spun Cones

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INTRODUCTION

Spinning is a metal shaping process that is widely used to fabricate pieces having rotational symmetry. In common spinning practice a pattern having the final shape of the desired piece is mounted on a lathe. A flat sheet of metal is then clamped to the pattern, and while the pattern and sheet are revolving, the sheet is forced back over the pattern by pressing aginst the sheet with some type of spinning tool. Reduction in thickness of the sheet may or may not take place. Generally the spinning tool is a roller or a heavy wooden stick.

The process can be done by hand, where the spinning is done by a skilled craftsman who knows by experience how to lay the sheet against the pattern; or it can be done mechanically, in which case the forces are applied by some mechanical system.

Many shapes and sizes can be spun, with pieces up to 10 feet in diameter being common. Because of the nature of the process very large reduction in thickness, up to 75% per pass in some cases, can be achieved. With suitable equipment it is also possible to hot spin. There does not seem to be any restrictions as to deformable materials which can be spun. Aluminum, brass, stainless steel, titanium, and super-alloys for example, have all been successfully spun.

Because of the simplicity of the operation, spinning offers some distinct economical advantages. Lengbridge (1) has shown that for producing a small number of pieces that spinning is more economical than deep drawing because of the low set-up time and costs. The pattern used for spinning, for example, can often be made of wood, which saves a great deal of tooling expense.

In spite of the relatively wide useage of spinning as a forming process there is very little information concerning the mechanical properties of spun pieces. Several investigations (2,3,4,5,6) have noted a considerable increase in hardness after spinning; and a general increase in the tensile strength and fatigue resistance (4,5,6). The effects produced by spinning appear to be quite similar to those produced by cold rolling, with the microstructures of spun pieces show grains elongated in the direction of spinning (5). To date, however, there has been no systematic attempt to determine how the mechanical properties in spun pieces vary with the shape of the piece, amount of reduction, and so forth.

In the same manner there is little analysis of a quantitative nature of the deformation process during spinning. Siebel and Droge (7) have shown that the reduction in thickness of a spun piece is proportional to the head-in pressure, that is, the pressure applied in a direction perpendicular to the pattern. The axial pressure, the pressure parallel to the pattern, increases only slightly with increasing reductions. Siebel and Droge also note that the head-in pressure is proportional to the feed rate, and that spinning tool should have a small radius of curvature in order to minimize the resistance to flow in the axial direction.

In the present investigation an attempt was made to determine the mechanical properties of spun materials, and also to study the plastic deformations produced by the spinning operation. A series of pieces were mechanically spun on a machine equipped with suitable guages and controls so that the various forces, feed rates, and other variables employed could be measured. After spinning, sections were cut from the pieces and the mechanical properties measured. Also, the dimensions of the pieces were measured before and after spinning in order to determine the nature of the deformations.

APPARATUS AND PROCEDURE

Materials

Two materials were used in this investigation, cartridge brass (70%Cu-30%Zn) and 1100 (2S) aluminum. The materials were purchased in the form of annealed sheet. The brass sheet was .081" thick. Two thicknesses of aluminum sheet were used, .081" and .125", so that the effect of sheet thickness could be determined.

Tests on As-Received Sheet

A series of hardness and tensile tests were performed on the as-received sheets to determine the variations in properties between sheets of the same material, and also to determine the extent of anisotropy in the sheets.

A further series of tensile tests were performed to determine the effect of the size of the tensile specimen on the tensile properties. The standard ASTM tensile specimens for sheet materials is one inch wide and eight inches long. It was felt that a specimen of this size would be too large for testing many of the spun pieces. Therefore tensile tests were conducted to determine the variation in tensile properties when smaller specimens were used.

Spinning Procedure

The spinning of the test pieces was done by Spincraft Inc. of Milwaukee, Wisconsin. The pieces were spun in the form of truncated cones. A photograph of a typical cone is given in Figure 1.

The different reductions were obtained by varying the apex angles of the cones. The angles selected as shown schematically in Figure 2, were 63°, 85°, and 108°. In all cases the final diameters of the cones was approximately constant, and equal to the original diameter of the unspun blank. This deformation process has also been called stretch-forming, roll-forming, hydroforming, and flow turning by various authors. For the brass cones this diameter was approximately 12 inches. For the aluminum cones of both thicknesses, the diameters were about 16 inches.

To aid in the study of the deformation process a number of cones were spun to 50% or 95% of completeness. These cones are shown schematically in Figure 3.

To further the study of the deformation process, grids were layed out on the blanks of all the cones that were fully spun. The grids, as shown schematically in Figure 4, consisted of two sets of points laid out at 90° to each other. Originally these grids were placed on the spun surface of the cones, that is to say the surface on which the spinning tool was applied. It was found however, that the tool tended to erase the grids during the spinning operation. The grids then were placed on the under surface of the cones , the surface that laid against the pattern, and these grids were preserved. By measuring the grids in a cone after spinning, the amount of the deformation of the piece could be ascertained. A series of small holes forming a grid pattern gave unsatisfactory results due to tearing during the spinning.

All of the cones were spun on the same machine and by the same operator. The machine was equipped with pressure guages, and a recording of the pressures, feed rates, spinning tool, was kept for each of the cones. A complete listing of all the cones that were spun and the spinning variables that were used is presented in Table I. The spinning variables listed in this table may be described as follows:

No load RPM - The speed of rotation of the lathe before the spinning tool was applied in revolutions per minute.

Full Load RPM -The speed of rotation of the lathe during the spinning operation (revolutions per minute).

Head-in Psi - The radial pressure (pressure in the cylinder forcing the tool in a direction perpendicular to the pattern) applied by the spinning tool against the piece. (pounds per square inch.)

Table forward iPM - The rate at which the tool traveled forward axially (inches per minute)

Roller radius - (See figure 5)

Roller land - (See figure 5)

Comments - Observations made by the operator during the spinning operation.

The following are kept constant for all the cones.
Table forward pressure = 700 psi = axial pressure, the pressure parallel to the pattern.
Clamp pressure = 600 psi - Pressure holding the sheet to the pattern.
Roller material and pattern material were of steel.
The lubricant used was the same Spincraft blend.

Testing of Spun Cones

1. Measurements of Mechanical Properties.

Tensile specimens were cut from all of the fully spun cones. In all cases a 4" specimen was used, as is shown schematically in Figure 6. The specimen had dimensions that are one-half of those of the standard ASTM 8" specimen. Four specimens were taken from each cone, two in an axial direction and two in a tangential direction (Figure 7). The specimens were taken with their axis either parallel or perpendicular to the original rolling direction of the sheets so that the effect of any anisotropy in the sheets could be determined.

Some curvature was noted in many of the specimens because of the curvature of the material from which they were cut. These specimens were straightened by hand, which might have caused some deviations in the recorded tensile properties. These deviations appear to be unavoidable, but are probably very small since the sheets were already in a heavily cold-worked condition.

Hardness readings were taken on the surface of a number of the cones. In some cases however, the variations in thickness of the specimens made accurate measurements difficult. Micro-hardness measurements were made on the cross sections of several cones in order to measure the variation in hardness from the spun surface to the surface lying against the pattern. Several additional spot tests were also made on some of the cones. These tests will be described later in the report.

2. Measurements of Deformations.

Two types of deformation measurements were made, measurements of the thickness, and measurements on the grids distorting the fully-spun cones.

Thickness measurements were made on all the cones and consisted merely of cutting pieces from the cones and measuring the thickness with a micrometer.

The grid measurements were made before the cones were sectioned and consisted of locating the points in the grid with a divider and measuring the distance between the divider points on a scale. The grid measurements were rather complex because the different types of deformation that were found. A full description of how these various deformations were measured will be given under "Results".

RESULTS

1 - Tests on Standard Sheets.

On the basis of the tensile and hardness tests of the as-received sheets it was concluded that the anisotropy in the sheets was negligible. The tests also showed that there was no significant difference in properties between sheets of the same material, except for a slight difference between the .125" and .081" aluminum. In this case it was found that the .125" aluminum had slightly lower tensile and hardness values that the .081" sheet. The average, as-received properties of the three types of sheet are summarized in Table II.

Tests using 4" and 8" sized tensile specimens are also listed in Table II. The results show that the 4" specimen had comparable tensile properties to the standard 8" specimen. In view of this similarity it seems likely that the 4" specimens that were used in the testing of cones, gave properties that would approximate very closely those that would be obtained using the standard 8" specimens.

2 - Mechanical Properties in Spun Cones.

The results of the tensile tests on the spun cones are summarized in Table II. The results show that the tensile and yield strengths increase as the cone angle decreases, or, in other words, the tensile properties increase with the increasing reductions in thickness, as would be expected. The elongations values decrease with increasing reductions which again is what would be expected.

In general it was found that the orientation of the specimens in the cone had no effect on the tensile properties. In some cones the specimens in the axial direction had slightly higher tensile strengths than those taken in a longitudinal direction, or vice versa, but these variations were not systematic. These local variations probably represent characteristics of an individual cone only and not the overall process.

In the same manner it was found that the original rolling direction of the sheet had no effect on the tensile properties. This result is not surprising since the anisotropy in the as-received sheets are negligible.

Some difficulty was encountered in performing the tensile tests because of the variations in thickness in the specimen. The magnitude of these thickness variations will be brought out in the next section. It should be pointed out however, that the specimens failed at the region of smallest cross-section. Therefore the reported tensile values are not representative of an average reduction of the cone but of some localized spot in the cone where the thickness was a minimum.

Finally the tensile data show that there is no significant difference in the properties of the .081" and .125" aluminum cones. Hence it would appear that the original thickness of the sheet, at least in the range studied, has no significant effect on the resultant mechanical properties.

The surface hardness of the spun cones are tabulated in Table IV. A great deal of scatter was observed in the hardness readings, and for this reason the average hardnesses only are tabulated in Table IV. The hardness values in general increase with increasing reduction in the expected manner.

Knoop microhardness readings were taken on the cross sections of a number of cones, but once again the scatter in the data tended to mask the hardness variations. The data for one of these cones is given in Table V, and plotted in Figure 8. Because of the scatter in the data the hardness values are probably best plotted as a band, as shown in Figure 8.

To determine just how much scatter might be found in microhardness readings of this order of magnitude, several pieces of the as-received sheet were cold-rolled to similar reductions in area. Microhardness measurements were then made on these pieces and the average variation was determined by statistical analysis. It was found that the variations in the cold-rolled pieces were of the same order of magnitude as those found in the cones. Hence the variations found in the cones appear to be due primarilly to the inherent scatter in the method of measuring the hardness, and not to variations in the cones themselves.

In general the hardnesses tabulated in Table V are typical of the cones examined, and the decrease in hardness with distance from the spun surface (Figure 8) is representative of most of the cones. Metallographic examination of the cones also show the variation in hardening under the spun surface. Some photomicrographs of cross-sections of the brass cones are given in Figure 9. The photomicrographs show that the spun surface of the cone is highly deformed, and that the deformation decreases as the distance below the spun surface increases.

As mentioned above, most of the cones showed a progressive decrease in hardness with increasing depth below the spun surface. Several cones however, showed a slight increase in hardness just below the spun surface. (Figure 10) In order to confirm this observation several additional tests were made on one of these cones.

The first test consisted of cutting a small section from the spun portion of one of these cones and measuring the Rockwell B hardness of the spun surface in the conventional manner. A layer of material was then removed from the spun surface by immersing the piece in concentrated nitric acid. The hardness of the newly exposed surface, which lay several thousanths under the original spun surface, was then measured. Another layer was then removed and the hardness measured again. Repeating this procedure several times gave the results shown in Figure 11. The figure shows that there appears to be a distinct increase in hardness in the region under the spun surface.

A second test consisted of immersing the piece in acid before and then measuring the X-ray line breadth after each surface removal. The results are shown in Figure 12. The increase in line breadth shows that the region under the spun surface shows greater distortion than the surface.

As a final test, several pieces of the cone were annealed at various lengths of time at 626°F and then examined metallographically. Courser grains were found under the surface which shows that recrystallization began in this region. This would be true only if the region had a larger amount of energy stored up through a larger distortion.

In view of these results it appears that the region under the surface of this cone is really harder than the spun surface. The reason for this behavior is uncertain, but is probably due to the partial recovery of the spun surface of the cone. Considerable heat is generated during spinning, and this heat could cause partial recovery of the highly deformed region at the spun surface. The region under the surface however, would not be subjected to temperatures as high as the surface temperature and therefore would not recover. Thus, after the spinning was completed the region under the surface would be the more distorted because no recovery had taken place.

There does not seem to be any reason in terms of the pressures, feed rate, and other spinning variables, why some cones should show partial recovery while others did not. A Possible explanation may be that insufficient lubricant was used during spinning of these pieces. This would increase the friction between the spinning tool and the sheet, and therefore produce a higher temperature in the sheet. Unfortunately there is no data to indicate whether or not this was the case.

In general the mechanical properties of spun pieces are similar to those produced by rolling. A comparison of the properties produced by these two methods are shown in Figure 13 and 14. The agreement seems quite good, particularly for the aluminum. Hardness values are not included in the aluminum data because of the uncertain values found.

Thus for these materials the tensile properties of a spun piece can be estimated by knowing the properties produced by cold rolling to the same reduction.

It must be recognized that the properties are not completely analogous, in view of the variations in work hardening from one surface to the opposite surface in a spun piece. This variation may be very important when one uses a spun piece in some service application. Spinning produces a much more non-homogeneous deformation than rolling, and it is only the average value taken through the whole cross-section of the piece which gives comparable properties with a cold rolled piece. Furthermore, as will be brought out in the next section, there may be large variations in thickness in a spun piece. The tensile properties of a spun piece are dependent upon its minimum thickness and not on the average thickness. Thus care must be taken to locate the region of minimum thickness and use the tensile value for the reduction in this region and not those for the overall reduction when making any estimates. With these limitations in mind however, it would seem fairly reliable estimates of the mechanical properties can be made from rolling data.

3 - Deformations in Spun Cones.

The thicknesses found in the spun cones are summarized in Figure 15. In these plots the thickness of each cone is plotted against the distance from the bend, that is, the radial distance from the spot where spinning began. As would be expected, the thickness of the cones depends upon the cone angle, with the smaller angle cones having smaller thicknesses. In general the results show this, but they also show that there may be considerable variations in thickness in a single cone, and also between cones of the same included angle. In general it appears that the variations in thickness are greater in the brass cones than in the aluminum ones.

Comparison of the results of the 50%, 95%, and fully spun cones for the same cone angle show that the thickness does not appear to be influenced by how much of the cone has been spun. In other words, it does not appear that further spinning on the piece alters the thickness of the portion that has already been spun. Thus the thickness at any region in the cone is dependent only upon the forces that act on that particular region, and is not affected by deformations taking place in other regions of the cone; that is, the plastic deformation takes place under the roller. Comparison of the thickness measurements of the 0.081" and 0.125" aluminum cones shows that the variations in thickness along the cone are of the same magnitude. Hence, the original thickness to have little effect on this aspect of the deformation. This result is in agreement with the mechanical tests, which showed that the tensile properties were the same.

The grid distortions found in the fully spun cones are shown schematically in Figure 16. As shown in the figure, two types of distortion were found. The first is a radial elongation of the grids because of the increase in length of the sheet in the spun region. The second is an tangential movement of the grids because of the shearing action of the spinning tool. The magnitude of this shear was determined by extending an original line of the grid from the unspun region of the cone and measuring the distance of this new extended line to the grid points. No change in the width of the grids was noticed.

The radial elongations vs the distance from the bend for the various cones are shown in Figure 17. In these figures the distance from the bend was taken at half the distance between the two grid points that give the corresponding elongation value. The overall elongation, that is the elongation between the first and last point, are also plotted. The results show that there are considerable variations in the elongations in the cones. It should be pointed out again however, that the grids were on the underside of the cones and thus only approximate the deformation of the whole piece. Once again the results on the aluminum sheets also suggest that the elongation is not affected by the original thickness.

Conservation of volume requires that there should be a direct relationship between the elongation and the thickness in a deformed piece. Comparison of the radial elongations and thicknesses in the fully spun cones are presented in Figure 18. The figures show that there is a sample linear relationship between the two.

The tangential movements of the grids are plotted in Figure 19 as a function of the distance from the bend. This distortion should be due to the shearing force, and if the shear force were constant these curves would be straight lines. In the present case it appears that the shearing force was usually lower at the start, and then increased slightly.

The overall results show groups of cones which seem inconsistent insofar as their deformation is concerned. The first set includes 4A1B and 4A1C. In these cones the thicknesses are greater than would be expected on the basis of the thickness values for the other 125" aluminum cones. The operators comments (Table I) note that not much spinning was done on cone 4A1C. The same could probably be said for 4A1B. It is interesting to compare the thicknesses of these two cones with that of the third cone, 4A1A, that was spun to this shape. The thicknesses of the first two cones are on the order of .096", while the thickness of 4A1A is about .066". Thus a difference in thickness of approximately 30% can be found in pieces of the same geometry. The spinning forces were not the same for these three cones, however.

The other data which appears out of line involves the tangential displacements in cones 3A3P and 3A3F, and 4A2M and 4A3E. It seems reasonable to assume that the amount of tangential displacement would increase with increasing reductions in thickness. In these two sets of cones however, the order of displacement is reversed. That is, a cone with greater reductions show less displacement and vice versa. The reason for this effect will be discussed in the following section

DISCUSSION

In order to correlate the deformations in the cones with the spinning variables used (Table I) it is necessary to establish certain basic assumptions. The first assumption is that spinning may be treated as a plastic flow problem, and that the general laws of plasticity are obeyed. The second assumption is that it would be desirable to spin a piece in which the thickness is constant. This assumption is certainly not the only one that could be made, and the problem could be treated equally well using other approaches. On the basis of strength, response to heat treatment, and other metallurgical variables, however, this second assumption is a very practical one. For example the age-hardening characteristics and the corrosion resistance could be markedly different in various regions of a spun piece if the deformation was not uniform. The final assumption is that the diameter of the piece after spinning is equal to the diameter of the unspun blank.

On the basis of these assumptions the thickness of the cone should be a function of the cone angle, and can be expressed by the relation:

$$S \triangleq S_o \sin \alpha/2$$

where S = thickness of the spun section
S_o = thickness of the blank
α = cone angle.

From the above equation the required thicknesses of the spun sections of the cones can be calculated. These calculated thicknesses are listed in Table VI.

