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RECRYSTALLIZATION OF DEFORMED ALPHA-URANIUM
SINGLE CRYSTALS

by

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RECRYSTALLIZATION OF DEFORMED ALPHA-URANIUM SINGLE CRYSTALS

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ABSTRACT

The orientation relationships between deformed alpha-uranium single crystals and recrystallized grains grown in them by annealing can be expressed as 27.5° rotations about axes located 70.0° from the $[100]$, 63.5° from the $[010]$ and 34.0° from the $[001]$ of the deformed orientation. The rotations are clockwise about two of the axes and counterclockwise about the other two. In deriving these relationships it was necessary to consider the recrystallized grains as originating from deformation twin orientations as well as from the parent crystal orientation. The relationship agrees well with experimental observations of recrystallization textures developed from deformation textures for polycrystalline rod and sheet uranium treated in the alpha phase.

I. INTRODUCTION

Recrystallization studies of deformed single crystals have been used by many workers as a means of contributing to the knowledge of recrystallization textures for face-centered-cubic⁽¹⁻⁹⁾ and body-centered-cubic^(10,11) metals. By determining the orientations of recrystallized grains and observing their grouping with respect to the orientation of the deformed single crystal, it normally is found that the grains are related to the parent crystal by angular rotations about axes normal to the most densely populated planes of the structure. For the most part, these orientation relationships also apply to comparisons of deformation and recrystallization textures of polycrystalline materials.^(12,13,14)

Numerous investigations of deformation and recrystallization textures have been reported for polycrystalline uranium rods⁽¹⁵⁻¹⁹⁾ and sheets^(20,21) fabricated and annealed in the alpha phase. The textures observed for these materials consist of several components and exhibit appreciable scatter; consequently, it is not practical to arrive at orientation relationships from these data. In view of the results obtained for recrystallization studies of deformed single crystals of cubic lattices and their agreement with texture studies for polycrystalline materials, it was believed that similar studies of deformed alpha-uranium single crystals could delineate the orientation relationship for this material.

II. EXPERIMENTAL TECHNIQUES

The single crystals used in the present work were from the room temperature deformation studies reported by Lloyd and Chiswik.⁽²²⁾ They were grown by the grain coarsening technique described by Fisher.⁽²³⁾ Each crystal was isolated from other grains and prepared for compression in a specific crystallographic direction by normal X-ray Laue back-reflection and uranium metallographic techniques. They were then compressed in the previously described apparatus and observed for operative deformation mechanisms.

A. Recrystallization Heat Treatments

The deformed crystals were prepared for recrystallization heat treatment as follows: They were electropolished in a bath of 5 parts 85% orthophosphoric acid, 5 parts ethylene glycol and 8 parts ethyl alcohol at a current density of 30 milliamperes per square centimeter with a stainless steel cathode and a platinum touch wire. Individual crystals were wrapped with thin tantalum foil and placed in Vycor glass tubes closed at one end. The tubes were then evacuated to pressures of 10^{-5} to 10^{-6} mm of mercury and sealed with an oxygen-hydrogen torch.

Heat treatments were performed by placing the encapsulated crystals in a stainless steel tube submerged in a lead pot furnace held at the desired temperature. After a specified period of time the capsules were removed from the furnace and allowed to cool to room temperature. The Vycor tubes were broken and the samples were removed and observed metallographically. Some of the deformed crystals were subjected to multiple heat treatments in the manner given above.

B. Orientation Determination of Recrystallized Areas

New metallographic surfaces were prepared by normal techniques on most of the samples which yielded evidence of recrystallization. These were as nearly parallel as possible to the original metallographic faces. X-ray Laue back-reflection photograms were then obtained from the recrystallized areas with the aid of the micrometer stage shown in Figure 1.

The stage assembly consisted of two mutually perpendicular ways driven by micrometer heads and mounted so that they were perpendicular to the X-ray beam. The specimen was mounted in plasticine or wax on a pedestal so that its metallographic surface was in the same plane as the surface of the pedestal above the sample and was parallel to the planes of the ways. The pedestal supporting the specimen was then rotated so that the reference line on the specimen, in this work the common edge formed by the two metallographic faces, was parallel to the edge of the upper way.

The exact position of the area on the specimen which was to be X-rayed was determined with reference to the small hole in the pedestal above the specimen. To do this the assembly was inverted and placed on a Bausch and Lomb Research Metallograph stage so that the three pointed supports seated into small indentations in the metallograph stage plate. The area to be X-rayed was brought into view and the micrometer readings were recorded. The micrometer screws were then turned so that the hole in the pedestal above the specimen was brought into the field of view and the micrometer readings were again recorded. The specimen stage assembly was then placed on an X-ray machine and it was moved so that the X-ray beam passed through the hole in the pedestal and fell upon the fluorescent screen behind it. The micrometer screws were rotated so that the portion of the specimen desired lay directly in the X-ray beam. By using a 0.005" diameter collimator, areas as small as 0.0015" in diameter could be covered with the X-ray beam.

The photograms obtained in the above manner constitute the basic data for the present work. These data were supplemented with metallographic observations at all times.

III. RESULTS

Fourteen of the room temperature compressed alpha-uranium single crystals were studied; the pertinent deformation data for these are given in Table I.(22) Table II lists the annealing heat treatments applied to the crystals. Only six samples gave recrystallized grains of sufficient size for orientation determinations by Laue back-reflection X-ray techniques; these were deformed crystals A, E, J, P, S and V. The others either did not show recrystallization or the grains formed were rather small and, for the most part, located near compression surfaces where deformations other than those imposed during the compression study could have been responsible for their presence.

A. Orientation Relationships

Composite representations of the metallographic faces of the recrystallized samples are given in Figures 2, 3, 4, 5, 6, 7 and 8. Each photograph shows the areas from which X-ray photograms were obtained; the size of the circles represent the size of the X-ray beam of the surface of the sample. One of the areas for each sample gave the original crystal orientation with the exception of sample P which recrystallized completely upon annealing. In this case, the original orientation was obtained from a photogram taken just prior to heat treatment. The other areas yielded orientations of recrystallized grains, with a few exceptions where the Laue patterns could not be solved. The various orientations were then represented collectively on a stereographic plot for each sample and observed for orientation relationships. To best illustrate the method of treating the raw data, the orientations obtained from sample A are discussed in detail below.

As Figures 2 and 3 indicate, two groups of data were obtained from sample A; one after annealing one-half hour at 525°C and a second after annealing one hour at 600°C. Obviously some of the orientations for these two groups are identical and, in addition, some of the orientations obtained from face A are identical to orientations for face B; the equivalent areas are given in Table III.

In all, 27 different recrystallized grain orientations were obtained from this sample. The locations of the three principal poles of these grains with respect to the original crystal orientation and the orientations resulting from twinning on the (130) and ($\bar{1}\bar{3}0$) planes are plotted on the stereographic projection of face A in Figure 9. For purposes of data treatment, the orientation of the parent crystal was then rotated into (001) standard projection and the other poles were rotated the same amount (Figure 10). The data in this form show strong groupings of the recrystallized grain (001) poles near the original crystal (001) pole and are suggestive of an orientation relationship between the deformed material and the recrystallized grains. The three exceptions to this behavior are orientations 29, 31 and 51.

If an orientation relationship does exist, then the other two principal poles of the recrystallized grains should indicate some form of grouping. There was strong evidence for the grouping of (100) poles of recrystallized grains near the {110} poles of the original crystal orientation and the {110} poles of its {130} twin orientations. Three of these groups are obvious in Figure 10; they are: orientations number (13, 16, 21, 30, 35, 38, 43, 45, 46); (26, 27, 28, 37) and (22, 23, 25, 32, 47). The first two groups lie near the (110) pole of the original crystal orientation, since the (110) pole is identical to the (110) pole. The difference for the two groups is the axis of rotation. The third group lies near the ($\bar{1}\bar{1}0$) pole of the (130) twin orientation. In a like manner, the (100) poles of orientations 7, 15 and 24 lie near the ($\bar{1}10$) or ($1\bar{1}0$) pole of the (130) twin orientation, (100) of 33 near the (110) of the (130) twin, (100) of 52 near the ($\bar{1}\bar{1}0$) of the ($\bar{1}\bar{3}0$) twin and (100) of 36 near the ($1\bar{1}0$) of the original orientation. Since the (001) and (100) poles of the recrystallized grains show groupings, the (010) poles must also be grouped. Examination of Figure 10 shows this to be true. The poles of recrystallized orientations 29, 31 and 51 have been disregarded in the further data treatment because of the gross displacement of their (001) poles from that of the original crystal.

The fact that the poles of the recrystallized grains show grouping indicated that there was some crystallographic axes about which rotation had occurred upon recrystallization. For purposes of further treatment, it was assumed that recrystallized grains which have their (100) poles near {110} poles of {130} twin orientations originated from the respective twinned material and those which have their (100) poles near the {110} poles of the deformed parent orientation originated from untwinned material.

On the basis of this assumption it was possible to reflect the principal poles of the orientations believed to have originated from $\{130\}$ twinned metal on the respective $\{130\}$ planes of the parent orientation and then treat them as if they originated from the parent orientation. In this manner the data were then referred to a single deformed orientation. Figure 11 shows the locations of the principal poles of the recrystallized grains after those assumed to originate from twin orientations, as given above, were reflected in the respective twin planes.

The principal poles of the recrystallized grains were further grouped by bringing them into crystallographic equivalent locations with respect to the original orientation by reflecting them in the (100) and (010) planes of the original orientation. The data treated in this manner are shown in Figure 12. Orientations 7, 15, 26, 27, 28, 33, 37, 52 were reflected in the (010) plane and orientations 24, 26, 27, 28, 33, 36 and 37 were reflected in the (100) plane.

With the data in this form it was possible to determine an axis of the original orientation about which rotation of the principal poles had occurred upon recrystallization. If corresponding sets of poles were considered with respect to the poles of the original orientation, 24 different axes and magnitudes of rotation would be obtained. It seemed more logical to treat the data in a statistical manner to obtain single values for the axis and magnitude of rotation. Two different approaches could be made: one was to determine an axis and magnitude of rotation for each individual grain and then average these, or the average position ("center of gravity") of each group of recrystallized grain poles could be evaluated and then a single axis and magnitude of rotation could be determined for these. The latter approach has been used to treat the data here.

Each recrystallized grain principal pole position on the stereographic plot was expressed in terms of two angles θ and ϕ : where θ was the longitude angle measured from the center of the plot with positive angles to the right and negative angles to the left; and ϕ was the latitude angle measured from the center of the plot with positive angles downward and negative angles upward. The values of these for the principal poles of recrystallized orientations for specimen A are given in Table III. To determine the average positions of the recrystallized poles, each group of angular coordinates was added algebraically and then divided by the number of recrystallized orientations. In averaging the data for the (010) poles the ones appearing at $-\theta$ and $+\phi$ angles had to be considered in terms of $+\theta$ and $-\phi$ angles; for example, the coordinates of the (010) pole for recrystallized grain 33 were $\theta = 98.5^\circ$ and $\phi = -35.5$. The average values of θ and ϕ determined in this manner and describing the location of the average recrystallized principal poles for specimen A are given in Table IX and shown graphically as "X" in Figure 12.

The average positions were then used to stereographically solve for the axis about which rotation had occurred. To do this the matching original orientation pole and average recrystallized pole were placed on the same small circle of a Wulff net and the locus of axes about which rotation could have occurred was the great circle which angularly bisects the two positions. Three such loci were constructed, one for each pair of poles and these intersected at a common point that represented the axis of rotation. Actually it was possible to find four such points of intersection. Three of these required large angular rotations to bring the two poles into coincidence and the fourth required a considerably smaller rotation. The axis selected as the proper one for the data here was the latter. Once the axis had been established the magnitude of rotation required about this axis to bring the two orientations into coincidence was readily determined stereographically. The rotational axis was translated to the center of the stereographic plot, the principal poles of the original orientation and the averages of the recrystallized grain principal poles were rotated the same amount and the rotation about the center of the plot necessary to superimpose one set of poles upon the other was measured. The angular location of the rotational axis and the magnitude of rotation about this axis for sample A are given in Table IX.

The recrystallized grain principal pole positions for samples E, J, P, S and V are tabulated in Tables IV, V, VI, VII and VIII and depicted graphically in Figures 13, 14, 15, 16 and 17. Each figure shows the final groupings obtained in the manner described above for sample A. Deformed orientations from which the recrystallized grains were assumed to have originated are tabulated for each sample in the respective tables. Table IX records the average positions of the recrystallized grain poles for each set of data and also gives for these the location of the rotational axis and the magnitude of rotation about this axis necessary to bring the orientations into coincidence. In addition, Table IX gives the over-all average positions of the recrystallized grain principal poles, as obtained by averaging all of the data, plus the rotational axis location and the magnitude of rotation about that axis for the over-all average positions. Finally, Table IX lists the standard deviations (σ) of the various angular measurements from the over-all average values as determined from the relationship:

$$\sigma = \frac{\sum_{i=1}^N |R_i|}{N} \sqrt{\frac{\pi}{2}}$$

where: R_i is the difference between the i th datum point and the average value and N is the number of observations.

Figure 18 graphically represents the over-all average orientation relationship between the original orientation and the recrystallized grain principal poles. This figure was constructed by considering all four of

the crystallographically equivalent rotational axes. The directions of rotation about the axis were clockwise for the ones located in the lower right and upper left quadrants and counterclockwise for the ones located in the lower left and upper right quadrants. The radii of the inscribed circles reflect the standard deviations for the respective principal pole groupings.

B. Metallographic Observations

In general, the heat treatment applied to the deformed crystals were designed to produce recrystallized grains of sufficient size for X-ray Laue back-reflection orientation determinations and not to investigate where recrystallization began. To accomplish the latter aim the samples would have had to be annealed successively for increasing times and/or at increasing temperatures. As is well known, such thermal cycles can produce drastic effects in alpha-uranium and possibly could have led to difficulty in interpreting the final orientation relationships of recrystallized grains. This is particularly true for those deformed crystals which contained twinned material. Since such treatments, in general, were avoided little can be said with regard to metallographic observations of the beginning stages of recrystallization; however, two particular types of metallographic observations are of interest.

1. Twin growth and absorption: One observation pertains to the behavior of twins upon annealing. All of the samples investigated for recrystallized grain orientations subsequent to annealing were twinned in the deformed state. Much of the twinned material was absorbed by recrystallized grains upon annealing; however, in most of the samples twinned material remained after heat treatment. In many areas the remaining twins had grown and absorbed surrounding deformed original crystal material and differently oriented twins; also, in some instances, the twins were absorbed by their parent orientation.

An example of twinned material which underwent both types of behavior is shown in Figure 19 which is a higher magnification photograph of an area on face B of sample J (Figure 5). In the deformed state this crystal contained sharply defined parallel sided $\sim\{172\}$ type twins. As a result of the annealing heat treatment the tip of the twin near the upper left corner has been absorbed by the parent orientation; the area in the lower left corner was a portion of a recrystallized grain. At the lower right corner the same twin had thickened by growing into the parent crystal and had finally merged with an adjacent twin. The shapes of the interfaces between the growing material and the material which was being absorbed indicated that the directions of growth were towards the centers of curvature of the interfaces; this is consistent with observations of grain growth in other metals. The fact that the same twin grew into other material as well as being absorbed can be explained only by inhomogeneities of strain throughout its length and in the surrounding material.

2. Preferential recrystallized grain growth: Many of the microstructures obtained for partially recrystallized samples were indicative of preferential grain growth with respect to the deformed structures. This was particularly evident on face B of sample A (Figure 2) where the recrystallized grains were elongated in directions nearly parallel to the original twin plane traces and the grains grew to greater extent in some local areas. Figure 20 represents higher magnification photographs of areas near the right hand edge of face B. In general, the grains appeared to grow by absorbing preferentially the lighter toned twinned material. This was indicated by portions of the darker twins protruding into the recrystallized grains. If a considerable portion of the deformed material in front of the recrystallized grain was the lighter twin, the grain had advanced more rapidly. Incidentally, the lighter twins represent the (130) twinned orientation which had a greater number of grains assumed to originate from it than did the $(\bar{1}30)$ twinned orientation.

Similar preferential growth observations were obtained from the sequence of anneals given sample G. A single recrystallized grain was found in the kinked area upon annealing for one hour at 650°C ; as the annealing time was increased this grain became larger. Upon annealing 26 hours at 650°C a second area of the same orientation appeared on the surface of the sample and after 50 hours at 650°C it had merged with the original grain. Annealing for times up to 215 hours resulted in further gradual increase in size of the recrystallized grain. Figure 21 is a drawing representing the successive growth stages of this grain. The grain occupied area 1 after one hour at 650°C . Annealing for 3 hours caused it to occupy areas 1 and 2, after 50 hours it occupied areas 1, 2 and 3, etc. It was obvious that the growth rate varied with crystallographic direction of the deformed crystal. For this particular plane of polish the direction of maximum growth appeared to be towards the left of the schematic drawing. The occurrence of the apparently disconnected second grain after the fourth annealing treatment could have been caused by its existence within the body of the crystal where it was actually a part of the original grain and it finally broke through the surface during this treatment. Therefore, the rapid growth in a downward direction between the fourth and fifth anneals was not representative of the true growth rate in that direction. An analysis for the crystallographic direction of maximum growth could not be made because the grain was found on one face only.