A comparison of the calculated thicknesses with those actually found in the cones shows that in most cases there is a distinct departure from the ideal case of constant thickness. Since the thickness of a cone is controlled by the spinning variables that were used, the problem is to show how changes in the spinning variables cause departures from constant thickness. Unfortunately the data are not sufficiently complete to make a fully rigorous solution possible. To do this would require information concerning the magnitudes and extent of the regions of elastic and plastic strains in the cone. It is possible however, to show in general how the thickness is influenced by the spinning variables.

On the basis of the thicknesses found in cones of the same geometry but spun to 50%, 95% and fully complete, it would appear that the thickness at any spot in the cone is determined solely by the action of the spinning tool as it went by that spot. In other words, the thickness at any spot is due only to the instantaneous spinning forces acting at the spot. Once the spot has been deformed its thickness is unaffected by the deformations in other regions of the cone. Thus variations in thickness must be due to variations in the applied forces, or to the variation in the resultant force.

In the present investigation two forces were measured, the force perpendicular to the surface of the cone (head-in pressure) and the force parallel to the cones surface (axial pressure). This second force (pressure) was kept constant for all of the cones that were spun in this investigation. The thickness of the cone would probably not be changed a great extent by changes in the axial force however, since its main use is only to bend the material down in front of the tool. (Figure 20) This conclusion is in agreement with Siebel and Droge (7), who show that the axial force changes only slightly with large thickness changes.

The force which primarilly controls the thickness is the head-in force (Figure 20). Siebel and Droge show that the change in thickness is almost directly proportional to the head-in pressure. Thus one should find that when this force is large the thickness is small, and vice versa. Comparison of the thickness data with the head-in pressures in Table I support this conclusion quite well. The magnitude of this force is of course dependent upon the material being spun. Thus one finds pressures on the order of 20-25 psi for the aluminum cones and 300-500 psi for the brass cones.

The magnitude of the head-in pressure will also depend upon the cone angle. Smaller cone angles will require a greater reduction in thickness and consequently a greater hand-in pressure. The relative change in pressure with thickness will of course be dependent upon the plastic properties of the material.

In the present investigation the applied pressures (radial and axial) were kept constant during the spinning of each single cone. Thus some question might be raised as to why the thickness of the cone varies as a function of the distance from the bend, if the pressure were constant.

The answer to this question hinges upon the resistance of the sheet to deformation. The resultant thickness depends upon the net force applied to the material, which is the sum of the applied forces (pressures) minus the sum of the resisting forces in the material. These resisting forces are a function of the distance from the bend. Thus the net force and consequently the thickness will be a function of the distance from the bend.

Let us consider the case where the spinning tool is still near the bend. (Figure 21) Ahead of the tool there is a ring of metal which is as-yet unspun. Now this ring of metal will be elastically stressed because of the deformation that has already taken place in front of this ring. These elastic stresses will then act to either aid or hinder the deformation stresses of the spinning tool.

Suppose that the head-in pressure is too small, and that the thickness of the spun region near the bend is therefore larger than the ideal thickness. The outer ring is then being pulled inward and consequently there is a tensile stress built up in the metal at the point where the spinning tool is being applied. This tensile stress favors the reduction in thickness and therefore the thickness should be less at this region. Continued spinning therefore should decrease the thickness of the piece. Further out from the bend however, some point must be reached where the elastic stresses in the ring become too small because the size of the ring has been progressively decreasing. The helping stress will then become progressively smaller until it becomes zero at the final outer edge of the cone. The thickness will therefore become greater toward the outer edge of the cone.

By the same style of reasoning it can be shown that when the head-in pressure is too large that the thickness should be less than the ideal thickness at the region near the bend. In this case however, the unspun ring will exert a compressive stress which will tend to act against the head-in pressure. Thus the thickness will increase with increasing distance from the bend. When the unspun ring becomes small the compressive stresses will be lessened, and thus the thickness will decrease at the outer edge of the cone.

On the basis of this type of reasoning the cone thicknesses should vary as shown schematically in Figure 22. Comparison of the predicted thickness variations with the actual variations found in the cones shows fairly good agreement. For example, cones 4A1A, 4A1C, 5A1F, and 5A1G have thicknesses that are greater than the predicted value, and in these cones the thickness is greater at the bend, decreases slightly, and then increases, in accordance with the general theory. For cones where thickness is less than the calculated value, the theory does not seem to hold as well. These cones have low thickness values at the bend and increase in thickness with increasing distances from the bend, in the expected manner. A decrease in thickness does not generally occur at some further distance from the bend, as would be predicted. Examples of this type are cones 5A2J, 5A2R, and 6A2S. It may be that some other variable is coming into play in these cases, such as the feed rate, which is tending to further affect the deformation.

The results also show that some of the cones are approaching the ideal condition where the thickness is the calculated thickness. These cones are 3A3DD, 3A2N, 3A1D, 3A3EE, 3A1E, 3A3FF, 3A1H, and 5A15. Thus it seems possible to produce cones of constant thickness by a proper selection of spinning variables. As mentioned previously, the results are not suitable for making a rigorous analysis, but they do show in which direction the variables should be altered in order to produce the calculated thickness.

In addition to the cone angle and the head-in pressure, other variables which will affect the deformation are the feed rate and the roller radius.

It is quite easy to see that an increase in the feed rate would tend to increase the thickness of the cone. Perhaps the best way to illustrate this is by analogy to the common tensile test. It is well known that the tensile strength increases when the strain rate is increased. In spinning, an increase in the feed rate is equivalent to increasing the strain rate. Thus the tensile strength of the material would be greater and consequently the reduction in thickness would be less. The net result would be that the final thickness would be greater with increasing feed rate. In most materials however, small changes in the strain rate do not significantly alter the tensile properties. Thus the thickness should not vary a great deal as long as the feed rate is not changed over several orders of magnitude. Other factors, such as the surface smoothness of the piece, also enter in when the feed rate is changed. It may be desirable, in some cases to change the feed rate in order to produce a good surface, regardless of the effect on the thickness.

The roller radius will also influence the thickness of the piece to some extent. The effect is comparable to the effect of the roll radius in cold rolling. When a smaller radius is used in cold rolling the contact area between the roll and the piece is decreased, if the applied force remains the same, of course. Because the contact area is decreased the applied pressure is greater and is also better directed, and therefore the deformation is greater. Spinning may be likened to cold rolling with only one roll, at least to a rough approximation, and thus the effect of decreasing roll radius should be to decrease to thickness of the spun piece with a given set of forces. It is difficult to find a concrete example of this effect in the data, but the general results tend to support this point of view. In addition Siebel and Droge also note that the roll radius should be kept small to minimize flow in the axial direction.

While all of the discussion thus far has been based on the thickness of the piece, the other deformations noted in the cones may also be related to the spinning variables in the same manner. The radial elongation was shown to be proportional to the thickness, for example, and thus the elongations in the cones can be explained in the same manner as the thicknesses.

The tangential displacements are also influenced by the spinning variables, but in this case the relationship is more uncertain. The tangential displacements are due to the tangential force produced in the cones. No direct measurement of this tangential force was made. The tangential force is actually a resultant force obtained from the head-in and axial forces, and thus is dependent upon the magnitudes of these forces. It is also dependent upon the cone angle. Furthermore the tangential force should also be dependent upon the friction between the roller and the cone, and although the same lubricant was used throughout, there is no guarantee that the friction force was constant.

In general one would expect to find that the tangential displacement increases with increasing applied pressures, and this seems to be true in most cases. The exceptions to this were noted in the results section, in which the displacements of several of the aluminum cones do not vary in this expected manner. A number of the spinning variables were altered between these cones and therefore it is not easy to assign the cause of the exceptions to a single variable. From an overall comparison of the variables in Table I, though, it would appear that the difference in the roller diameter is the most likely cause. The cones which show too much deflection were formed with the 3/8" radius roller, while those showing too little deflection were formed with the 1/8" radius roller. In view of the comments already made concerning the effect of the roller radius it would seem likely that a larger radius roller would tend to produce a greater tangential force, and vice versa. A difference in the friction could also account for the differences in deflection however, and therefore a definite conclusion cannot be made. In any case this concern over the tangential displacement may be of little importance since it would not be of major concern in determining the properties of the piece.

The foregoing discussion has been intended to describe how the deformations produced by spinning are controlled by the various spinning variables. It should not be implied however, that the variables that were discussed are the only ones which will affect the deformation. Examples of the variables that have not been systematically varied are; rotational speed of the spinning lathe, spinning tool shape, lubrication, and the initial blank temperature. It is expected that the effects of these variables will be considered in future work.

CONCLUSIONS

On the basis of this investigation the following conclusions can be made concerning the properties of spun pieces.

1 - Mechanical Properties.

a) The tensile and yield strength and hardness of spun pieces increases with increasing reductions.

b) The tensile elongations decrease with increasing reductions.

c) The tensile properties and hardness produced by spinning are in general quite similar to those produced by cold rolling to the same reduction. Thus, to a first approximation, the mechanical properties of spun pieces may be estimated from the cold-rolled properties. Some care must be taken to locate the region of minimum thickness in the spun piece because this is where tensile failure will occur.

d) There is a difference in the degree of cold working from the spun surface to the opposite surface. In some cases the maximum residual distortion may occur beneath the spun surface, presumably because of the recovery of the spun surface.

e) For the thicknesses studied, the resultant mechanical properties do not depend on the original thickness of the sheet.

2 - Deformations.

a) There may be large variations in thickness of spun pieces, and also large variations in thicknesses between pieces spun to the same reduction.

b) In the same manner there may be large variations in the elongations and the tangential displacements in the pieces.

c) Spinning to 50%, 95% or 100% completion does not appear to alter the deformations in the pieces.

d) It seems that a qualitative picture of the deformation process can be used to describe the deformation process, and how the thickness should vary in terms of the spinning variables. In general the spinning variables should act as follows:

1. The reduction in thickness is controlled primarily by head-in pressure, and large head-in pressure should cause large reductions.

2. Smaller feed rates should cause greater reductions.

3. Small roller radius should increase the reduction, and probably tend to decrease the tangential displacements.

4. The axial pressure, and the rotational speed of the lathe do not appear to be important variables, and small changes in these quantities should not affect the reduction.

REFERENCES

1. J. Lengbridge. Tool Eng. 30 (1953) 89
2. J. R. Young - Machinery - London 86 (1955) 187.
3. F. L. Banta - Product Eng. 25 (1954) 189.
4. K. Stalker and K. Moore - Am - Machinist 99 (1955) 126.
5. Anon. - Product Eng. 27 (1956) 135.
6. K. W. Stalker - ASME preprint no. 57-A-271 - 1958.
7. E. Siebel and K. Droge - Werkstatt. and Mach. 45 - 1955.

Table I - Listing of Spun Cones

Sample No.	%Spun	No Load RPM	Full Load RPM	Head-in psi	Table Forward 1 p.m.	Roller Rad.	Roller Land	Comments
5A1G	50	400	400	400	20	1/8"	1/4"	Metal not completely on block. Not enough head-in pressure.
5A1F	95	400	40	300	20	1/8"	1/4"	Metal did not lay down on block completely. Not enough head-in pressure.
5A1J	100	400	400	500	20	1/8"	1/4"	Large amount of head-in pressure required to metal on block.
3A1D	50	350	350	25	28	1/8"	1/4"	Unspun portion of blank distorted due to excess table forward.
3A1E	95	350	350	25	25	1/8"	1/4"	Cut down table forward speed to eliminate wrinkle on end.
3A1H	100	350	350	25	25	1/8"	1/4"	O.K.
4A1C	50	350	350	50	28	1/8"	1/4"	Speed of spindle unchanging during spinning. Not much spinning was done.
4A1B	95	350	320	50	28	1/8"	1/4"	Increase table speed to eliminate spirals.

Sample No.	%Spun	No Load RPM	Full Load RPM	Head-in psi	Table Forward 1 p.m.	Roller Rad.	Roller Land	Comments
4A1A	100	350	300	50	20	1/8"	1/4"	Table forward speed too slow spirals occur in spinning. Spindle speed drop occurs at maximum stroke.
6A2S	50	440	440	500	20	1/8"	1/4"	O.K.
5A2R	95	440	440	550	20	1/8"	1/4"	O.K.
5A2T	100	400	400	425	20	1/8"	1/4"	O.K.
3A2N	50	400	400	25	48	1/8"	1/4"	O.K.
3A2O	95	400	400	25	48	1/8"	1/4"	O.K.
3A2P	100	400	400	20	48	1/8"	1/4"	O.K.
4A2K	50	350	350	50	25	1/8"	1/4"	Table forward was too slow. Spirals occured on large end.
4A2L	95	350	350	50	28	1/8"	1/4"	Table forward too slow spindle speed too slow. Spirals occured.
4A2M	100	400	400	50	48	1/8"	1/4"	Increased speed of spindle and table forward to eliminate spirals. Piece good.

Sample	%Spun	No Load RPM	Full Load RPM	Head-in psi	Table Forward 1 p.m.	Roller Rad.	Roller Land	Comments
6A3GG	50	500	480	375	20	1/8"	1/4"	Head-in pressure too great. Metal flared back against roller.
6A3HH	95	500	480	300	20	1/8"	1/4"	Head-in pressure still too great. Metal falring back.
5A3JJ	100	500	480	275	20	1/8"	1/4"	O.K.
3A3DD	50	460	460	10	42	3/8"	3/16"	O.K.
3A3EE	95	460	460	10	42	3/8"	3/16"	O.K.
3A3FF	100	460	460	10	42	3/8"	3/16"	O.K.
4A3AA	50	400	400	25	28	1/8"	1/4"	Roller too sharp and head-in pressure too great. Material tends to back over radius of roller.
4A3BB	95	460	460	15	28	3/8"	3/16"	O.K.
4A3CC	100	460	460	15	28	3/8"	3/16"	O.K.

For all Specimens

Table forward psi = 700

Clamp psi = 600

Lubricant = Socony Spincraft Blend #1.

Legend

In the sample numbers, the first number refers to the material.

No. 5 and 6 = Brass

No. 3 = .081" aluminum

No. 4 = .125" aluminum

TABLE II

Tensile Tests Data on As-Received Sheets

Material	Total Length	Width Test Section	Avg. Tensile Strength psi	Avg. Yield Strength psi	% Elong.
Brass					
.081" thick	9"	.562"	47,650	16,400	57
	8"	.500"	47,500	16,800	65
	7"	.423"	48,500	17,000	65
	6"	.500"	47,700	17,500	67
	6"	.378"	48,200	19,500	63
	5"	.338"	48,100	17,800	70
	4"	.500"	47,800	17,800	70
	4"	.250"	47,100	17,200	65
	4"	.125"	52,100	20,300	60+
Aluminum					
.081" thick	8"	.500"	13,600	5,400	41
	6"	.375"	13,600	5,700	40
	4"	.250"	13,600	6,200	37
Aluminum					
.125" thick	8"	.500"	11,100	4,100	40
	4"	.250"	11,600	4,600	38

TABLE III - Tensile Properties of Spun Cones

Each value is average of two specimens, one parallel and one perpendicular to the original rolling direction.

radial direction = direction from center of cone to outer edge.
tangential direction = direction parallel to outer edge of cone or perpendicular to radial direction.

Cone	Cone Angle	Average Thickness "	Tensile Strength (psi)	Yield Strength psi .2% offset	Elongation % 1"
Brass 5-A-1J--radial dir.	63°	.042	79,900	75,100	7
tang. dir.	63°	.042	86,000	68,000	9
Brass 5-A-2J--radial dir.	85°	.051	77,800	62,500	10
tang. dir.	85°	.051	80,000	63,200	*
Brass 5-A-3J--radial dir.	108°	.063	69,500	66,200	9
tang. dir.	108°	.063	71,100	57,800	12
.081" Al 3A1H-radial dir.	63°	.044	18,500	17,190	9
tang. dir.	63°	.044	18,600	17,250	9
.081" Al 3A2P-radial dir.	85°	.051	17,700	16,150	10
tang. dir.	85°	.051	17,900	16,900	9.5
.081" Al 3A3FF-radial dir.	108°	.062	15,950	15,050	12
tang. dir.	108°	.062	15,800	15,070	11
.125" Al 4A1A-radial dir.	63°	.177	19,200	18,400	8.5
tang. dir.	63°	.177	19,200	17,950	10
.125" Al 4A2M-radial dir.	85°	.194	18,250	17,300	9.5
tang. dir.	85°	.194	18,950	17,600	10.5
.125" Al 4A3CC-radial dir.	108°	.235	16,150	15,050	13.5
tang. dir.	108°	.235	16,100	14,900	15

* Both specimens broke at gage marks.

MECHANICALLY SPUN

Table IV

Hardness of Spun Surface of Mechanically Spun Cones

Cone	Average Hardness Rockwell B Scale
63° Brass	87
85° Brass	85
108° Brass	80
	Average Brinnel Hardness No. 500 Kg load 10 mm ball
63° 081" Al	30
85° 081" Al	28
108° 081" Al	27
63° 125" Al	29
85° 125" Al	27
108° 125" Al	27

Table V - Microhardness Readings on Cross-sections of cone 6A3GG.
Knoop indenter, 1000 gram load.
Positions 1 and 2 are in the unspun section of the cone. The remaining positions are all at a various region in the spun section.