IV. DISCUSSION

A. Justification of Orientation Data Treatment

In the final analysis the proof of a method used in treating data for relationships between deformed and recrystallized orientations is the ability to develop a reasonably compact grouping of the latter with respect to the former. In this sense, the method used here appears to be quite valid; only 4 grains out of 75 could not be related simply to the deformed orientations.

The primary assumption employed in treating this data was that the recrystallized grain originated from the deformed orientation whose (001) pole lay near the grain's (001) pole. Then to fix the relationship in three dimensional space it was assumed that the (100) pole of the recrystallized grains took up a position near the $\{110\}$ poles of the deformed orientation. Both of these were not assumptions in the true sense since the data indicated these relationships. The interesting aspect of the method used for treating the data was the referral of recrystallized grains to twin orientations as well as to the deformed original crystal orientation. The various twins were not used promiscuously but rather the orientations assumed to originate recrystallized grains were directly related to the twins found in the crystals upon deformation as is pointed out below.

Both (130) and ($\bar{1}\bar{3}0$) twins were formed upon compression of crystal A. From a critical resolved shear stress viewpoint the formation of ($\bar{1}\bar{3}0$) twins was favored over that of the (130) twins. In the as-deformed state it was impossible to determine metallographically if one twin predominated over the other. The preponderance of the recrystallized grains related to (130) twins indicated that twinning on this plane resulted in greater internal straining of the twinned material than did twinning on the ($\bar{1}\bar{3}0$) plane. This agrees with what would be expected intuitively since ($\bar{1}\bar{3}0$) twinning would probably precede (130) twinning and greater internal straining would be expected in the latter. In turn, the material with the greater internal straining would probably give rise to recrystallized grains more readily.

In addition, it may be noted that sample A shows the largest proportion of recrystallized grains originating from the deformed original crystal orientation. This sample was compressed in an apparatus where the platens were not free to move in a plane perpendicular to the compression direction as was the case for the other samples. The end restraints imposed upon this sample undoubtedly resulted in proportionately greater internal straining of the original crystal orientation than occurred in the other samples where end restraints were at a minimum. The fact that minimum end restraints and accompanying smaller residual lattice strains were imposed by the apparatus with movable platens was substantiated by

the fact that crystals which deformed by slip mechanisms only could not be recrystallized; particularly sample M which was compressed 7.4% whereas sample P, also compressed 7.4% and deformed by $\{130\}$ and $\sim\{172\}$ twinning as well as by slip, completely recrystallized due to the lattice strains associated with twinning.

Upon compression of crystal E, the primary deformations were twinning on the irrational $\sim\{176\}$ planes with small quantities of twinning on the (130) plane. None of the recrystallized grains for this sample were found to originate from the original crystal orientation. Ten of the 13 recrystallized orientations originated from $\sim\{176\}$ twins and the remainder were from $\{130\}$ twins. Of the 10 grains from $\sim\{176\}$ twins, eight originated from $\sim(176)$ and $\sim(1\bar{7}6)$ twins; the more prevalent of this type of twin. The other two grains originated from $\sim(\bar{1}76)$ twins. These latter grains were found in the lower third of the sample (Table IV and Figure 4) where that particular twin system was observed upon deformation. This correspondence between the relative position of the observed twins and related recrystallized grains further substantiates the validity of assuming grains to originate from certain deformed twin orientations.

Compression of crystal J resulted in deformation by twinning on $(1\bar{3}0)$ and $\sim(1\bar{7}2)$ planes. Of the five recrystallized orientations obtained from this sample two were referred to $(1\bar{3}0)$ twins, two were referred to $\sim(1\bar{7}2)$ twins and one originated from the original crystal orientation. Not too many recrystallized grains were found in this sample; this behavior could be ascribed to the relatively simple deformations in that only one twin system was observed for each of the two twin types. In such a situation the residual lattice strains after deformation would not be as great as in the cases where two or more twins of the same type were operative and twin intersections would occur more readily.

Crystal P also deformed by $\{130\}$ and $\sim\{172\}$ type twins upon compression; however, in this case two planes of each type were operative as shown in Table I. Upon annealing the sample completely recrystallized and 16 different grain orientations were determined; nine of these originated from $\{130\}$ twinned material, one from $\{172\}$ twinned material, five from the original crystal orientation and one grain could not be related simply to any of the deformed orientations. Of the $\{130\}$ twin deformations, the (130) occurred first and was more prevalent than the $(1\bar{3}0)$; five grains formed from $(1\bar{3}0)$ material and four from (130) . This agrees with the observations of sample A where it was concluded that twinning on the second plane of a single type causes greater residual internal strains in that twin and, therefore, preferential formation of recrystallized grains. Since only one grain was associated with $\sim\{172\}$ twins no conclusions can be drawn with respect to preferential recrystallization for this type of twin. The reasonably large number of grains associated with the deformed original crystal orientation points up the greater residual internal strains caused by multiple twin plane operation.

Compression of crystal S resulted in twinning on both $\{130\}$ planes with the $(\bar{1}30)$ more prevalent than the (130) . Of the eight recrystallized grain orientations 5 originated from $(\bar{1}30)$ twins, two from (130) twins and one from the deformed original crystal orientation. The results obtained for this sample contradict those for samples A and P since more grains originate from the more readily created twin orientation; however, the relative proportion of $(\bar{1}30)$ twins in this crystal was considerably greater than the (130) , whereas in samples A and P the two twins were present in more nearly equal quantities. On this basis it was not difficult to rationalize more grains originating from $(\bar{1}30)$ twins than from (130) twins.

The last sample (V) also deformed by $\sim(\bar{1}72)$ and $(\bar{1}30)$ twins. Three of the orientations originated from the $\sim(\bar{1}72)$ twins, one from the $(\bar{1}30)$ twins and two from the original crystal orientation. Again the correlation between observed twin deformations and material originating recrystallized grains was good.

Thus, the observed recrystallized grain orientations were directly related to the deformed orientations found in the crystals. Grains were found to originate from all three types of twins which are formed upon compression at room temperature; namely, the $\{130\}$, $\sim\{172\}$ and $\sim\{176\}$. In addition, they originated from deformed original crystal orientations. It was unfortunate that recrystallized grains could not be obtained in crystals that had deformed by slip mechanisms alone. If the recrystallized grain found in such cases had been related to the deformed original crystal orientation alone, this would have been further indirect proof of the validity of assuming recrystallized grains to originate from twinned orientations.

The four grains whose orientations could not be related simply to the deformed orientations present in the crystals could easily have originated from twins created within twins where two systems intersect. Such deformed orientations were not considered in treating the present data.

Calais, Mandin and Lacombe⁽²⁴⁾ have reported observations, very similar to those given here, of orientation relationships between recrystallized grains and deformed alpha-uranium crystals. Their data are shown graphically in Figure 22. Figure 22a represents the orientation relationship for eight grains found upon annealing a crystal deformed by tension in a $\langle 231 \rangle$ direction. From considerations of the operative deformation mechanisms at room temperature,⁽²²⁾ this crystal was probably not deformed by twinning, but it should have deformed by kinking; this is the type of deformation the authors have reported. The orientation relationship found by Calais et al., agrees well with the one observed in the present work. The axis of rotation was located close to the average axis of the present work, the magnitude of rotation, 30° , agrees well with the 27.5° found here and the directions of rotation were the same.

The data shown in Figure 22b pertained to a crystal deformed by tension in a $\langle 321 \rangle$ direction. In this case the crystal probably deformed by twinning on one of the $\{130\}$ planes as well as by $(010) - [100]$ slip deformations. If these data were treated in the same manner as the data of the present work, the grouping of principal poles with respect to the deformed orientations (M in Figure 22b) in standard projection was obtained as shown in Figure 23. In this treatment grains 2 and 3 were assumed to have originated from (130) twins; this is the twin which could have operated under the conditions of deformation. Again the various features of the orientation relationship were in agreement with those observed in the present work. These strong similarities in the orientation data from two independent sources serve to further justify the data treatment method and results presented herein.