Position on Specimen	Total thickness (relative units)	Distance from Spun surface (relative units)	Knoop Hardness Number
1	202	25	79.9
		65	83.4
		105	76.2
		145	77.7
		185	78.8
2	200	20	75.2
		60	83.0
		100	80.7
		140	81.1
		180	79.5
3.	180	20	164.6
		50	157.1
		80	166.9
		110	159.2
		135	143.4
		160	133.1
4	174	20	176.4
		48	165.7
		76	170.4
		104	168.0
		132	139.0
		154	133.9
5	170	17	182.8
		55	180.2
		83	171.5
		101	163.5
		129	149.0
		153	123.8
6	160	15	171.5
		42	178.9
		69	165.7
		96	168.0
		123	153.0
		145	152.0

Position on Specimen	Total thickness (relative units)	Distance from Spun Surface (relative units)	Knoop Hardness Number
7	158	15	182.8
		42	188.2
		69	182.8
		96	178.9
		123	157.1
		145	149.0
8	152	18	185.4
		48	180.2
		78	186.8
		108	165.7
		134	149.0
9	147	18	193.7
		48	186.8
		78	175.2
		108	169.2
		129	155.0
10	146	18	198.1
		48	180.2
		78	178.9
		108	160.2
		130	154.0
11	149	18	188.2
		48	184.1
		78	177.7
		108	158.1
		130	145.2

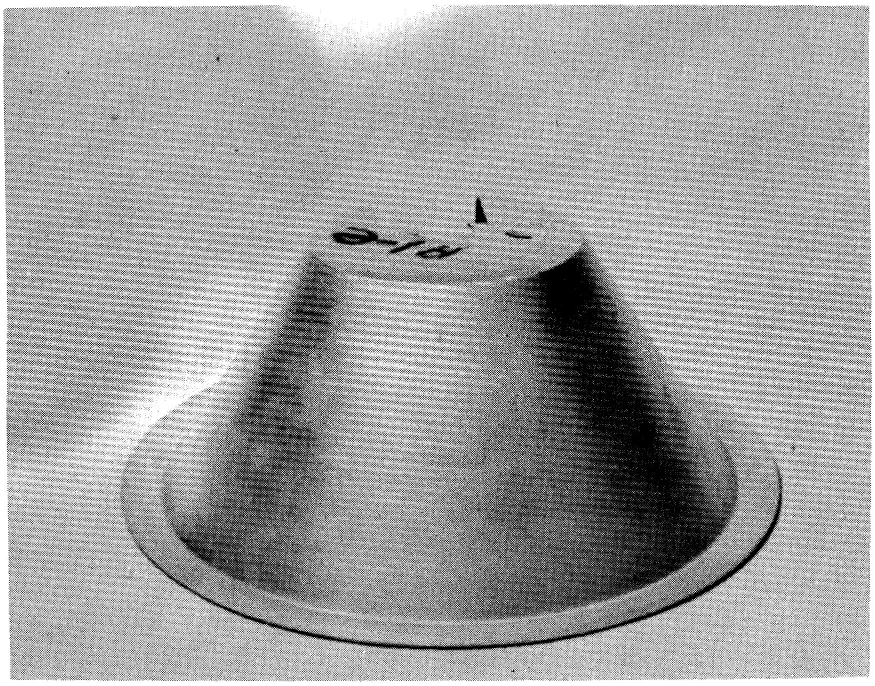
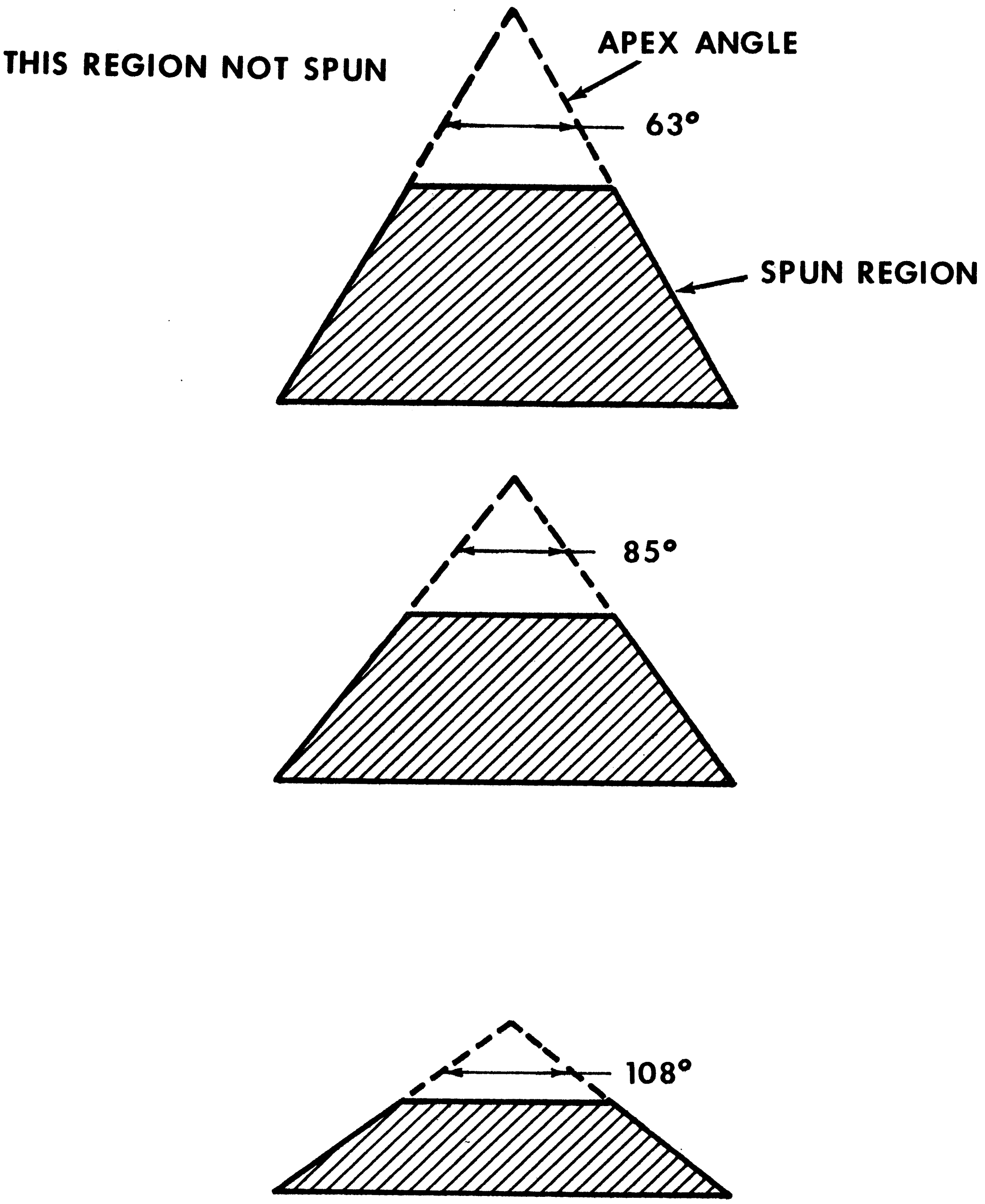
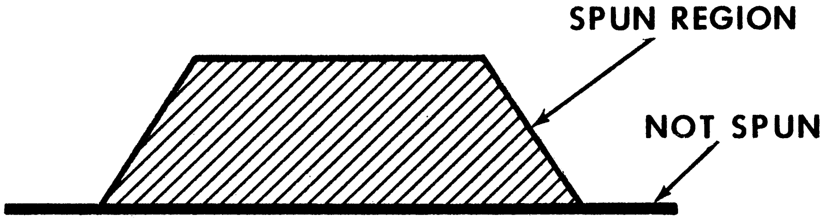


Fig. 1. Photograph of spun cone.

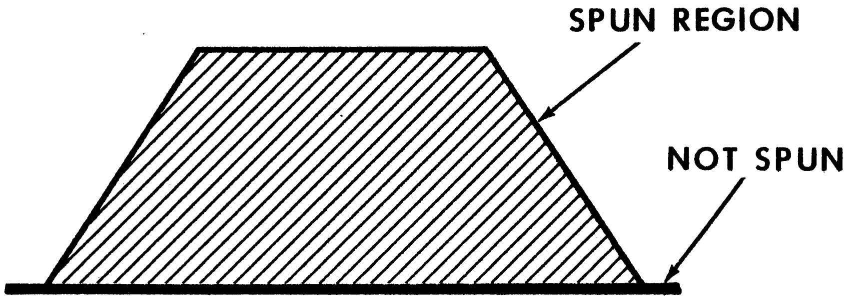


SCHEMATIC VIEW SHOWING CONE ANGLES

FIG. 2



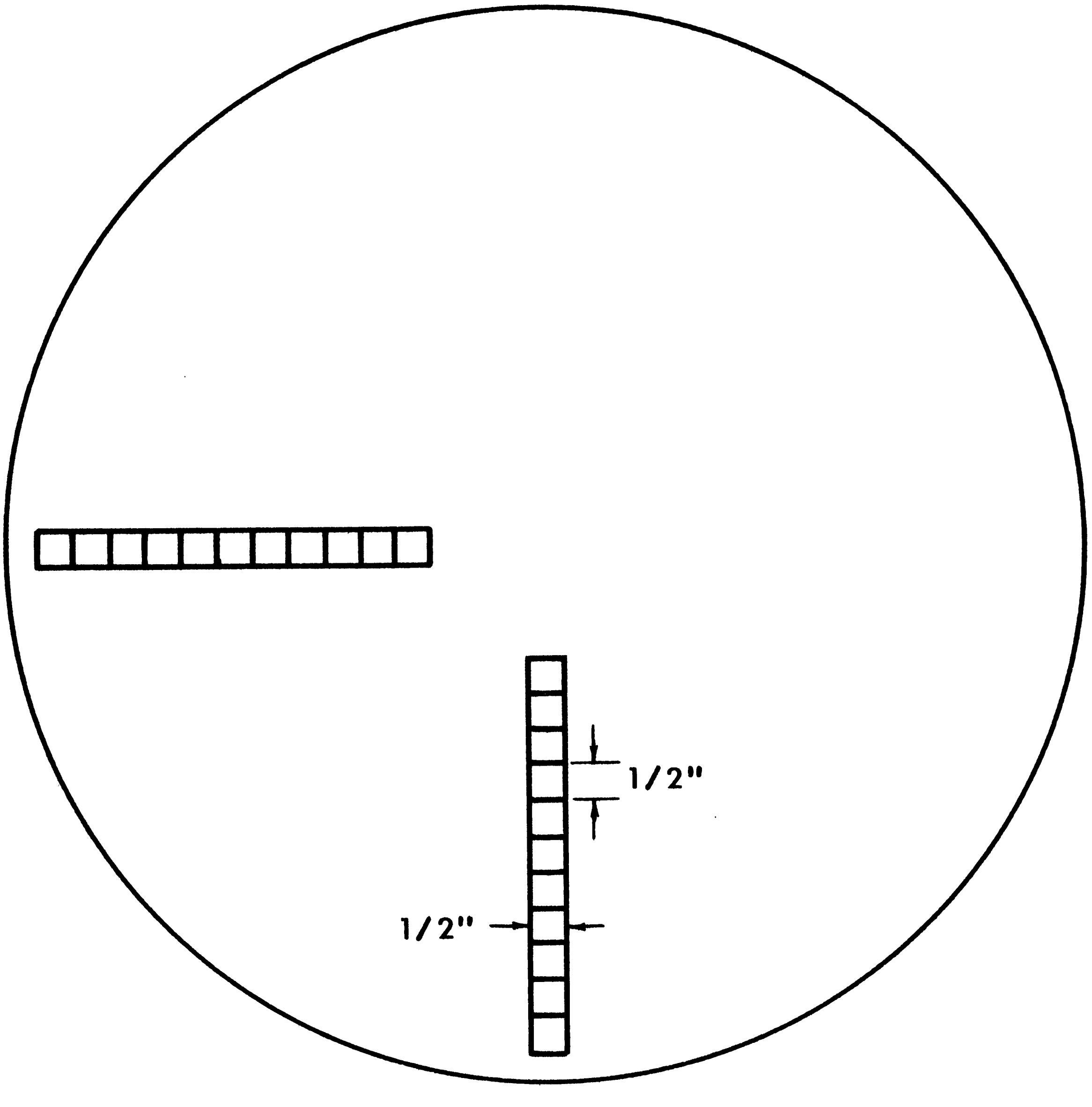
50% SPUN



95% SPUN

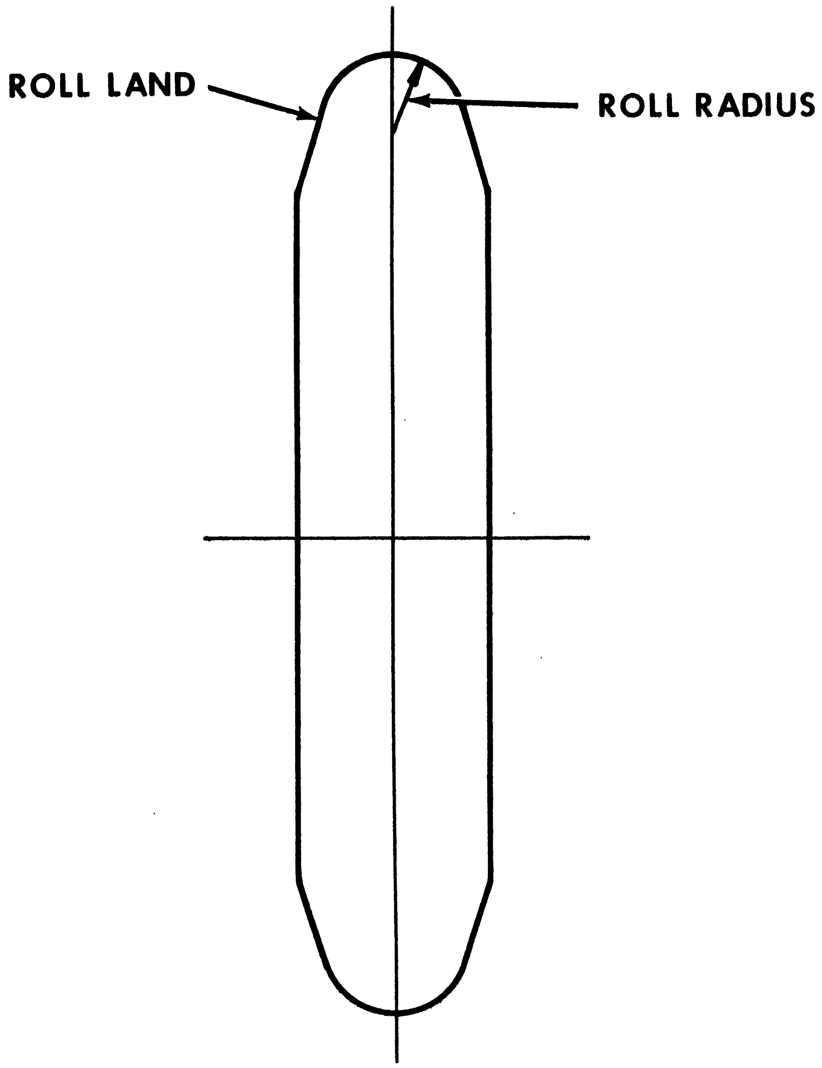
SCHEMATIC VIEW SHOWING 50% AND 95% SPUN CONES

FIG. 3



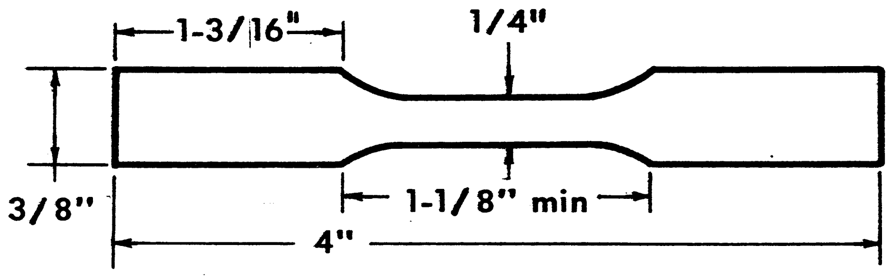
LAYOUT OF GRIDS ON BLANKS BEFORE SPINNING

FIG. 4



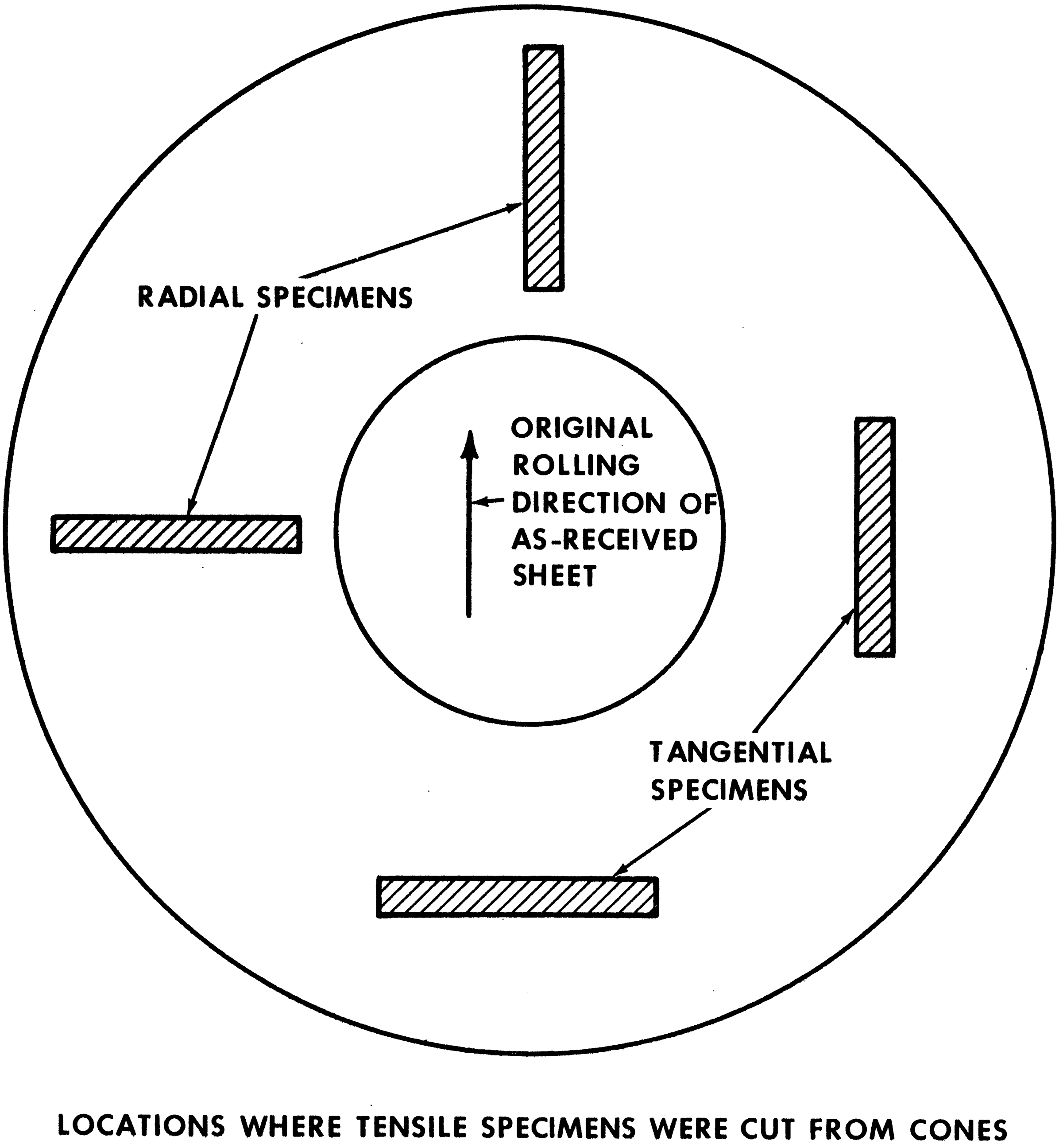
SCHEMATIC VIEW OF ROLLER
SHOWING RADIUS AND LAND

FIG. 5



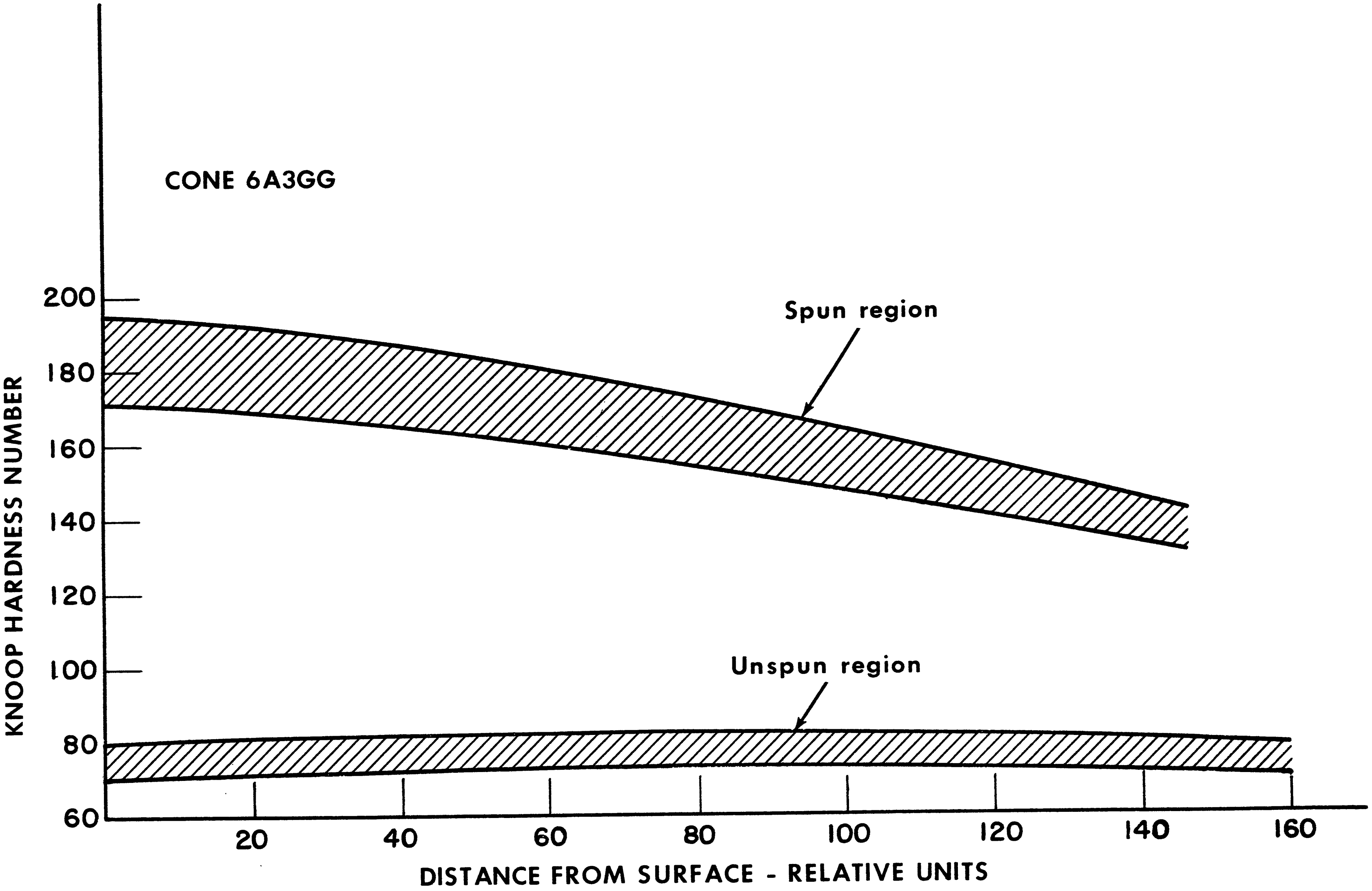
FOUR INCH TENSILE SPECIMEN

FIG. 6



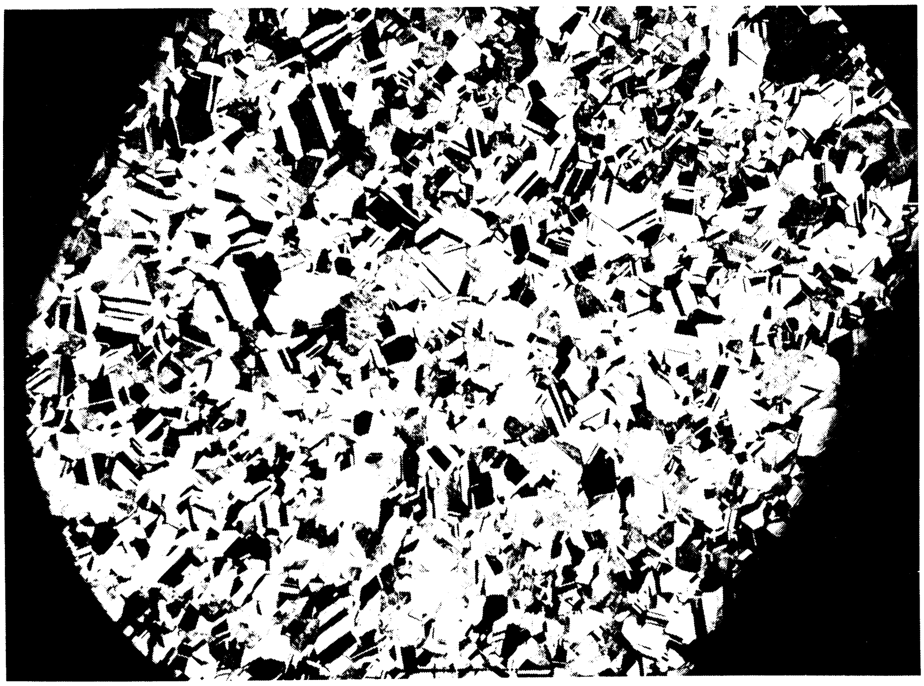
LOCATIONS WHERE TENSILE SPECIMENS WERE CUT FROM CONES

FIG. 7

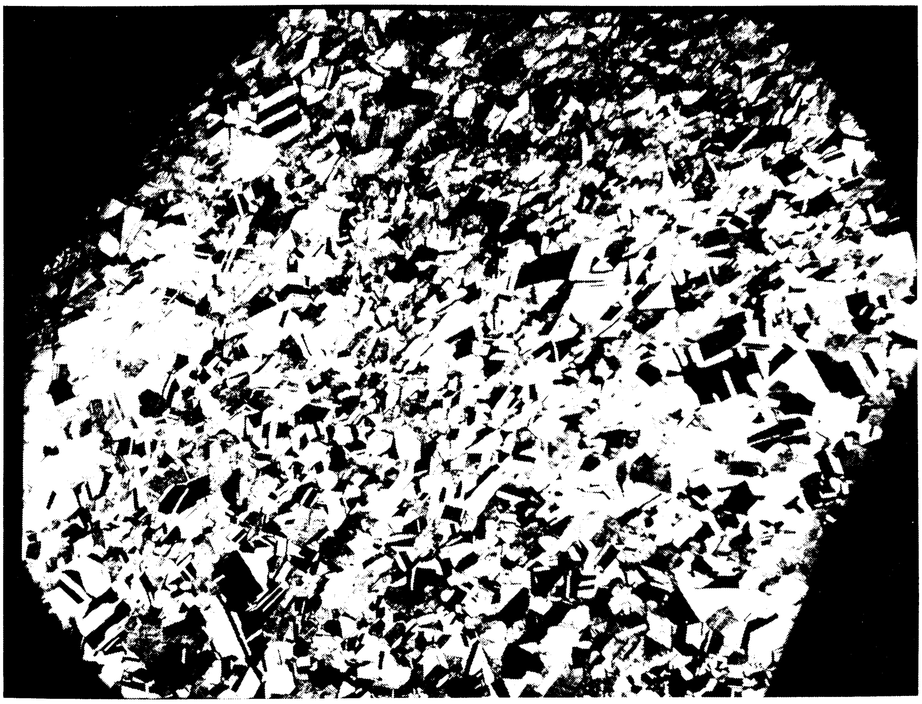


VARIATION IN MICROHARDNESS WITH DEPTH BELOW SPUN SURFACE

FIG. 8

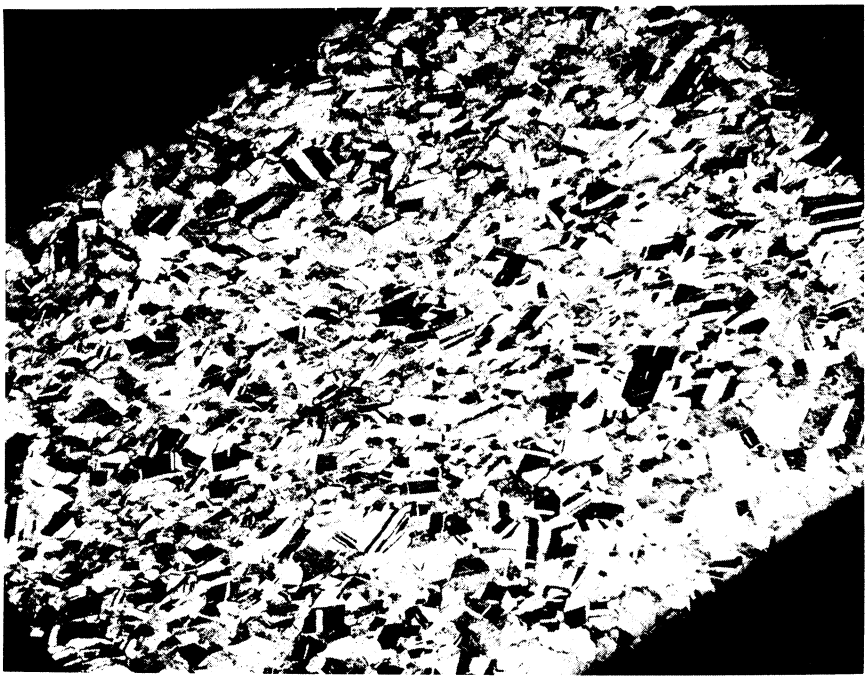


(a) Unspun center portion of cone.



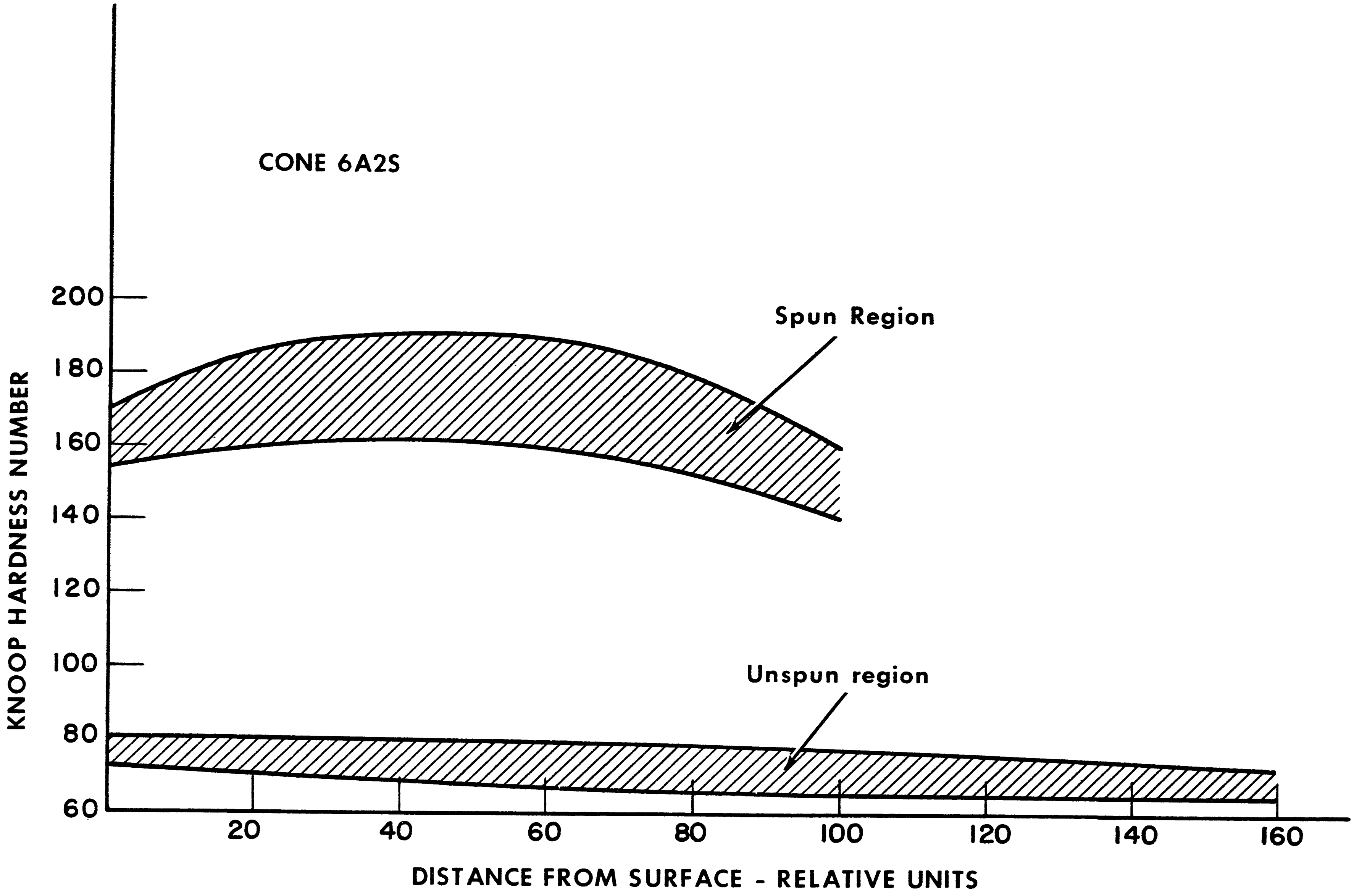
(b) Region at bend of cone. Note beginning of cold worked microstructure.

Fig. 9. Photomicrographs of cone 6A3GG. All photos 100X. Pictures tilted to show complete cross section.



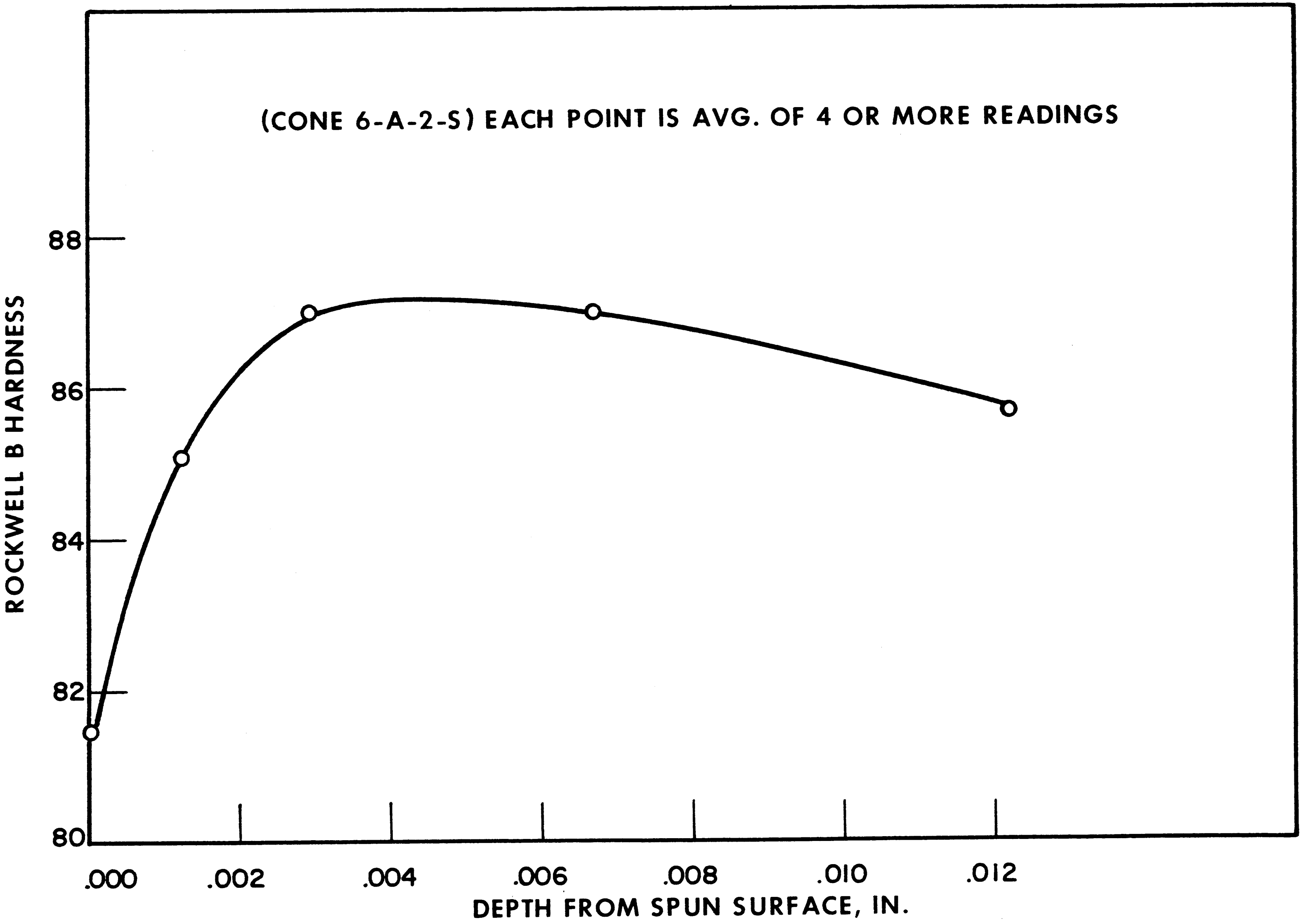
(c) Spun region of cone. Note difference in microstructure at top (spun surface) and bottom.