B. Deformation and Recrystallization Textures

As was pointed out above, several studies of deformation and recrystallization textures have been reported for both rod and sheet samples of alpha-uranium. These data can be used to check the orientation relationship between deformed and recrystallized materials as suggested by the single crystal studies.

1. Fiber textures: Table X records data pertaining to the deformation and recrystallization fiber textures of alpha-uranium rods.⁽¹⁵⁻¹⁹⁾ The locations of the major and minor components, as plotted on inverse pole figure charts, are expressed in terms of the two angles θ and ϕ . The pole figures in the original data were plotted as one quadrant of the (001) standard projection with contours representing the concentrations of plane poles parallel to the rod axes. The locations represented by the angular measurements in Table X are the texture components reported by the respective investigators. The table also includes the locations of recrystallization texture components constructed by reorienting the deformation texture components according to the orientation relationship of the present work.

In general, the agreement between observed and constructed recrystallization texture components was good, particularly for the observed major components. The constructed textures, of course, did not agree exactly with the observed ones because of the diffuse nature of texture measurement data in general; however, it was obvious that many constructed components lie close to the observed ones. The multiplicity of the constructed components was indicative of the general broadening and decrease in intensity of observed recrystallization textures in comparison to deformation textures. Of particular interest was the indication that minor deformation components contribute to the observed major recrystallization components.

The only group of data with quantitative measures of the texture components was that of Jetter and McHargue.⁽¹⁹⁾ They reported 70 volume per cent of the structure to be associated with the major deformation component and 30% with the minor component. After annealing, 65% of the structure was associated with the major recrystallization component and 35% with the minor component. It was interesting to compare the individual components of the constructed recrystallization texture with the reported components. For simplicity, the constructed components are referred to by number; components 1, 2, 3 and 4 originated from the major deformation texture component in the order given in Table X, from top to bottom, and components 5 and 6 originated from the minor deformation component. Constructed components 1, 2, 5 and 6 were the ones contributing to the observed major recrystallization component; they were essentially uniformly spaced about it and were displaced by 13° , 20° , 10° and 12° , respectively. Constructed components 3 and 4 constituted the minor observed recrystallization component and were located 16° and 10° from it, respectively. The interesting feature was that half of the major deformation component contributed the observed minor recrystallization component and the reported proportions of these components were in perfect agreement; that is, half of the 70 volume per cent major deformation texture component, or 35%, gave the minor recrystallization texture component reported to represent 35% of the recrystallized structure. The other 65% of the recrystallized structure, representing the observed major recrystallization texture component, originated from one half the major deformation texture component, or 35%, plus the 30% ascribed to the minor deformation texture component.

2. Sheet textures: Investigations of deformation and recrystallization textures for sheet samples have been reported by Mueller, Knott and Beck⁽²⁰⁾ and Mitchell and Rowland.⁽²¹⁾ The results of the latter investigators were quite similar to those of the former, but not as detailed. For this reason the following discussion deals with the data of the former investigators only.

The locations of the principal poles of ideal texture components reported by Mueller et al., are tabulated in Table XI. In this case the angular positions refer to the rolled sheet and not to a (001) standard projection. θ was the longitude angle measured from the normal to the rolling plane (center of the stereographic projection) towards the direction transverse to the rolling direction and lying in the rolling plane. ϕ was the latitude angle measured from the normal to the rolling plane towards the rolling direction.

These ideal texture components are depicted graphically in Figure 24. The locations of the principal poles of the deformation texture components are shown in the upper left quadrant of the figure. Their identities are given by the indicated principal pole symbols and numbers

referring to the ideal texture component. It is obvious that the principal poles shown for a particular ideal texture are not depicted in their true spatial relationship as they would be if the proper multiplicity were plotted in all four quadrants of the standard projection. The representation here is sufficient, however, since the sheet was rolled in a manner as to make the texture data symmetrical about the transverse and rolling directions.

The other three quadrants plot the reported ideal recrystallization texture components; each quadrant plots the locations of one principal pole. Included in these quadrants are the locations of recrystallization texture components constructed from the ideal deformation texture components and the observed orientation relationship between deformed and recrystallized single crystals. These are plotted as "X" and the numbers refer to the ideal deformation textures from which they originated.

The agreement between observed and constructed recrystallization texture components was reasonably good with the exception of ideal component number 5. None of the constructed (100) and (001) positions agreed with this component although its (010) position was in an area of agreement. This particular component was reported as the least important of the ideal recrystallization textures. The best agreement occurred for number 6 observed ideal recrystallization component and the one constructed from number 2 ideal deformation texture. All three poles of the reported ideal component were centrally located with respect to the constructed poles. This was particularly interesting since ideal deformation texture number 2 and ideal recrystallization texture number 6 were reported as the respective important components and it would be logical to assume that 6 had as its origin component number 2.

The agreement between observed and constructed recrystallization texture components for both rod and sheet materials constitutes further indirect evidence of the validity of the proposed orientation relationship between deformed and recrystallized alpha-uranium. It is particularly gratifying to find this relationship applies to deformed and recrystallized polycrystalline materials as well as to single crystals.

C. Origin of Recrystallization Orientation Relationships

For several years there have been differences in opinion as to the factors controlling the origin of recrystallization textures in metals. Two schools of thought prevail: one states that recrystallization textures originate from the preferential orientations of recrystallization "nuclei" with respect to the deformed material and the other ascribes the textures to preferential grain growth. The status of these two theories as of 1953 were presented in debate fashion by Beck⁽²⁵⁾ for oriented growth and by Burgers and Tiedema⁽²⁶⁾ for oriented nucleation. Beck has further discussed the

two theories in a later paper.⁽²⁷⁾ To this date these differences in opinion prevail, although the recent experiments on deformed aluminum single crystals^(8,9) appear to substantiate the oriented growth theory, at least for that face-centered-cubic metal. It is not intended to discuss the merits of these two theories nor to present the status of them at this time, but rather to consider the orientation relationships found between deformed and recrystallized structure by workers in this field and to compare these to the results reported here for alpha-uranium.

In the observed orientation relationships for grains formed upon recrystallization of deformed single crystals with cubic lattices, the axes of rotation found are ones normal to the most densely populated planes and also the primary slip planes; these planes are the $\{111\}$ for face-centered-cubic metals and $\{110\}$ for body-centered-cubic metals. Beck⁽²⁷⁾ has pointed out that the axis of rotation observed from recrystallization studies of polycrystalline hexagonal metals also is one normal to the most densely populated plane and the primary slip plane, the $[001]$. This generalization does not apply to the present results for alpha-uranium. At room temperature, where the crystals were deformed, the most densely populated plane is the (001) and the primary slip plane is the (010) .

Beck⁽²⁷⁾ also pointed out that the observed orientation relationship, at least for face-centered-cubic and hexagonal metals, corresponds to one with maximum boundary mobility upon recrystallization. This type of information is not available for either body-centered-cubic metals or orthorhombic alpha uranium.

Kronberg and Wilson⁽²⁸⁾ have attempted to rationalize the deformed-recrystallized orientation relationship for face-centered-cubic metals in terms of the atomic movements accompanying rotations about $\langle 111 \rangle$ axes. The primary difficulty with this approach, as pointed out by Yoshida, et al.,⁽⁹⁾ is that the experimentally observed magnitudes of rotation vary for different face-centered-cubic metals, for example, 30° for copper and 40° for aluminum. Thus, the relationship between atom sites is not a universal one and, therefore, recrystallization orientation relationships are not controlled by crystallographic structure factors alone.

Although the existence of orientation relationships between deformed and recrystallized materials are well established experimentally, the question still remains as to what basic factors determine these relationships. From a fundamental viewpoint there should be an explanation for this behavior which would apply to all types of lattice structures. Such a theory would undoubtedly involve the behavior during plastic deformation and annealing of lattice imperfections such as vacancies and dislocations.

It is somewhat difficult to discount the oriented nucleation dependency of recrystallization textures, at least for alpha-uranium in light of the data treatment method of the present work. This conclusion is based on the

fact that twin orientations had to be considered before an overall orientation relationship could be arrived at. This implies that the deformed orientations present are instrumental in controlling the orientations of recrystallized grains and consequently the grains could be dependent upon orientation of the recrystallization nuclei. Also it should be pointed out that the grains originating from twins appeared to grow into deformed parent orientations with equal ease as those originating in the latter deformed material, thus indicating that oriented growth might not be important. Of course, it could be argued that, by the time the recrystallized grains become large enough to see, oriented growth had already operated and only those grains which were suitably oriented from a growth viewpoint persisted and were able to grow into the parent orientation as well as into the twin orientation.

The referral of recrystallized grains to deformation twin orientations as well as to the deformed parent crystal orientations, as employed in the present work with alpha-uranium single crystals, might well apply to similar types of studies for hexagonal single crystals where twinning is also an important deformation mechanism. Such studies would add to the knowledge of recrystallization textures of metals with this structure although it is difficult to envision contributions to the basic question of what fundamental factors control the observed orientation relationships.

In a somewhat broader sense, electron and optical microscopy observations of the first formed recrystallized grains in hexagonal metals and their behavior with time, especially those in twins, might contribute to a solution of the problem concerning the origin of recrystallization textures, namely oriented nucleation versus oriented growth.

V. CONCLUSIONS

Orientation studies of grains grown from room temperature deformed alpha-uranium single crystals with respect to the orientations present in the deformed crystals yielded a relationship which can be expressed as a rotation of 27.5° about axes located 70.0° from the $[100]$, 63.5° from the $[010]$ and 34.0° from the $[001]$. Rotation for the axes located in the first and third quadrants of a (001) standard projection were in a clockwise direction and for axes in the second and fourth quadrants, counterclockwise. In arriving at this relationship the grains were considered to originate from deformation twin orientations as well as from the original crystal orientation. The twin orientations in a particular crystal which were necessary to explain the observed recrystallized grain orientations corresponded exactly with the operative twin systems found in the crystals. The recrystallization orientation relationship for alpha-uranium differed from similar observations for face-centered-cubic, body-centered-cubic and hexagonal metals in that the axes of rotation were not normal to the most densely populated planes of the crystal structures.

Metallographic observations gave limited qualitative evidence that the recrystallized grains grew preferentially with respect to the deformation orientations. This behavior is in agreement with the oriented growth theory of recrystallization texture formation, but may be controlled by the magnitude of internal straining within the various deformed orientations.

Comparisons of observed recrystallization textures for polycrystalline alpha-uranium rods and sheets with ones constructed from the observed deformation textures and the orientation relationship found in the present work showed good agreement. It was not possible to reconstruct the observed recrystallization textures precisely because of the appreciable scatter of preferred orientations found for both deformation and recrystallization textures of uranium treated in the alpha phase region.

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VII. REFERENCES

1. Maddin, R., Mathewson, C. H. and Hibbard, W. R., Jr., "The Origin of Annealing Twins in Brass," Trans., A.I.M.E. (1949), 185, p. 655-662.
2. Becker, J. J. and Hobstetter, J. N., "Orientation Relationships in the Recrystallization of Deformed Cu Single Crystals," Trans. A.I.M.E. (1953), 197, p. 1235-1238.
3. Liu, Y. C., "Cube Texture in Copper," Trans. A.I.M.E. (1957), 209, p. 836-842.
4. Liu, Y. C. and Hibbard, W. R., Jr., "Recrystallization Textures of a Cold-Rolled Aluminum Single Crystal," Trans. A.I.M.E. (1955), 203, p. 1249-1251.
5. Graham, C. D., Jr. and Cahn, R. W., "Grain-Growth Rates and Orientation Relationships in the Recrystallization of Al Single Crystals," Trans. A.I.M.E. (1956), 206, p. 517-521.
6. Liebmann, B., Lücke, K. and Masing, G., "Study of the Relation Between the Orientation and the Rate of Growth in the Primary Recrystallization of Aluminum Single Crystals," Z. Metallkunde (1956), 47, p. 57-63.

7. Merlins, Alfonso, "The Origin of Annealing Textures," *Rev. Met* (1957), 54, p. 817-820.
8. Kohara, S., Parthasarathi, M. N. and Beck, P. A., "Annealing Texture in a Rolled and Artificially Nucleated Aluminum Single Crystal," *Trans. A.I.M.E.* (1958), 212, p. 875-881.
9. Yoshida, H., Liebmann, B. and Lücke, K., "Orientation of Recrystallized Grains in Strained Aluminum Single Crystals," *Acta Met.* (1959), 7, p. 51-56.
10. Dunn, C. G. and Koh, P. K., "Primary Recrystallization Textures in Cold Rolled Si Fe Crystals," *Trans. A.I.M.E.* (1956), 206, p. 1017-1024.
11. Dunn, C. G. and Koh, P. K., "Simple Orientation Relationships for Secondary Recrystallization in Iron-Silicon," *Trans. A.I.M.E.* (1957), 209, p. 81-86.
12. Liu, Y. C. and Hibbard, W. R., Jr., "On the Relationships of Texture Changes of Cold-Rolled Face-Centered-Cubic Metals During Recrystallizations," *Trans. A.I.M.E.* (1955), 203, p. 381-384.
13. Wiener, G. and Concoran, R., "Deformation and Recrystallization of Silicon-Iron," *Trans. A.I.M.E.* (1956), 206, p. 901-906.
14. Hu, Hsun, "Cross-Rolling and Annealing Textures in High-Purity Iron," *Trans. A.I.M.E.* (1957), 209, p. 1164-1168.
15. Chernock, W. P. and Beck, P. A., "Quantitative Determination of Rolling and Recrystallization Textures in 600°C and 300°C Rolled Uranium Rods," ANL-4839 (August 1951), AECD 3663.
16. Mueller, M. H., Knott, H. W., Chernock, W. P. and Beck, P. A., "Preferred Orientation in Rolled Uranium Rods," *Trans. A.I.M.E.* (1958), 212, 793-798.
17. Mueller, M. H. and Knott, H. W., "Effect of Varying Temperature on the Preferred Orientation in Rolled Uranium Rods," ANL-5329 (March 1957).
18. Mueller, M. H. and Knott, H. W., "Preferred Orientation in Rolled and in Recrystallized High Purity Uranium Rod," ANL-5887 (May 1958).
19. Jetter, L. K. and McHargue, C. J., "Preferred Orientation of Extruded Uranium Rod," *Trans. A.I.M.E.* (1957), 209, p. 291-292.

20. Mueller, M. H., Knott, H. W. and Beck, P. A., "Deformation and Recrystallization Textures of Rolled Uranium Sheet," Trans. A.I.M.E. (1955), 203, p. 1214-1218.
21. Mitchell, C. M. and Rowland, J. F., "Preferred Orientation of Alpha Uranium," Acta Metallurgica (1954), 2, p. 559-572.
22. Lloyd, L. T. and Chiswik, H. H., "Deformation Mechanisms of Alpha-Uranium Single Crystals," Trans. A.I.M.E. (1955), 203, p. 1206-1214.
23. Fisher, E. S., "Preparation of Alpha-Uranium Single Crystals by a Grain Coarsening Method," Trans. A.I.M.E. (1957), 209, p. 882-888.
24. Calais, D., Mandin, N. and Lacombe, P., "Orientation Relationships Between Recrystallized Grains and Deformation Bands in Alpha-Uranium," Comptes rendus, (1958), 247, p. 646-649.
25. Beck, P. A., "Notes on the Theory of Annealing Textures," Acta Met. (1953), 1, p. 230-234.
26. Burgers, W. G. and Tiedema, T. J., "Notes on the Theory of Annealing Textures," Comments on a paper by P. A. Beck with the same title. Acta Met. (1953), 1, p. 234-238.
27. Beck, P. A., "Annealing of Cold Worked Metals," Advances in Physics (1954), 3, p. 245-324.
28. Kronberg, M. L. and Wilson, F. L., "Secondary Recrystallization in Copper," Trans. A.I.M.E. (1949), 185, p. 501-514.