Fig. 9. Continued



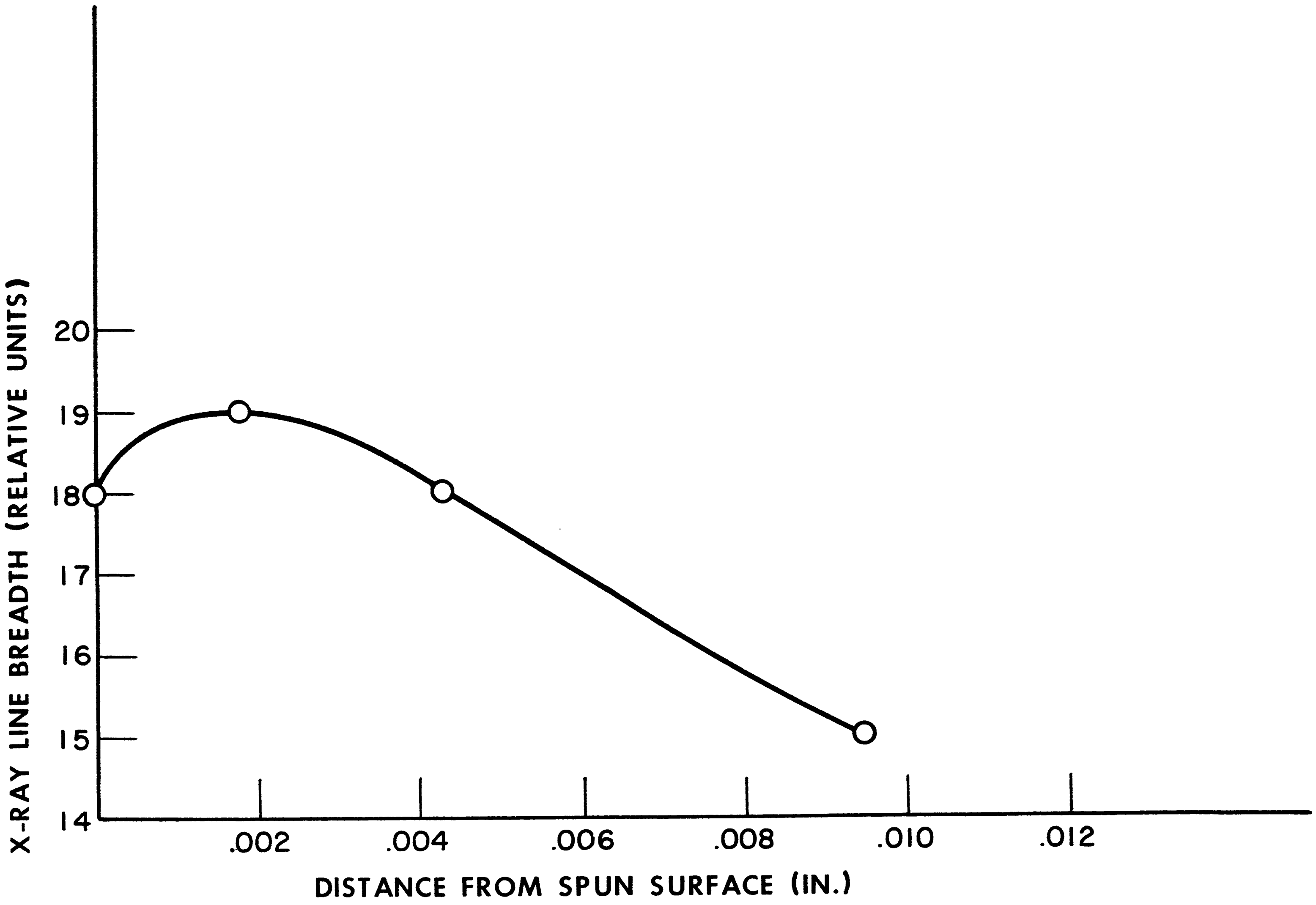
VARIATION IN MICROHARDNESS WITH DEPTH BELOW SPUN SURFACE

FIG. 10



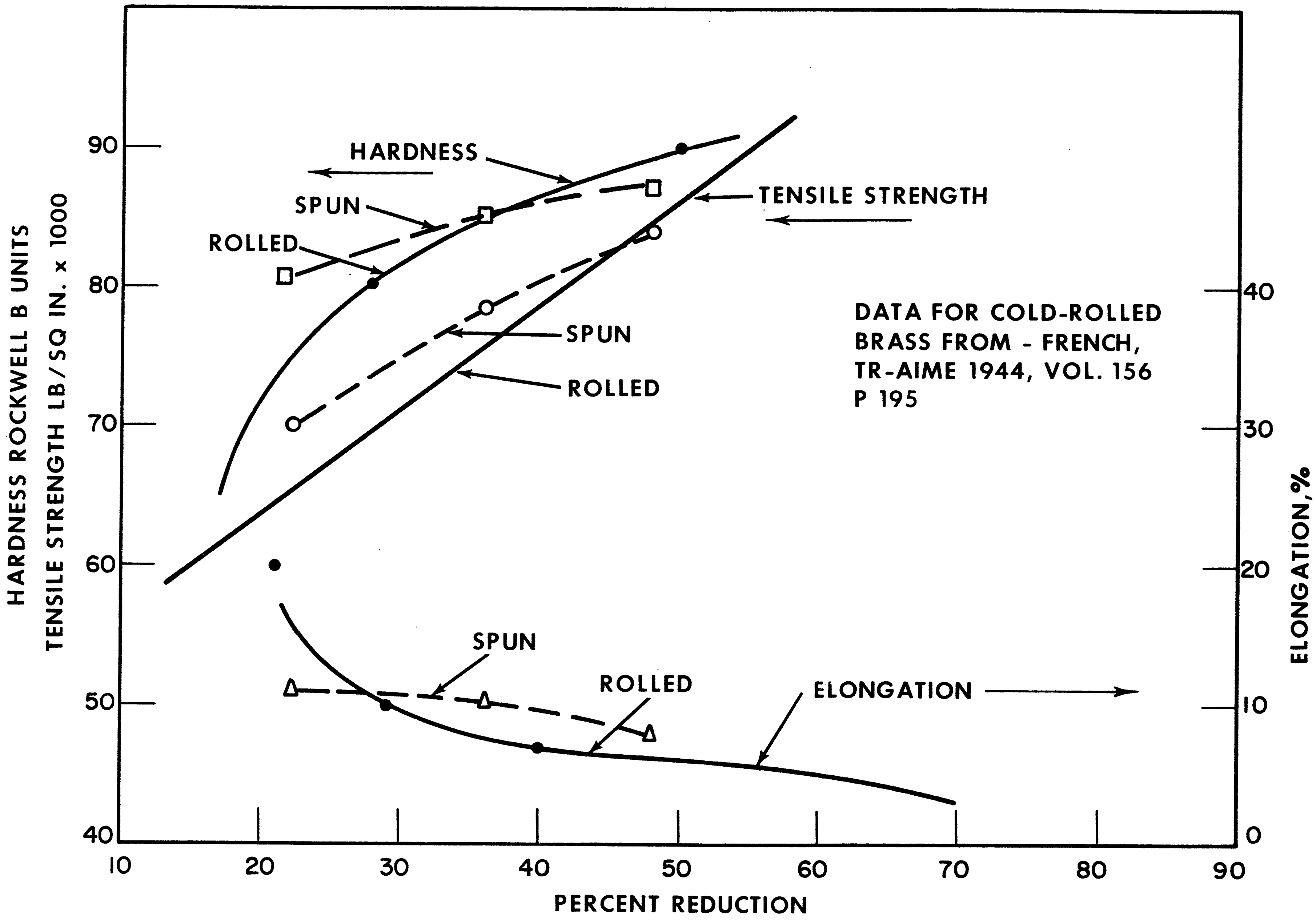
VARIATION OF HARDNESS WITH DEPTH FROM SPUN SURFACE

FIG. 11



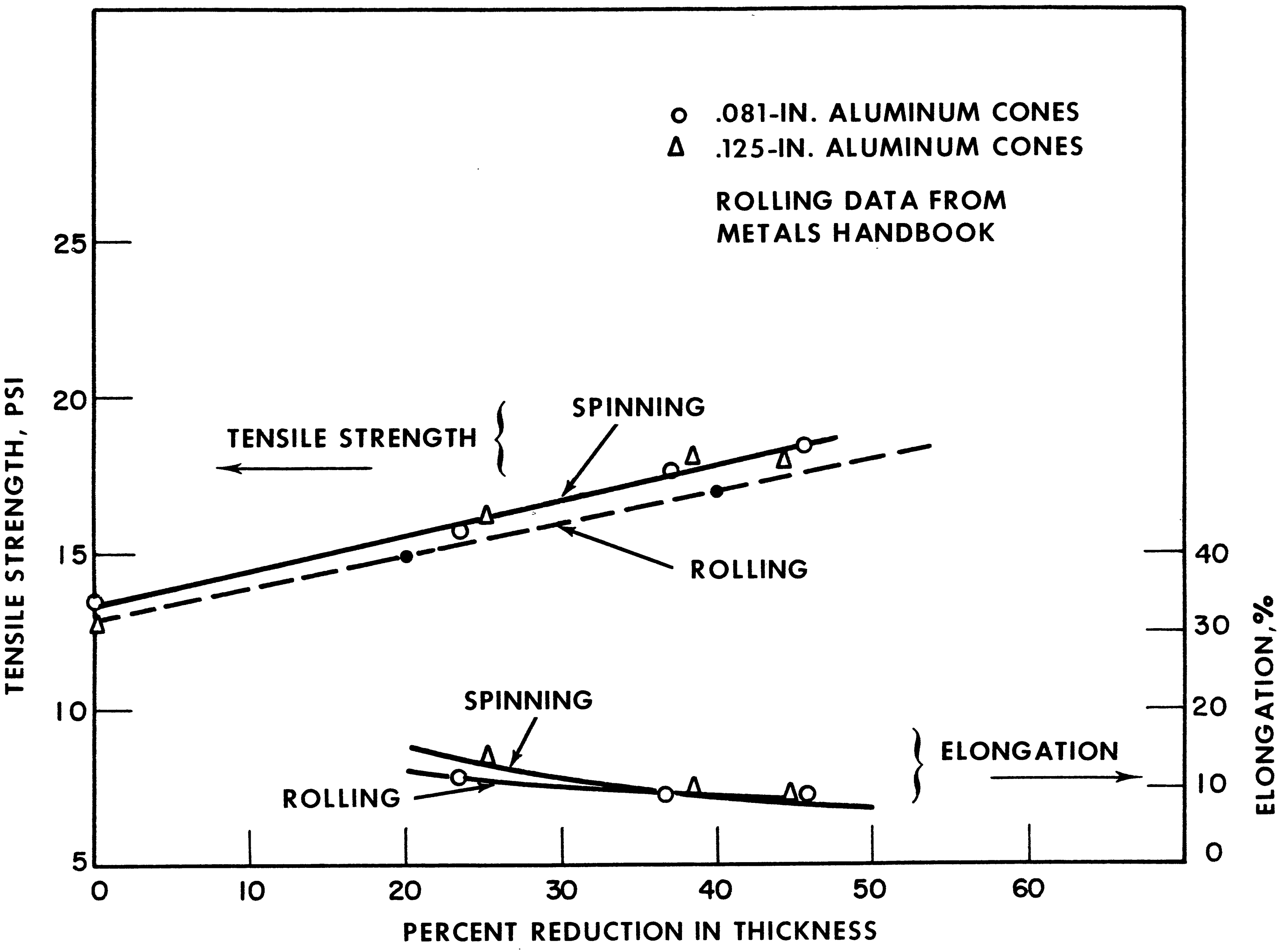
X-RAY LINE BREADTH vs DISTANCE FROM SPUN SURFACE CONE 6A2S