TABLE I
Deformation Data for Alpha-Uranium Single Crystals

Crystal	Compression Direction Location with Respect to Principal Directions - (Degrees)			Total Deformation (%)	Deformation Mechanisms	
	[100]	[010]	[001]		Slip	Twinning
A*	88	16.5	74	2.0	-	(130), ($\bar{1}\bar{3}0$)
E	87	89	3	55.0	(011), ($0\bar{1}1$)	$\sim(176)$, $\sim(1\bar{7}6)$ $\sim(\bar{1}76)$, $\sim(\bar{1}\bar{7}6)$, (130)
G	2	89	88.5	2.4	(010), (010) kink	-
I	74	16	89.5	10.9	(010)	(130), ($\bar{1}\bar{3}0$)
J	73	24.5	73	9.0	(010)	($\bar{1}\bar{3}0$), $\sim(1\bar{7}2)$
L	89	1.5	89.5	2.1	(010)	(130), ($\bar{1}\bar{3}0$)
M	64	78	29	7.4	(010) (010) - (001) cross-slip	-
P	89	61	29	7.4	(010)	(130), ($\bar{1}\bar{3}0$) $\sim(1\bar{7}2)$, $\sim(172)$
Q	59	88.5	31	1.2	(010) (010) - (001) cross-slip	-
S	89.5	9.5	80.5	29.0	(010)	(130), ($\bar{1}\bar{3}0$)
T	27.5	90	62.5	3.5	(010), (010) - (001) cross-slip, (010) kink	-
V	70	49.5	47.5	8.0	(010)	($\bar{1}\bar{3}0$), $\sim(\bar{1}72)$
W	51.5	46	49	24.4	(010)	-
Y	46	89	44	3.2	(010), (010) - (001) cross-slip, (011), ($0\bar{1}1$)	$\sim(176)$, $\sim(1\bar{7}6)$

*Crystal A was compressed in an apparatus with rigid compression platens. All of the other crystals were compressed in a fixture where one of the compression platens was supported by ball bearings and it was relatively free to move in a plane perpendicular to the crystal's compression direction.

TABLE II
Annealing Heat Treatments for Deformed Alpha-Uranium Single Crystals

Crystal	Annealing Treatments		Remarks
	Time - (hours)	Temperature - (°C)	
A	0.5	200	No recrystallization
	0.5	300	" "
	0.5	325	" "
	0.5	350	" "
	0.5	375	" "
	0.5	400	" "
	0.5	425	" "
	0.5	450	" "
	0.5	475	" "
	0.5	500	" "
	0.5	525	Partially recrystallized
E	1.0	600	Almost completely recrystallized
	2.0	575	Partially recrystallized
G	1	650	A few recrystallized areas were found among the kink bands. The growth of one of these areas was followed with increasing annealing time.
	2	650	
	7	650	
	16	650	
	24	650	
	65	650	
I	100	650	No recrystallization
	16	650	
J	1	650	Partially recrystallized
L	0.5	500	No recrystallization
	0.5	525	" "
	0.5	550	" "
	0.5	575	" "
	0.5	600	" "
	0.5	625	" "
	0.5	650	" "
M	24	650	" "
	0.66	550	No recrystallization
	0.66	575	" "
	0.66	640	" "
	6	650	" "
P	24	650	" "
	1	645	Completely recrystallized
Q	1	650	No recrystallization
	24	650	" "
S	0.75	410	Partially recrystallized
T	1	-	Sample was heated into the β phase
V	1	650	Partial recrystallization
W	1	575	No recrystallization
	17	650	" "
Y	2	650	No recrystallization

TABLE III
Recrystallized Grain Orientations for Deformed Crystal A

Area Number*	Equivalent Areas		Assumed Deformed Orientation from which Grain Originated	Recrystallized Grain Principal Pole Locations with Respect to Corresponding Principal Pole of the Deformed Single Crystal in (001) Standard Projection**					
	First Recrys- tallization	Second Recrys- tallization		(100)		(010)		(001)	
				θ (degrees)	ϕ (degrees)	θ (degrees)	ϕ (degrees)	θ (degrees)	ϕ (degrees)
1	-	34	-	Orientation of Deformed Single Crystal					
7	-	-	(130) twin	-57.5	-64.5	-77.0	24.0	16.5	6.5
13	-	-	original crystal	-59.0	-56.5	-81.0	32.0	15.5	10.0
15	-	-	(130) twin	-73.5	-63.0	-79.0	26.0	11.5	2.0
16	-	-	original crystal	-54.0	-60.5	87.0	-23.5	4.0	14.5
21	-	-	original crystal	-60.0	-62.0	-82.0	24.5	12.0	9.0
22	-	-	(130) twin	-58.5	-63.5	-86.5	23.5	7.5	11.5
23	-	-	(130) twin	-55.0	-61.5	-87.0	24.5	13.5	9.0
24	19	-	(130) twin	-75.5	-63.5	77.0	-16.0	-7.0	11.0
25	20	-	(130) twin	-38.5	-61.0	-82.5	21.0	19.0	20.0
26	3, 8	39	original crystal	-60.5	-51.0	81.5	-33.0	4.5	19.0
27	18	-	original crystal	-33.0	-73.5	-83.5	10.5	10.0	16.5
28	2, 9, 10	40	original crystal	-64.5	-58.0	84.5	-28.5	2.0	12.5
29	17	-	?	-	-	-	-	-	-
30	4, 11	42	original crystal	-51.0	-64.5	-82.5	22.0	12.5	11.0
31	5	-	?	-	-	-	-	-	-
32	-	-	(130) twin	-65.0	-52.0	79.5	-33.5	4.5	18.5
33	6	44	(130) twin	-72.5	-57.0	-81.5	35.5	12.0	5.0
35	-	-	original crystal	-49.5	-50.0	86.5	-42.5	15.5	19.0
36	-	-	original crystal	-61.5	-53.5	84.0	-23.0	0.0	13.5
37	14	-	original crystal	-60.5	-55.5	75.0	-26.5	-4.0	20.5
38	-	-	original crystal	-60.0	-44.5	85.0	-39.5	11.5	17.5
43	-	-	original crystal	-62.0	-60.5	79.5	-23.5	-3.5	15.0
45	12	-	original crystal	-63.0	-59.0	85.0	-22.0	1.5	17.0
46	-	-	original crystal	-47.5	-63.5	83.5	-19.0	-0.5	17.5
47	-	-	(130) twin	-59.0	-60.0	-86.5	25.5	8.5	13.0
51	-	-	?	-	-	-	-	-	-
52	-	-	($\bar{1}30$) twin	-46.5	-57.5	85.5	-25.0	4.5	21.0

*X-ray Laue back-reflection photograms obtained from areas #41, 48, 49 and 50 did yield solvable patterns.

** θ = longitude angle measured from center of stereographic projection; angle to right is positive and angle to left is negative.

ϕ = latitude angle measured from center of stereographic projection; angle downward is positive and angle upward is negative.

TABLE IV
Recrystallized Grain Orientations for Deformed Crystal E

Area Number	Grain Number	Assumed Deformed Orientation from which Grain Originated	Recrystallized Grain Principal Pole Locations with Respect to Corresponding Principal Pole of the Deformed Single Crystal in (001) Standard Projection*					
			(100)		(010)		(001)	
			θ^- (degrees)	ϕ^- (degrees)	θ^- (degrees)	ϕ^- (degrees)	θ^- (degrees)	ϕ^- (degrees)
4	-	-	Orientation of Deformed Single Crystal					
1 {	1	$\sim(176)$ twin	-24.0	-80.0	-86.0	4.5	4.0	8.5
	2	(130) twin	-33.0	-78.0	-76.0	9.0	15.5	8.0
2 {	3	$\sim(176)$ twin	-77.0	-80.5	-72.5	10.0	17.5	0.0
	4	(130) twin	-47.0	-78.0	-83.5	10.5	8.0	5.0
3	5	$\sim(176)$ twin	-68.5	-51.0	85.0	-35.5	7.0	11.0
5	6	(130) twin	-37.0	-67.5	-76.0	17.5	19.5	12.5
6	7	$\sim(176)$ twin	-90.0	-87.5	73.5	-13.0	-16.5	2.0
7 {	8	$\sim(176)$ twin	-63.0	-49.5	-86.0	38.0	13.0	12.0
	10	$\sim(176)$ twin	-71.0	-86.0	-80.0	15.0	11.5	6.0
8 {	11	$\sim(176)$ twin	-70.0	-85.0	-70.0	13.5	22.0	- 0.5
	12	$\sim(176)$ twin	-57.5	-64.5	71.0	-16.0	-14.0	19.0
9	13	$\sim(176)$ twin	-14.0	-87.5	88.5	- 4.0	- 2.0	11.5
4	14	$\sim(176)$ twin	-62.5	-68.0	-79.0	21.5	12.5	5.5

* θ = longitude angle measured from center of stereographic projection, angle to right is positive and angle to left is negative.

ϕ = latitude angle measured from center of stereographic projection, angle downward is positive and angle upward is negative.

TABLE V
Recrystallized Grain Orientations for Deformed Crystal J

Area Number	Grain Number	Assumed Deformed Orientation from which Grain Originated	Recrystallized Grain Principal Pole Locations with Respect to Corresponding Principal Pole of the Deformed Single Crystal in (001) Standard Projection*					
			(100)		(010)		(001)	
			θ^- (degrees)	ϕ^- (degrees)	θ^- (degrees)	ϕ^- (degrees)	θ^- (degrees)	ϕ^- (degrees)
4	-	-	Orientation of Deformed Single Crystal					
1	1	(130) twin	-72.0	-60.5	-82.0	27.5	6.5	9.0
2	2	$\sim(172)$ twin	12.5	-65.5	-77.5	- 0.5	19.0	27.5
3	3	$\sim(172)$ twin	-46.0	-50.5	-55.5	40.0	37.0	3.0
5	5	(130) twin	-75.5	-61.5	-84.5	28.5	7.5	4.0
6	6	original crystal	-65.5	-52.5	-76.0	37.0	16.5	4.0

* θ = longitude angle measured from center of stereographic projection, angle to right is positive and angle to left is negative.

ϕ = latitude angle measured from center of stereographic projection; angle downward is positive and angle upward is negative.

TABLE VI

Recrystallized Grain Orientations for Deformed Crystal P

Area Number*	Grain Number	Assumed Deformed Orientation from which Grain Originated	Recrystallized Grain Principal Pole Locations with Respect to Corresponding Principal Pole of the Deformed Single Crystal in (001) Standard Projection**					
			(100)		(010)		(001)	
			θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)
9	1	original crystal	-69.5	-47.5	-69.0	41.0	21.0	- 1.0
8	2	original crystal	-64.5	-48.0	-67.0	41.5	24.0	0.5
12	3	$\sim(1\bar{1}2)$ twin	7.0	-74.0	-84.5	1.0	5.0	16.5
15	4	$(1\bar{1}0)$ twin	-56.0	-58.5	86.0	-27.0	8.0	16.5
10	5	$(1\bar{1}0)$ twin	-65.0	-65.5	-77.5	23.5	15.0	4.5
11	6	$(1\bar{1}0)$ twin	-49.0	-57.5	-89.0	27.5	10.5	19.0
13	7	$(1\bar{1}0)$ twin	-80.5	-51.5	-69.5	38.0	15.0	- 6.0
13	8	$(1\bar{1}0)$ twin	-57.0	-62.0	-80.0	26.0	15.0	8.0
1	9	original crystal	-57.0	-55.5	-75.5	34.0	20.5	7.5
1	10	$(1\bar{1}0)$ twin	-76.0	-70.5	-73.5	19.5	17.0	- 1.5
6	11	$(1\bar{1}0)$ twin	-88.0	-64.0	-74.0	24.0	12.5	- 5.0
6	12	$(1\bar{1}0)$ twin	-80.5	-70.0	-75.5	18.5	14.0	- 2.5
7,14	13	$(1\bar{1}0)$ twin	-80.5	-60.0	-71.0	29.5	17.0	- 3.0
5	14	?						
3	15	original crystal	-49.0	-60.0	-72.0	27.0	23.5	9.5
	16	original crystal	-66.5	-57.0	-68.0	31.0	21.5	0.0

*X-ray Laue back-reflection photograms obtained from areas #2 and 4 did not yield solvable patterns

** θ = longitude angle measured from center of stereographic projection, angle to right is positive and angle to left is negative.

ϕ = latitude angle measured from center of stereographic projection, angle downward is positive and angle upward is negative.

TABLE VII

Recrystallized Grain Orientations from Deformed Crystal S

Area Number*	Grain Number	Assumed Deformed Orientation from which Grain Originated	Recrystallized Grain Principal Pole Locations with Respect to Corresponding Principal Pole of the Deformed Single Crystal in (001) Standard Projection**					
			(100)		(010)		(001)	
			θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)
11	-	-	Orientation of Deformed Single Crystal					
7	2	$(1\bar{1}0)$ twin	-68.0	-58.5	83.5	-26.5	1.0	12.5
2,9	3	$(1\bar{1}0)$ twin	-64.0	-63.0	-79.5	26.0	13.0	6.0
8	4	original crystal	-66.0	-57.5	-79.0	31.5	14.5	6.0
12	5	$(1\bar{1}0)$ twin	-81.0	-65.0	-72.0	25.0	17.5	- 3.5
4,5,10	6	$(1\bar{1}0)$ twin	-61.5	-65.0	-84.0	24.0	10.0	8.5
14	7	$(1\bar{1}0)$ twin	-62.5	-64.5	-84.0	23.5	8.5	8.5
1	8	$(1\bar{1}0)$ twin	-29.5	-68.5	-81.0	14.5	12.5	15.0
6,13	10	$(1\bar{1}0)$ twin	-59.5	-65.0	-86.5	22.5	8.0	10.5

*X-ray Laue back-reflection photogram obtained from area #3 did not yield a solvable pattern.

** θ = longitude angle measured from center of stereographic projection, angle to right is positive and angle to left is negative.

ϕ = latitude angle measured from center of stereographic projection, angle downward is positive and angle upward is negative.

TABLE VIII
Recrystallized Grain Orientations from Deformed Crystal V

Area Number	Grain Number	Assumed Deformed Orientation from which Grain Originated	Recrystallized Grain Principal Pole Locations with Respect to Corresponding Principal Pole of the Deformed Single Crystal in (001) Standard Projection*					
			(100)		(010)		(001)	
			θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)
5	-	-	Orientation of Deformed Single Crystal					
1	1	$\sim(1\bar{1}2)$ twin	-19.0	-73.0	-60.0	13.5	33.0	12.0
2	2	$\sim(1\bar{1}2)$ twin	-4.5	-56.0	-84.0	5.0	9.0	33.5
3	3	$(1\bar{1}0)$ twin	-35.0	-38.0	-86.5	38.0	29.0	29.0
4	4	$\sim(1\bar{1}2)$ twin	-42.5	-60.5	-66.0	27.5	27.0	9.5
6	6	original crystal	-16.5	-69.5	-88.0	6.0	4.5	21.0
7	7	original crystal	-50.0	-86.5	-65.5	2.0	24.0	1.0

* θ = longitude angle measured from center of stereographic projection; angle to right is positive and angle to left is negative.

ϕ = latitude angle measured from center of stereographic projection, angle downward is positive and angle upward is negative.

TABLE IX
Orientation Relationship Data for Average Principal Pole Positions of Recrystallized Grains Observed in the Deformed and Annealed "Crystals"

Sample	Average Position of Recrystallized Grain Principal Poles with Respect to Corresponding Principal Pole of the Deformed Single Crystal in (001) Standard Projection*						Location of Axis and Magnitude of Rotation about the Axis to Bring Average Poles into Coincidence with Original Poles		
	(100)		(010)		(001)		Axis Location		Magnitude of Rotation about Axis - (degrees)
	θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)	
A	-57.8	-59.0	89.4	-26.0	7.1	13.8	30.0	-7.0	31.0
E	-55.0	-74.1	-85.5	16.0	7.5	7.7	32.5	-22.0	17.5
J	-49.3	-58.1	-75.1	26.7	17.3	9.5	31.0	-31.0	29.0
P	-62.1	-60.1	-76.1	27.3	16.0	4.2	18.5	-30.0	28.0
S	-61.5	-63.4	-82.8	24.2	10.6	7.9	23.5	-19.5	27.0
Y	-27.9	-63.9	-75.0	15.3	21.1	17.7	53.5	-35.0	31.5
All Data	-55.5	-62.8	-83.3	23.4	11.4	10.0	28.0	20.0	27.5
σ^{**}	18.9	9.7	11.1	9.6	9.0	8.0			

* θ = longitude angle measured from center of stereographic projection, angle to right is positive and angle to left is negative

ϕ = latitude angle measured from center of stereographic projection, angle downward is positive and angle upward is negative

**Standard deviation of respective angles from values for average of all data

TABLE X
Deformation and Recrystallization Textures of Uranium Rods

Investigators	Final Fabrication Treatment		Location of Deformation Texture Components on Inverse Pole Figure*				Annealing Temperature (°C)	Location of Recrystallization Texture Components on Inverse Pole Figure*				Location of Deformation Texture Components Reoriented by Proposed Recrystallization Orientation Relationship			
	Reduction in Area - (%)	Temperature (°C)	Major Component		Minor Component			Major Component		Minor Component		Major Component		Minor Component	
			θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)		θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)		
Chernock and Beck ⁽¹⁵⁾	84	300	90 0	0 0	90.0	64.0	575	90.0	27.0	90.0	0 0	82 5	23 5	85 0 80 0	38 5 76 5
Mueller, Knott, Chernock and Beck ⁽¹⁶⁾	70	300	73.5	0 0	90.0	46 0	550	90.0	27.0	90.0	0 0	61.5 85.0	16 0 24 5	52.0 88.5	64.5 23.5
Mueller and Knott ⁽¹⁷⁾	75	300, 400 and 500	90 0	0.0	90.0	46 0	625	90.0	27 0	90 0	0.0	82.5	23.5	52.0 88.5	64.5 23.5
Mueller and Knott ⁽¹⁸⁾	85	300	73.5	0.0	65 0	48.0	475	75.0	33.0	73 5	0 0	61.5 85.0	16.0 24.5	72.5 72.0 23.5 85.5	22.5 33.0 55.5 73 0
Jetter and McHargue ⁽¹⁹⁾	92	500**	75.0	67.0	83.5	0.0	550	76.5	29 0	65.0	77.0	75.0 89.5 6.5 11.0	42.0 46.0 71.0 82.0	71.5 89 0	20.0 24 0