FIG. 12



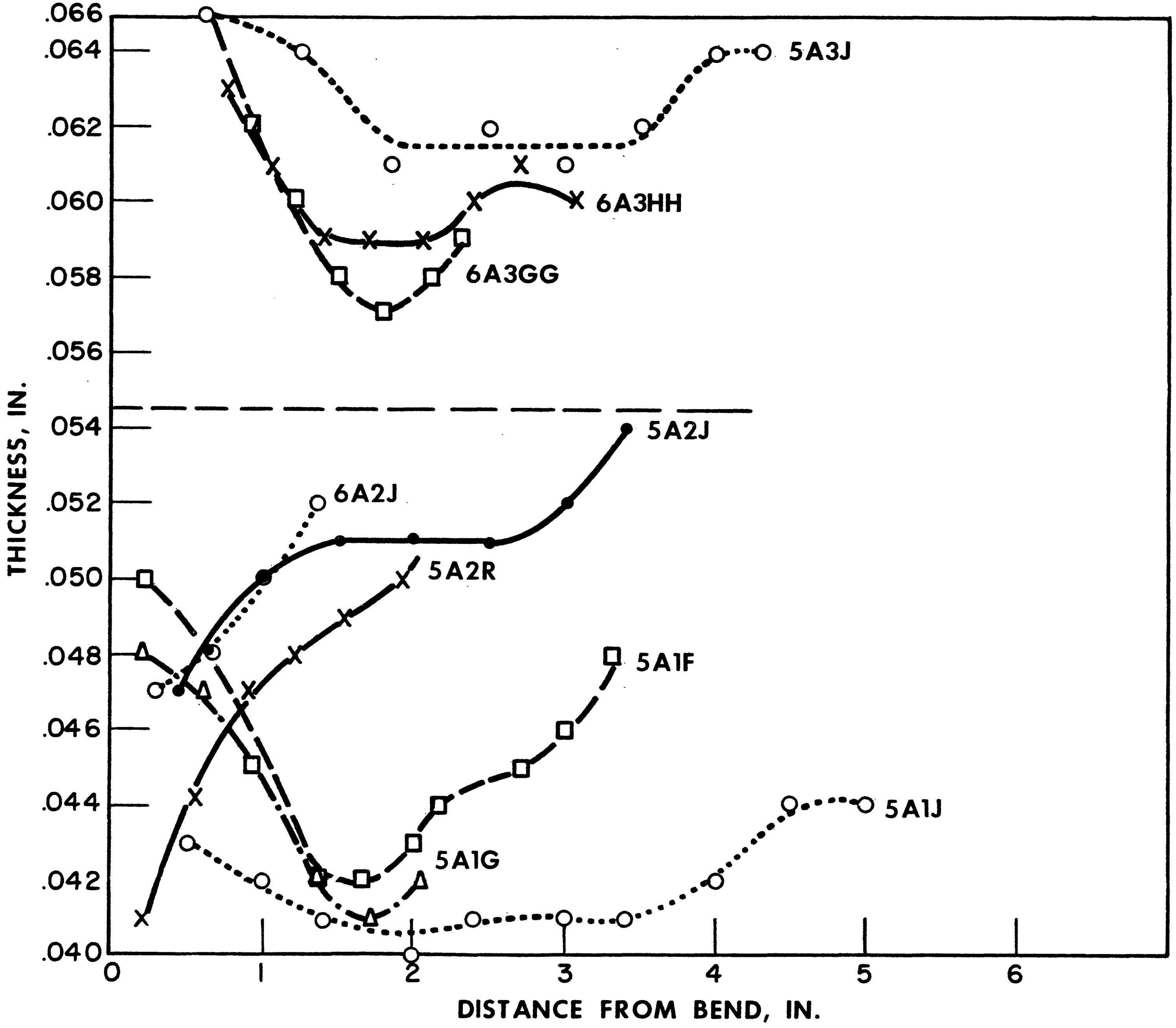
COMPARISON OF MECHANICAL PROPERTIES OF BRASS PRODUCED BY SPINNING AND ROLLING

FIG. 13

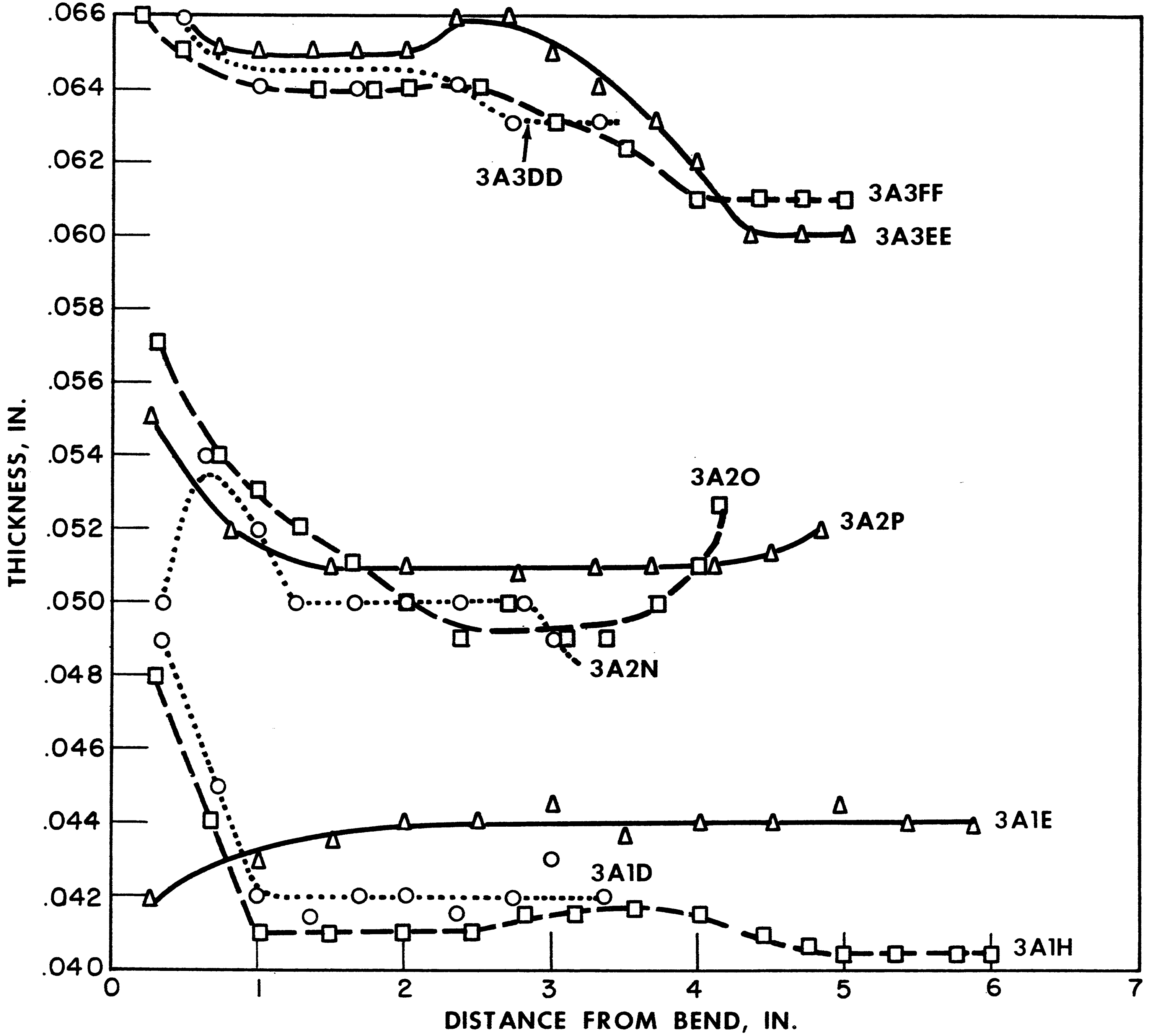


COMPARISON OF MECHANICAL PROPERTIES OF ALUMINUM PRODUCED BY SPINNING AND ROLLING

FIG. 14

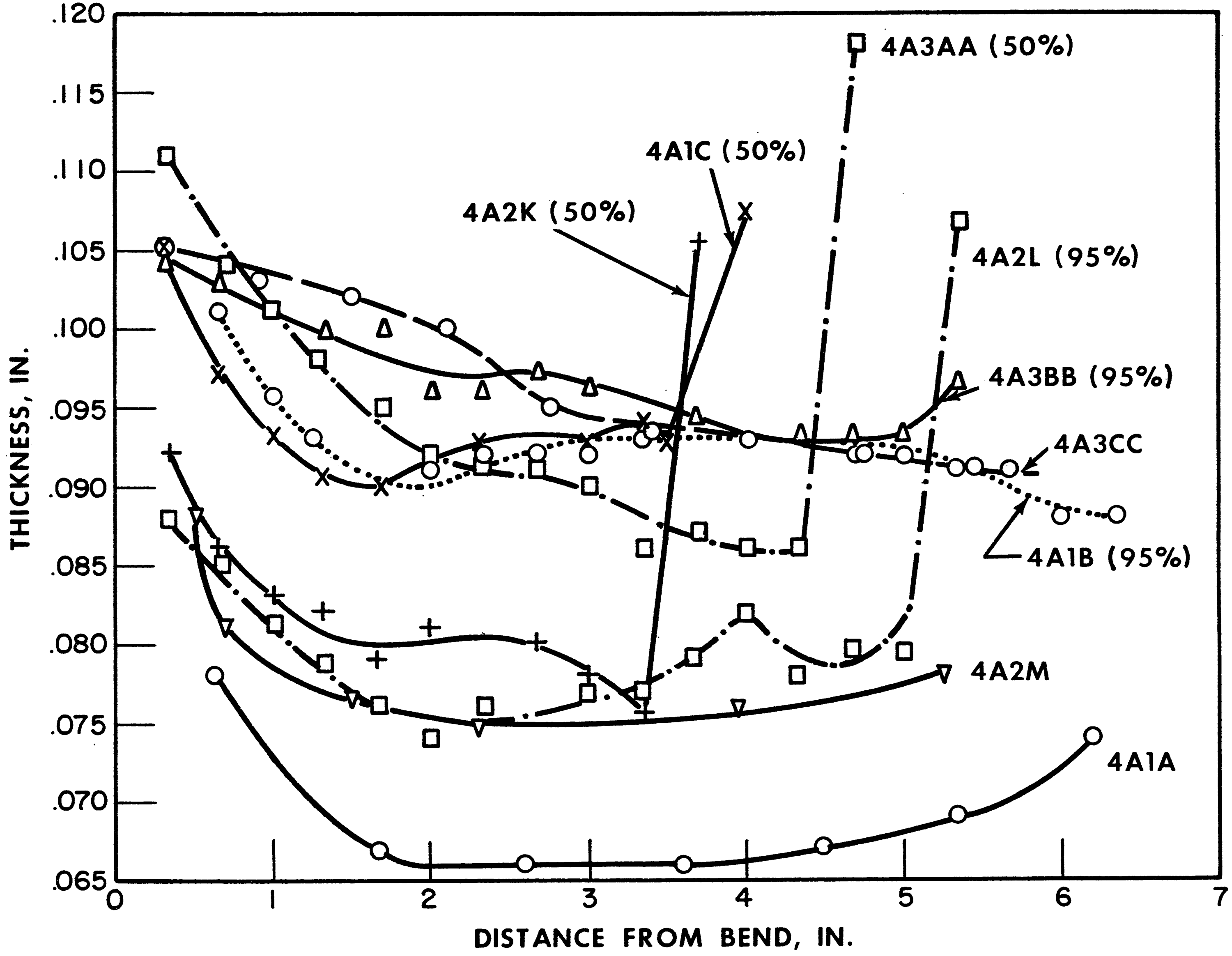


THICKNESS vs. DISTANCE FROM BEND - BRASS CONES
FIG. 15a



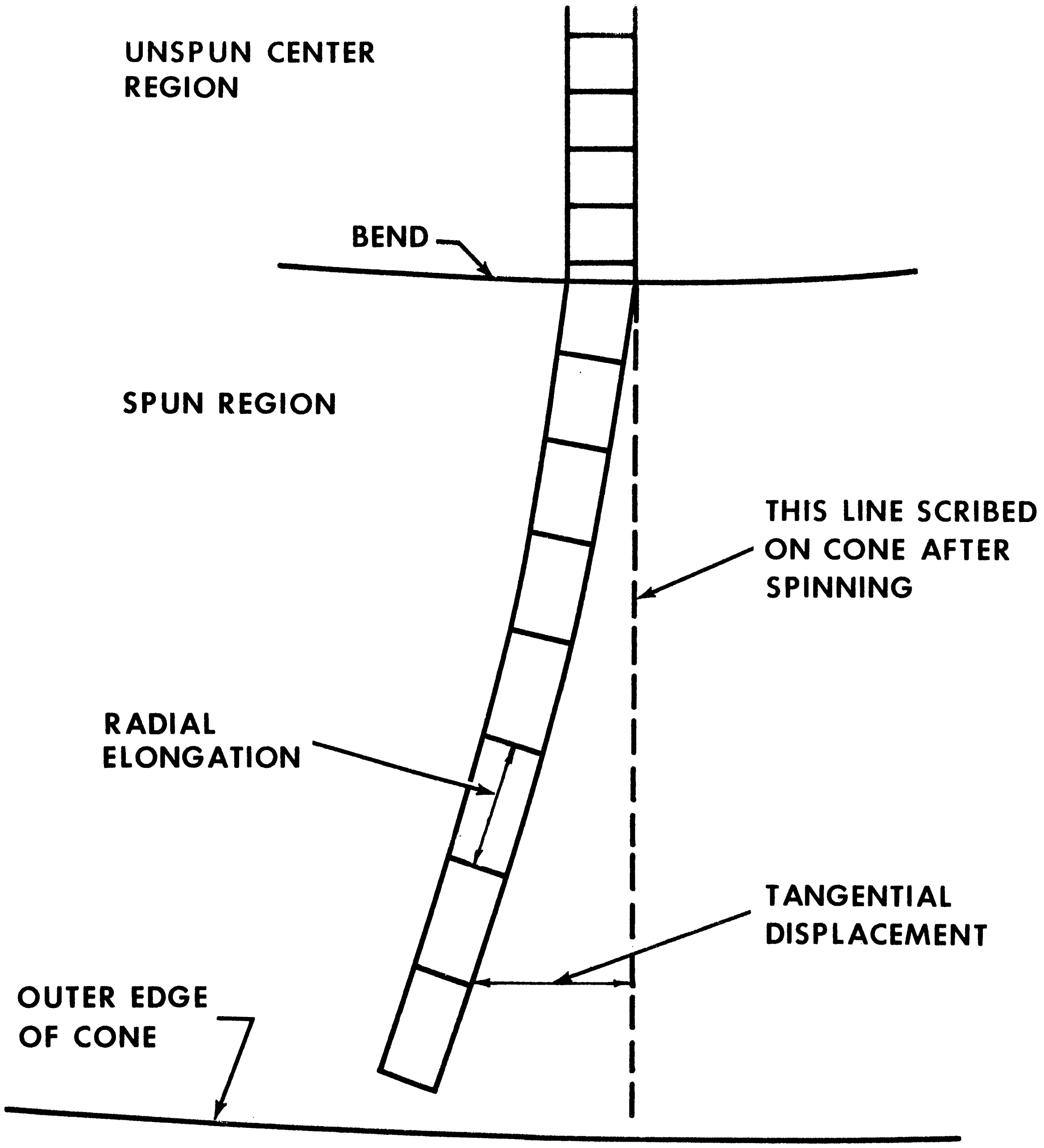
THICKNESS vs. DISTANCE FROM BEND - .081-IN. ALUMINUM CONES

FIG. 15b



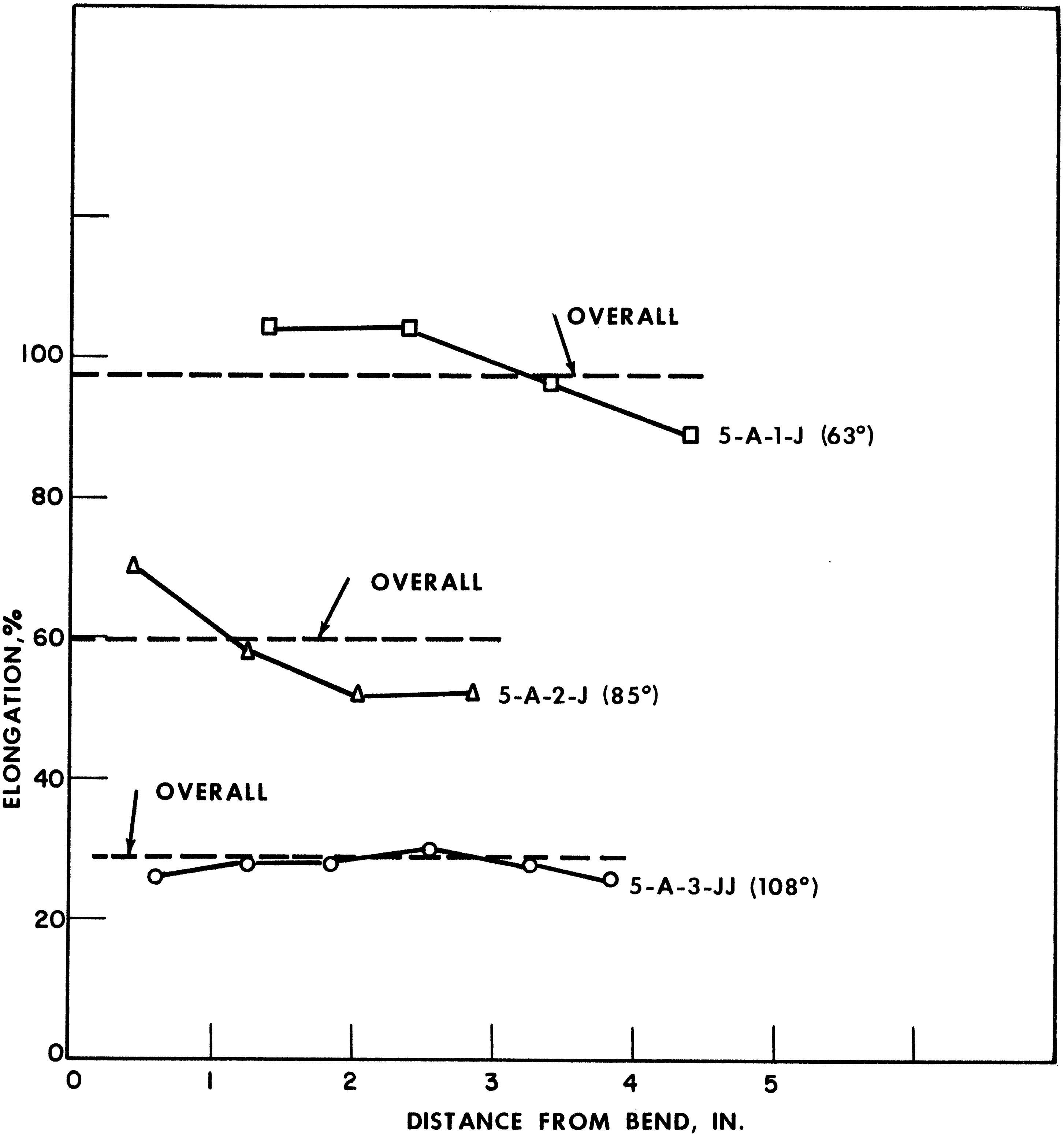
THICKNESS vs. DISTANCE FROM BEND - 0.125-IN. ALUMINUM