* θ = longitudinal angle measured from center of stereographic projection; angle to right is positive and angle to left is negative

ϕ = latitude angle measured from center of stereographic projection; angle downward is positive and angle upward is negative

** Rod extruded at 500°C - all other materials were rolled at indicated temperatures.

TABLE XI

Ideal Orientations of Deformation and Recrystallization
Textures of Uranium Sheet(20)

Ideal Orientation	Locations of Principal Poles with Respect to Pole Figure Stereographic Plot of Uranium Sheet*					
	(100)		(010)		(001)	
	θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)	θ - (degrees)	ϕ - (degrees)
Ideal Orientations of Deformation Texture						
2 {	60	0	0	90	-30	60
	-60	0	0	-90	30	-60
1 {	-58	62.5	-58	-27.5	32	0
	-58	-62.5	-58	27.5	32	0
	58	62.5	58	-27.5	-32	0
	58	-62.5	58	27.5	-32	0
3 {	81.5	-25	58.5	-58.5	0	18
	-81.5	-25	-58.5	-58.5	0	18
	81.5	25	58.5	58.5	0	-18
	-81.5	25	-58.5	58.5	0	-18
4 {	90	0	0	-72	0	18
	-90	0	0	72	0	-18
Ideal Orientations of Recrystallization Texture						
6 {	-58	25.5	-58	-64.5	32	0
	-58	-25.5	-58	64.5	32	0
	58	25.5	58	-64.5	-32	0
	58	-25.5	58	64.5	-32	0
2 {	60	0	0	90	-30	60
	-60	0	0	-90		-60
7 {	-74	-40.5	72	-44	0	18
	74	-40.5	-72	-44	0	18
	-74	40.5	72	44	0	-18
	74	40.5	-72	44	0	-18
5 {	0	0	0	90	90	0
	0	0	0	-90	-90	0

* θ = longitudinal angle measured from the normal to the rolling plane towards the direction transverse to the rolling direction, angle to the right is positive and angle to the left is negative

ϕ = latitude angle measured from the normal to the rolling plane towards the rolling direction; angle downward is positive and angle upward is negative

Figure 1: Micrometer X-ray Specimen Stage Assembly

13,733

3/4 X

Figure 2: Composite Photograph of Metallographic Faces of "Crystal" A after Annealing One-Half Hour at 525°C. Circles represent areas from which Laue back-reflection photograms were obtained.

25,300

Pol. Light

26X

Figure 3: Composite Photograph of Metallographic Faces of "Crystal" A after Annealing One Hour at 600°C. Circles represent areas from which Laue back-reflection photograms were obtained.

25,301

Pol. Light

26X

Figure 4: Composite Photograph of Metallographic Faces of "Crystal" E after Annealing Two Hours at 575°C. Circles represent areas from which Laue back-reflection photograms were obtained.

16,943

Pol. Light

50X

Figure 5: Composite Photograph of Metallographic Faces of "Crystal" J after Annealing One Hour at 650°C. Circles represent areas from which Laue back-reflection photograms were obtained.

25,302

Pol. Light

33X

Figure 6: Line Drawing of the Grain Boundaries Appearing on "Crystal" P after Annealing One Hour at 645°C. Circles represent areas from which Laue back-reflection photographs were obtained.

16,907

35X

Figure 7: Composite Photograph of Metallographic Faces of "Crystal" S after Annealing Forty-Five Minutes at 410°C. Circles represent areas from which Laue back-reflection photograms were obtained.

16,944

Pol. Light

50X

Figure 8: Composite Photograph of Metallographic Faces of "Crystal" V after Annealing One Hour at 650°C. Circles represent areas from which Laue back-reflection photograms were obtained.

25,303

Pol. Light

43X

Figure 9: Stereographic Projection on Face A of Deformed and Partially Recrystallized "Crystal" A Showing Locations of the Three Principal Poles of the Twenty-Seven Recrystallized Grains with Respect to the Orientation of the Original Crystal and the Orientations Resulting from Twinning on the (130) and $(\bar{1}\bar{3}0)$ Planes.

25,304

Figure 10: Grouping of the Three Principal Poles of the Recrystallized Grains for "Crystal" A with Respect to the Original Crystal Orientation in (001) Standard Projection.

25,305

Figure 11: Grouping of Principal Poles of Recrystallized Grains for "Crystal" A with Respect to the Original Crystal Orientation in (001) Standard Projection. Poles of grains believed to originate from twinned material have been reflected on their respective {130} twin planes.

25,306

Figure 12: Grouping of Principal Poles of Recrystallized Grains for "Crystal" A with Respect to the Original Crystal Orientation in (001) Standard Projection. Poles of grains rotated into crystallographically equivalent positions by reflection in (100) and (010) planes. Average position for each group of poles is indicated as "X".

25,307

Figure 13: Grouping of Principal Poles of Recrystallized Grains for "Crystal" E with Respect to the Original Crystal Orientation in (001) Standard Projection. Average position for each group of poles is indicated as "X".

25,308

Figure 14: Grouping of Principal Poles of Recrystallized Grains for "Crystal" J with Respect to the Original Crystal Orientation in (001) Standard Projection. Average position of each group of poles is indicated as "X".

25,309

Figure 15: Grouping of Principal Poles of Recrystallized Grains for "Crystal" P with Respect to the Original Crystal Orientation in (001) Standard Projection. Average position of each group of poles is indicated as "X".

25,310

Figure 16: Grouping of Principal Poles of Recrystallized Grains for "Crystal" S with Respect to the Original Crystal Orientation in (001) Standard Projection. Average position of each group of poles is indicated as "X".

25,311

Figure 17: Grouping of Principal Poles of Recrystallized Grains for "Crystal" V with Respect to the Original Crystal Orientation in (001) Standard Projection. Average position of each group of poles is indicated as "X".

25,312

Figure 18: Graphical Representation of Orientation Relationship Between Deformed Material and Recrystallized Grains. Deformed orientation is in (001) standard projection and recrystallized grain principal pole locations are represented as circles.

25,313

Figure 19: Growth and Absorption of $\sim\{172\}$
Twins in Deformed and Annealed
"Crystal" J.

17,748

P.L.

250X

Figure 20: Preferential Growth of Recrystallized Grains into $\{130\}$ Twins of Deformed "Crystal" A.

a.

13,422

P.L.

250X

b.

13,421

P.L.

250X

Figure 21: Successive Stages in the Growth of a Recrystallized Grain in the Kinked Area of Deformed "Crystal" G.

25,314

30X

Figure 22: Deformed Single Crystal and Recrystallized Grain Orientations Reported by Calais, Mandin and Lacombe⁽²⁴⁾.

- a. Stereographic projection representing the orientation of eight reasonably identical grains (in dashed lines) and that of the polygonized matrix (in full lines). XX' is the tension axis.
- b. Stereographic projection showing the orientation of the crystal before pulling (C), of the polygonized matrix (M) after annealing and of three recrystallized grains (1,2,3). XX' is the tension axis.

Figure 23: Grouping of Principal Poles of Recrystallized Grains for Data of Calais, Mandin and Lacombe (Figure 22b) with Respect to the Polygonized Matrix in (001) Standard Projection. Grains 2 and 3 were assumed to originate from (130) twins. Deformed single crystal orientation is related to the average principal pole positions (X) by a counterclockwise rotation of 24° about an axis located 82.5° from the $[100]$, 67.0° from the $[010]$ and 24.0° from the $[001]$.

25,391

Figure 24: Ideal Deformation and Recrystallization Textures of Alpha-Uranium Sheet⁽²⁰⁾. Circular points represent reported texture components; X's represent recrystallization texture components constructed from ideal deformation texture components.

25,364