FIG. 15c



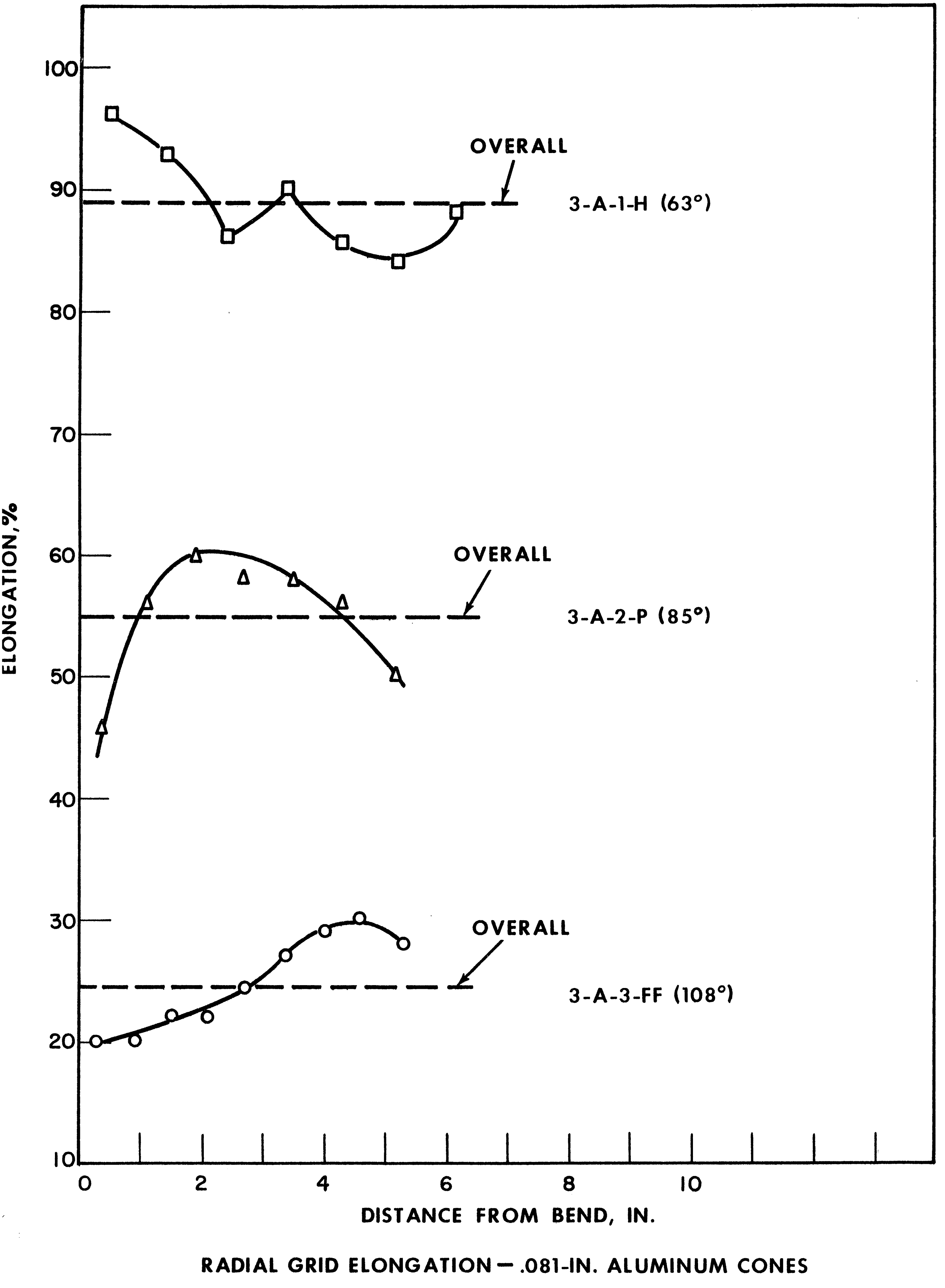
GRID DISTORTIONS IN FULLY SPUN CONES

FIG. 16



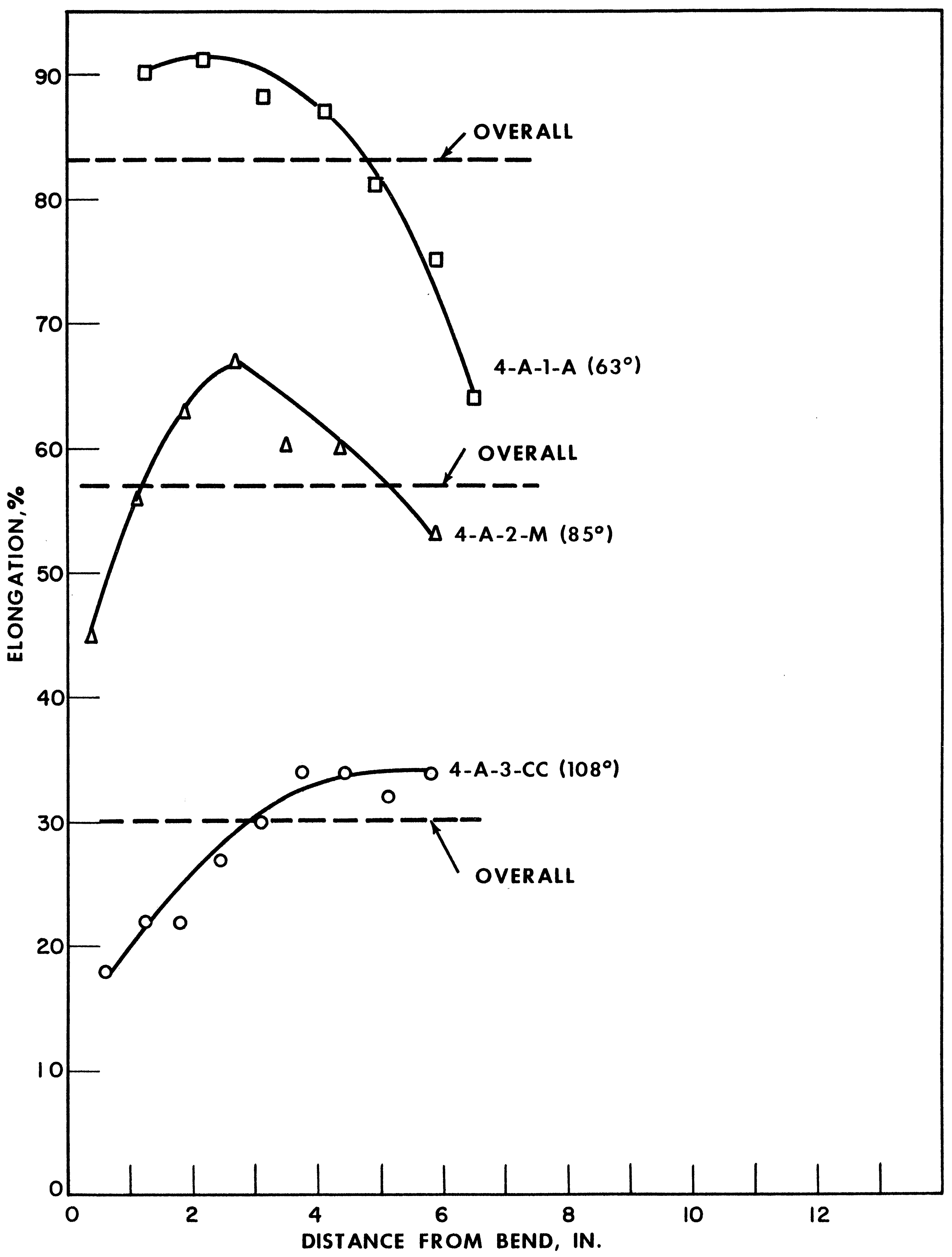
RADIAL GRID ELONGATION—BRASS CONES

FIG. 17a



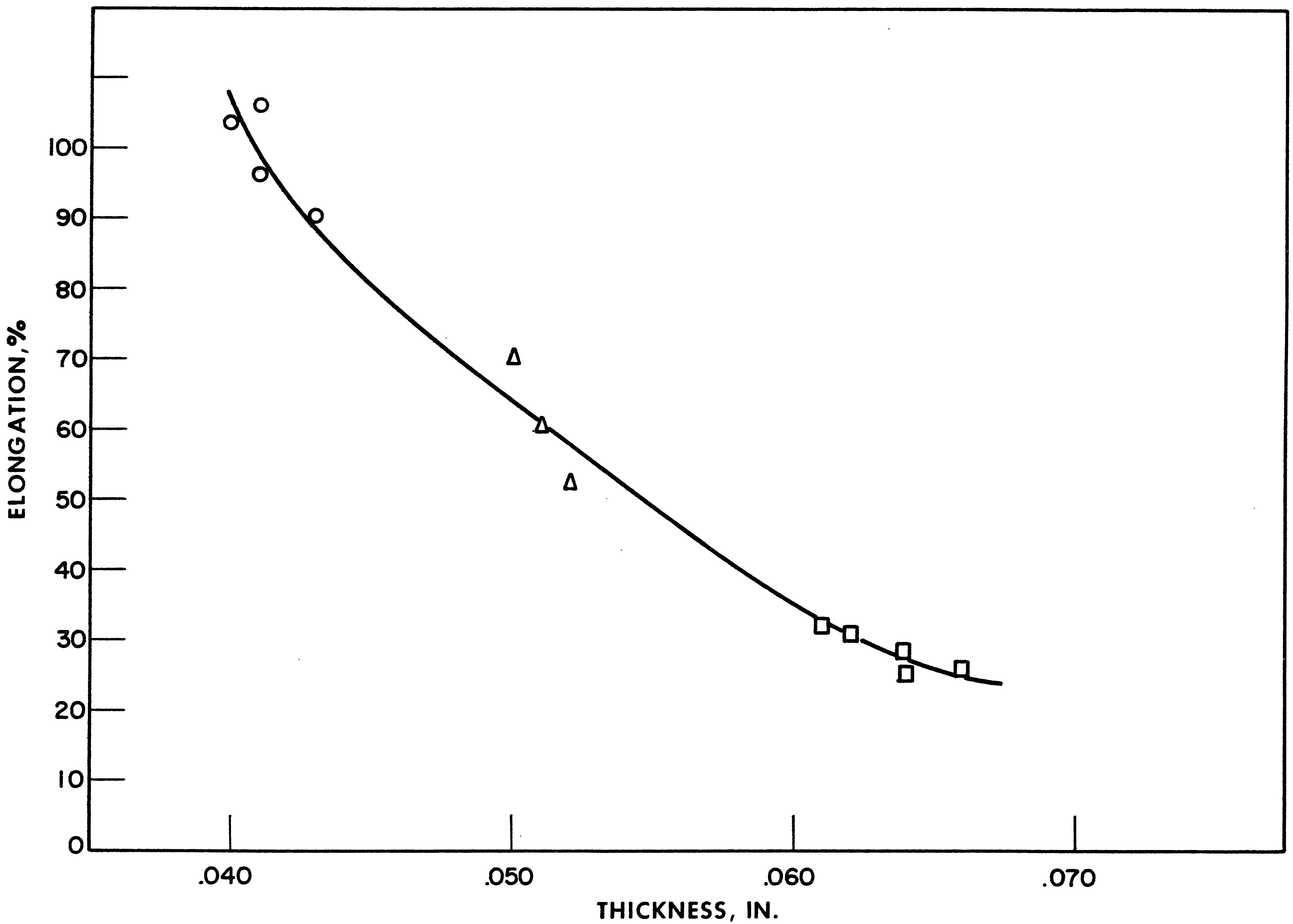
RADIAL GRID ELONGATION — .081-IN. ALUMINUM CONES

FIG. 17b



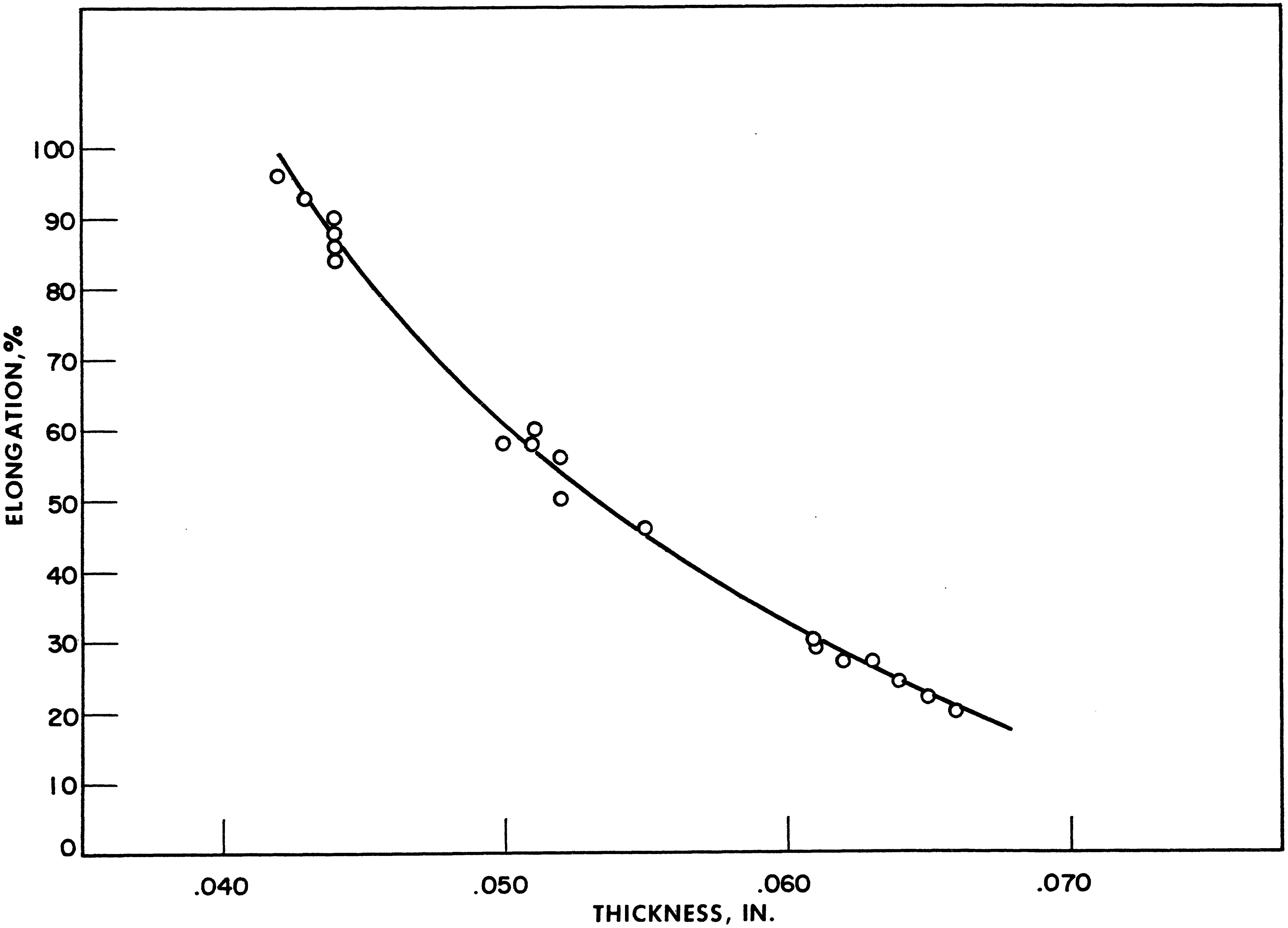
RADIAL GRID ELONGATION–.125-IN. ALUMINUM CONES

FIG. 17c



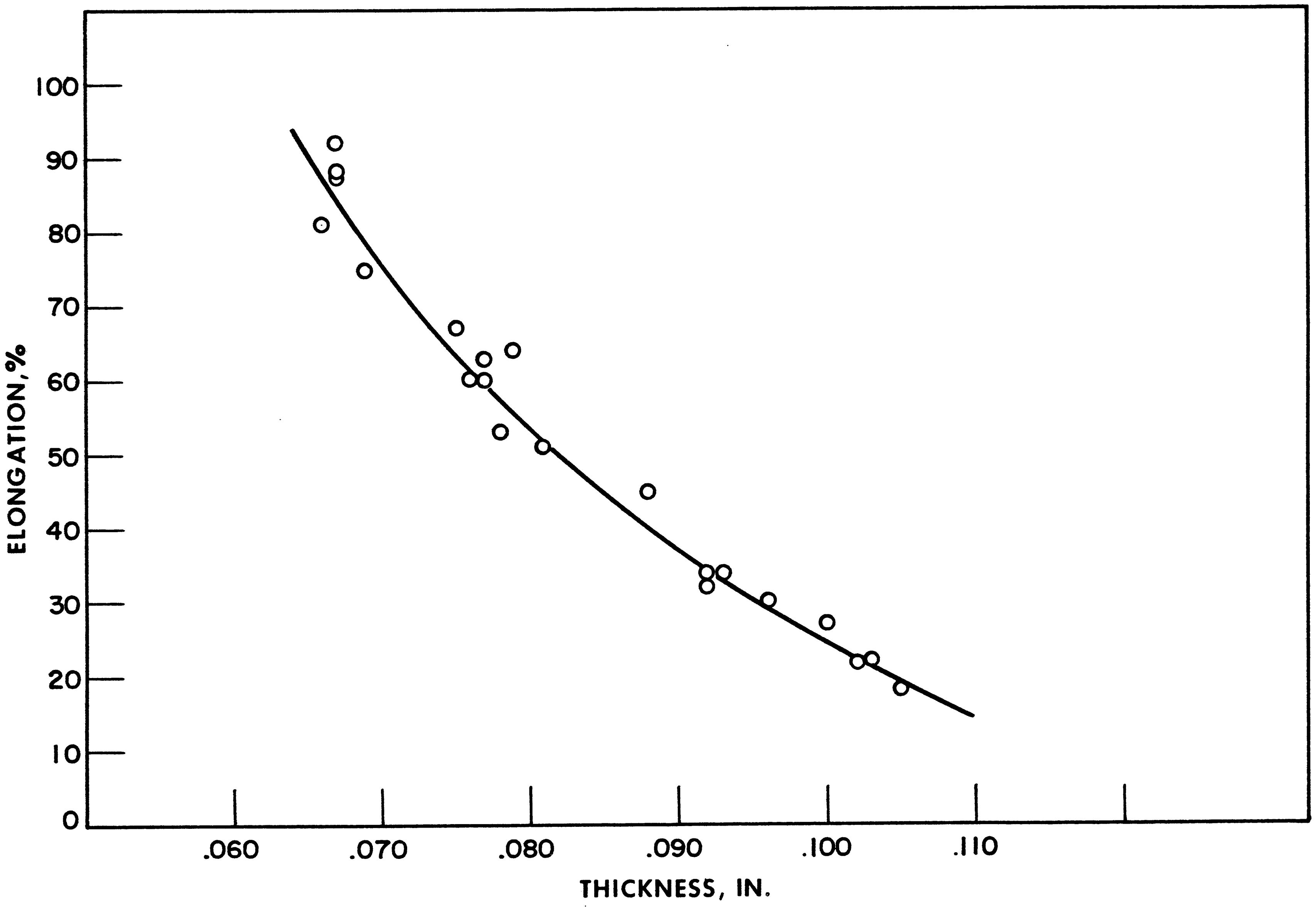
ELONGATION vs. THICKNESS—BRASS CONES

FIG. 18a



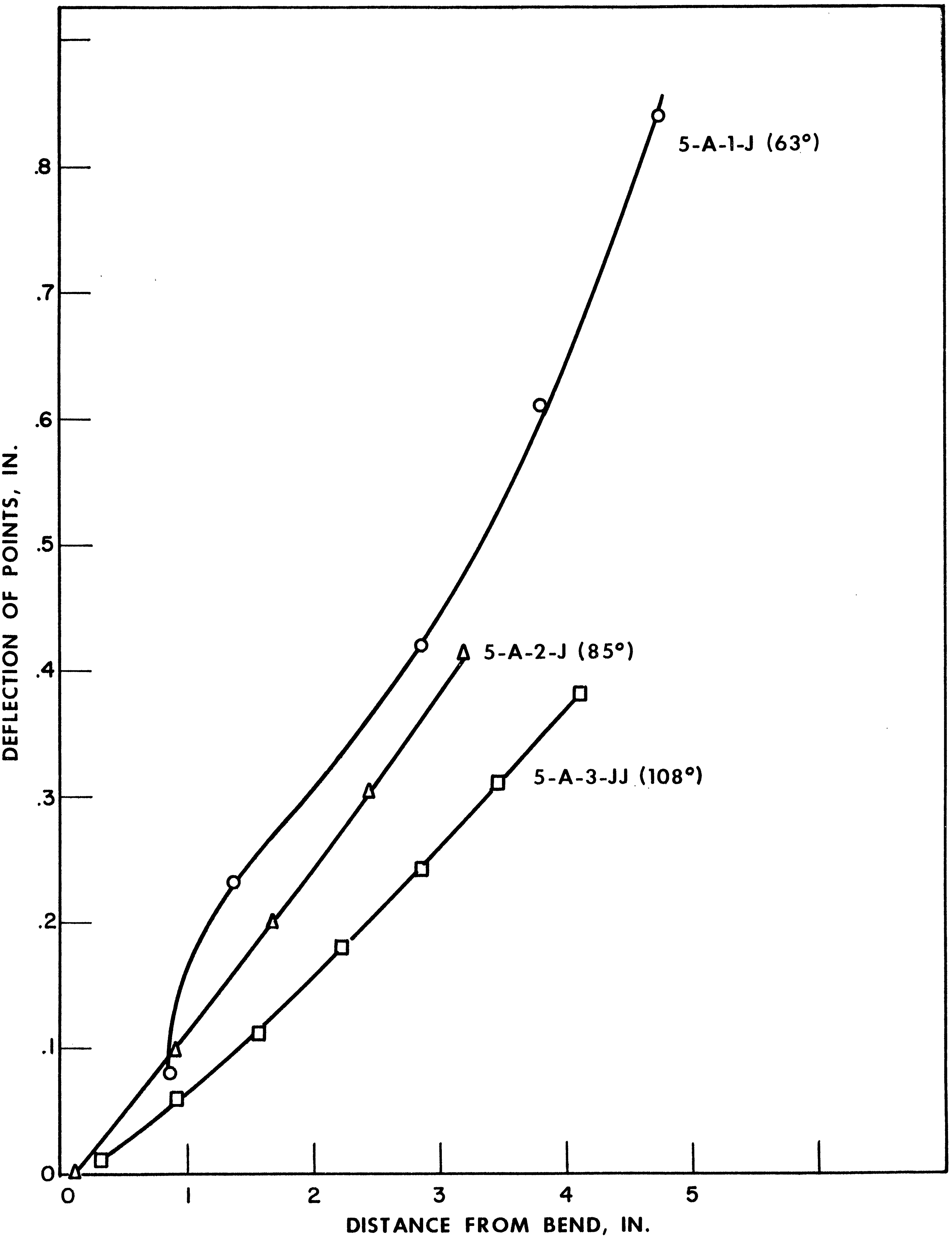
ELONGATION vs. THICKNESS– .081-IN. ALUMINUM CONES

FIG. 18b



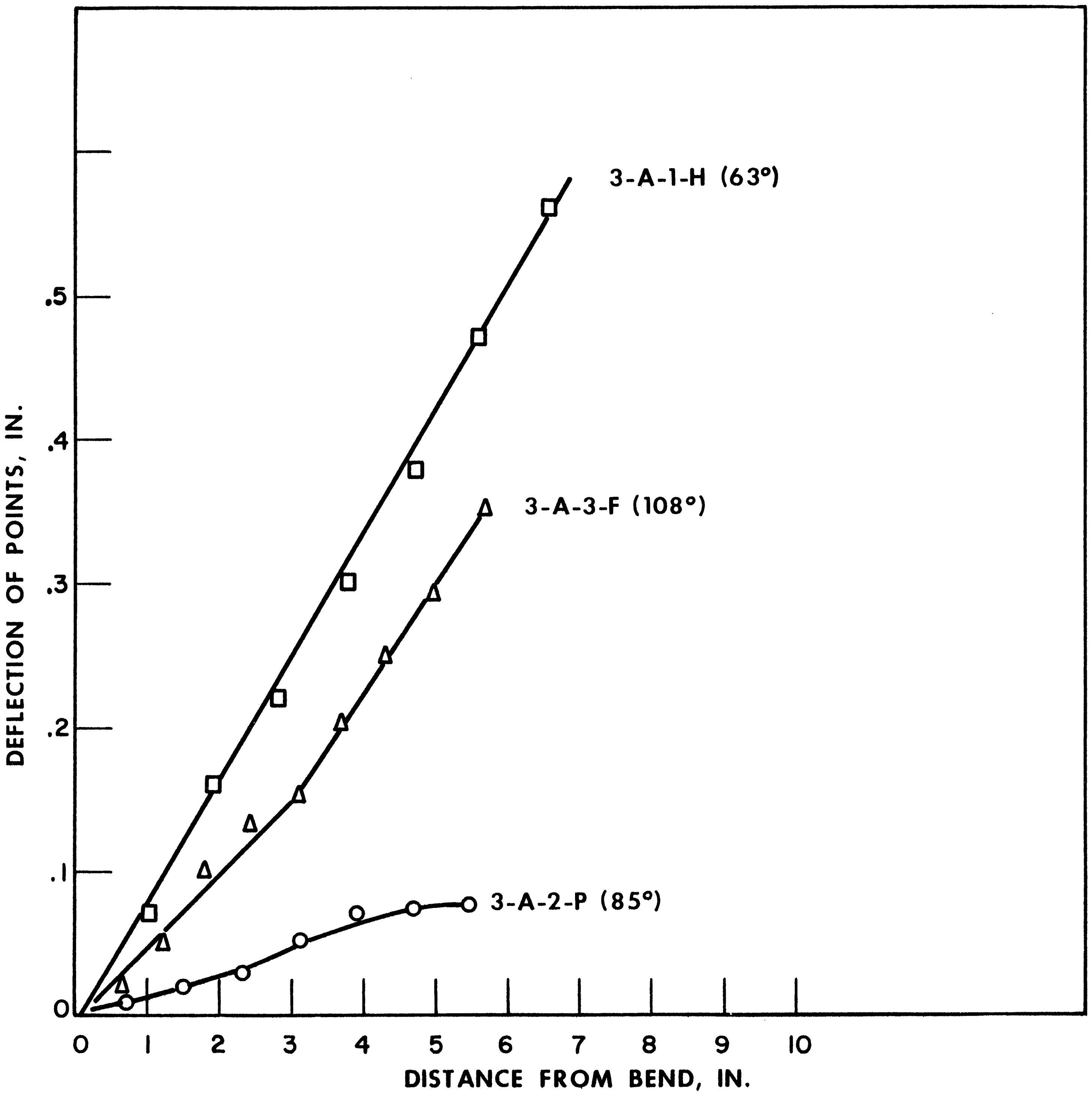
ELONGATION vs. THICKNESS—.125-IN. ALUMINUM CONES

FIG. 18c



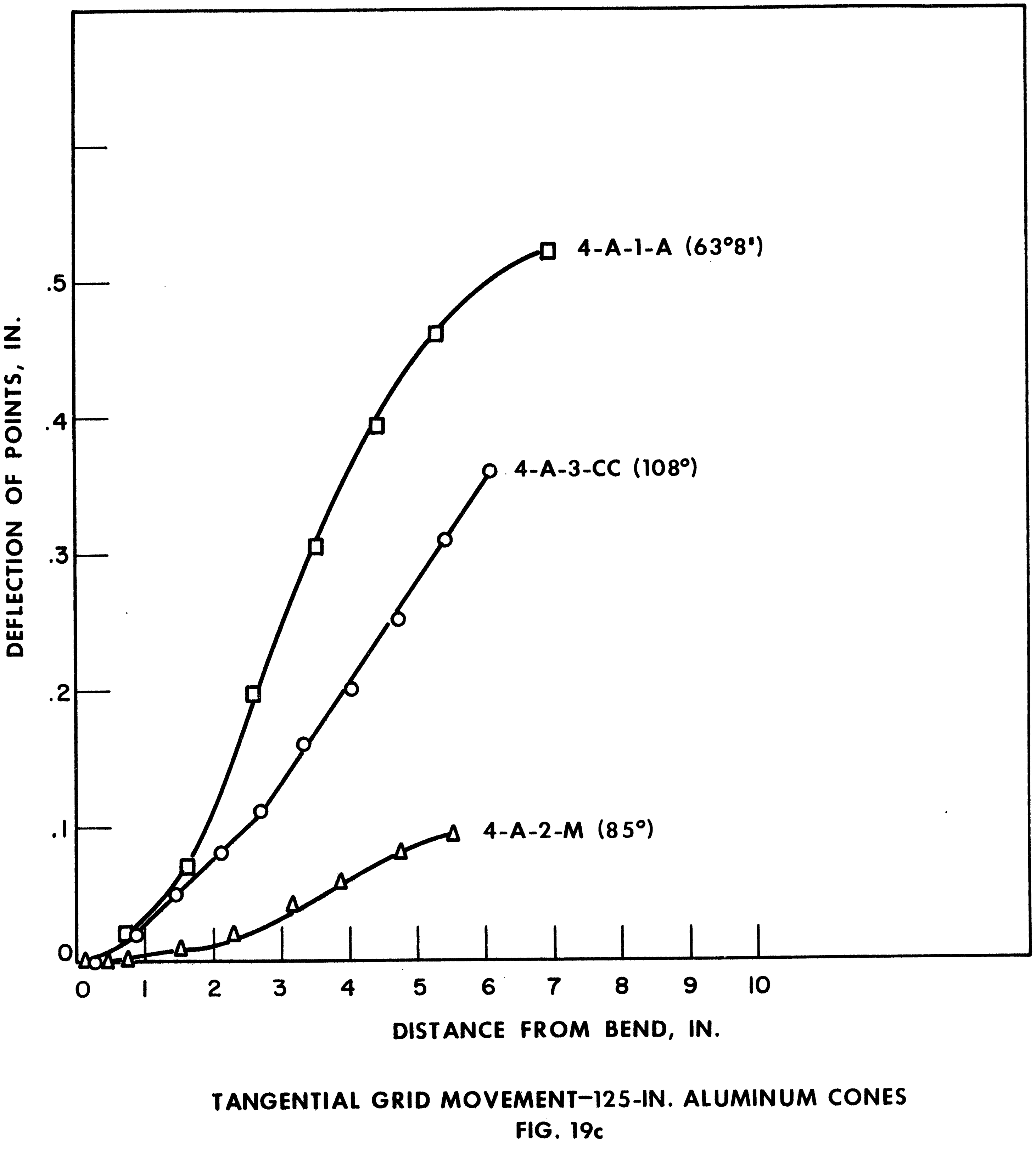
TANGENTIAL GRID MOVEMENT—BRASS CONES

FIG. 19a

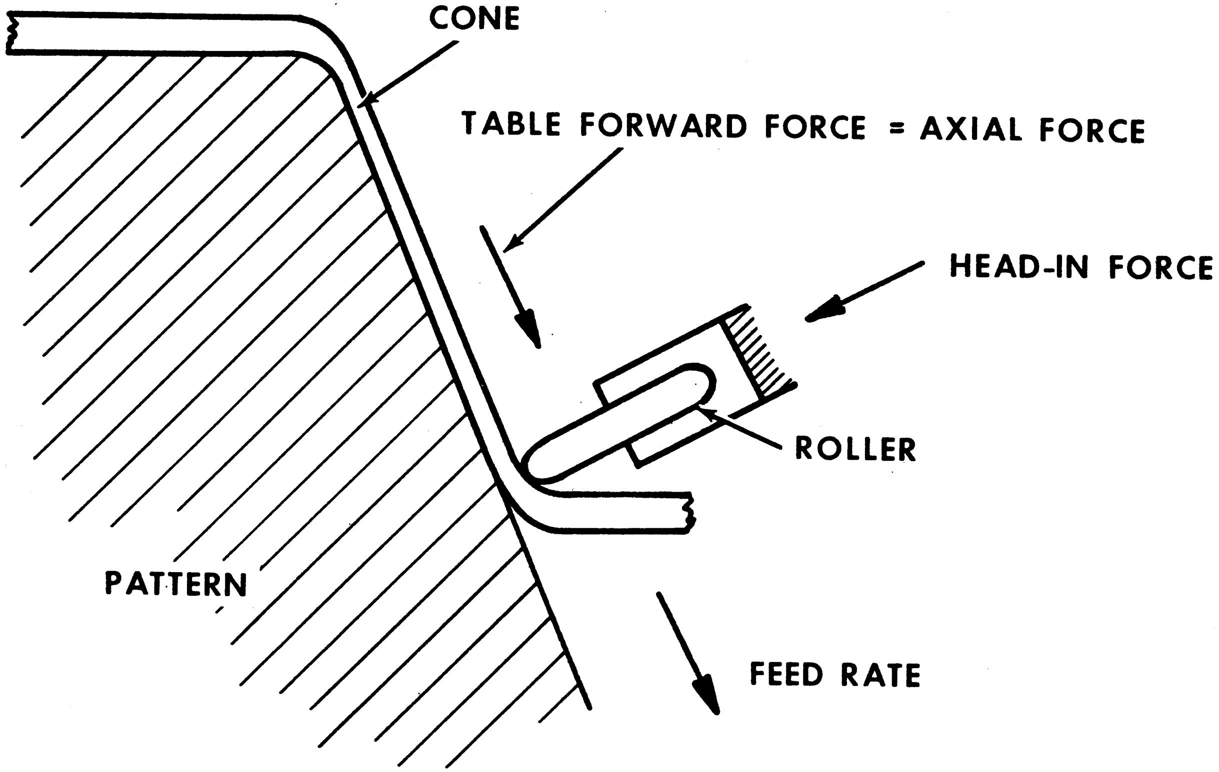


TANGENTIAL GRID MOVEMENT-.081-IN. ALUMINUM CONES

FIG. 19b

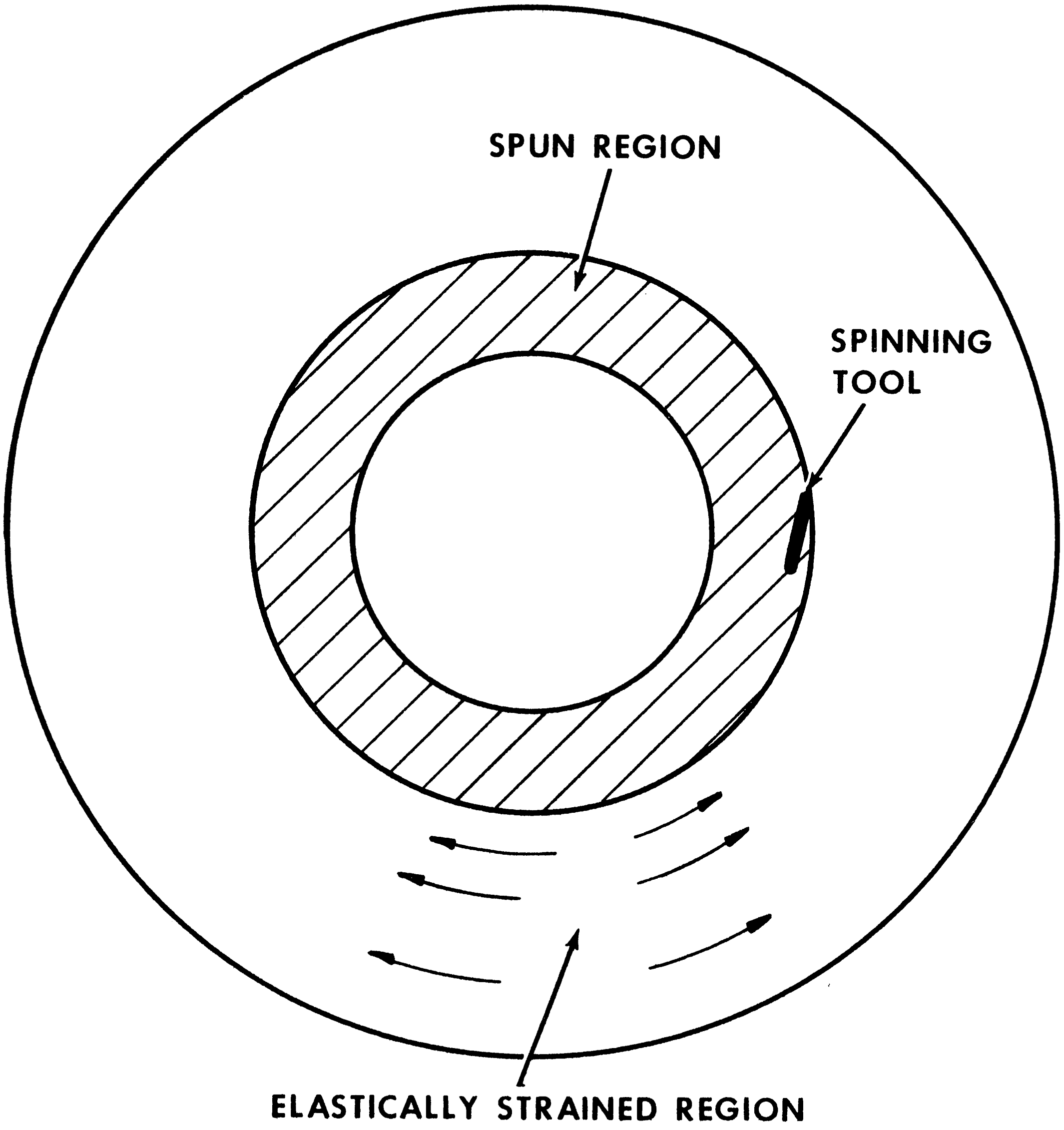


TANGENTIAL GRID MOVEMENT—125-IN. ALUMINUM CONES
FIG. 19c



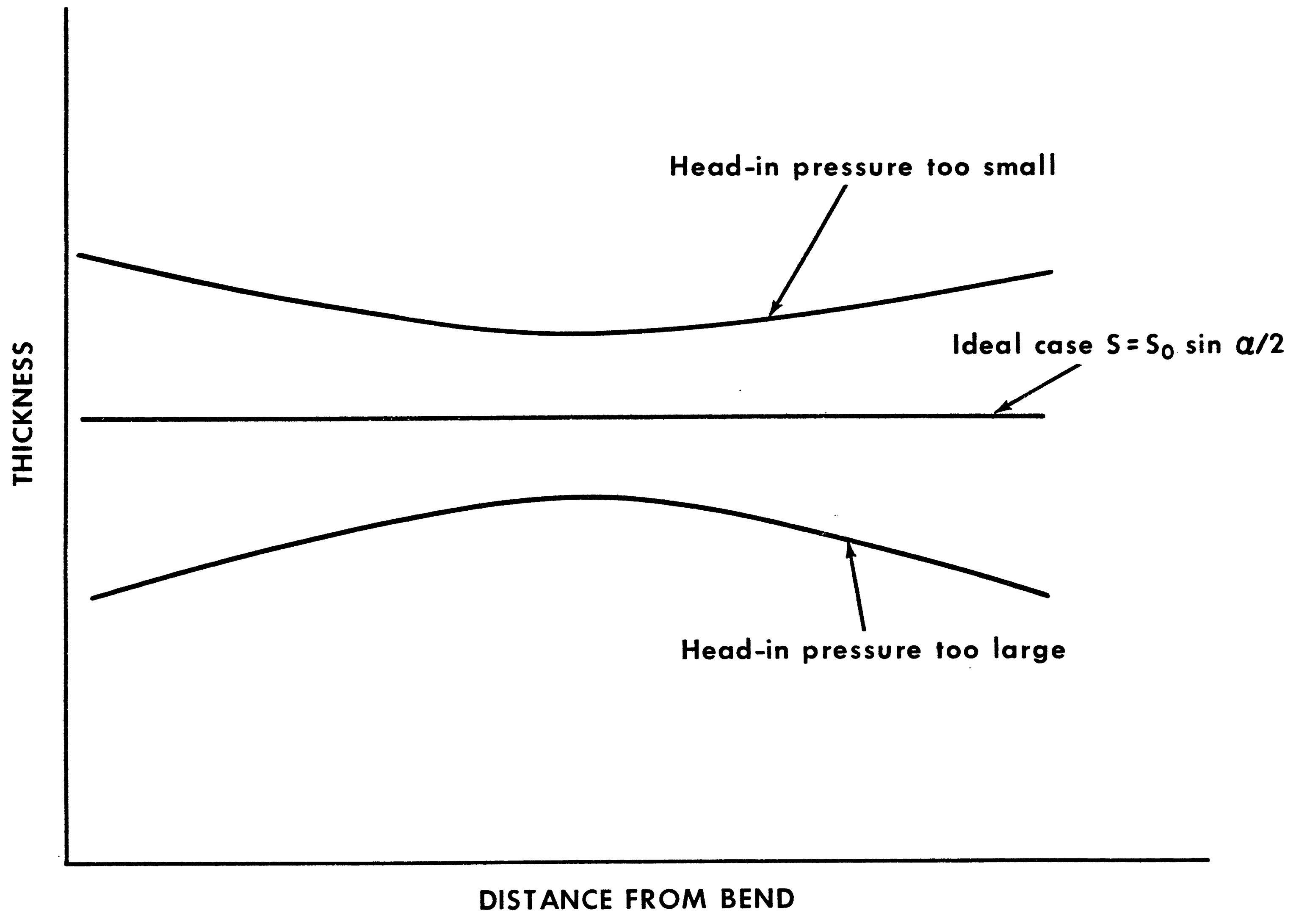
SCHEMATIC VIEW OF SPINNING FORCES

FIG. 20



ELASTIC STRESSES DURING SPINNING

FIG. 21



PREDICTED VARIATION IN THICKNESS vs DISTANCE FROM BEND

FIG. 22