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DEVELOPMENT OF TEXTURE IN COPPER BY COLD-ROLLING

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ABSTRACT

The structural changes occurring in one polycrystalline and in five monocrystalline specimens as they were cold-rolled from 1- to 0.005-inch thickness were studied largely by X-ray diffraction methods. A pole-figure of the polycrystalline specimen after 99.5-percent reduction indicated twin $110-1\bar{1}2$ and twin $112-\bar{1}\bar{1}1$ orientations as the preferred orientations of severely cold-rolled copper. The macrostructure of cross sections of monocrystalline specimens, after increasing reductions, showed that in some specimens two or three distinct layers were developed whose boundaries were approximately parallel to the rolling plane. Changes in orientation showed that the lattices of adjacent layers of a monocrystalline specimen rotated in opposite directions around axes nearly parallel to the transverse direction to positions approximating two of five intermediate orientations. Orientations present after 99.5-percent reduction indicated that the five intermediate orientations were in the process of being changed to twin $110-1\bar{1}2$ or twin $112-\bar{1}\bar{1}1$ orientations.

CONTENTS

I. INTRODUCTION

Metallographic examination of polycrystalline copper that has been cold-rolled shows that, in general, the grains are elongated in the rolling direction, shortened in the normal direction, and almost unchanged in the transverse direction. Thus, the shape of a grain is oriented in respect to the principal directions of the strip. X-ray diffraction patterns of sections of rolled copper strip indicate that simultaneously with the change in shape of the grains there is a rotation of the crystal lattices so that they approach or attain preferred orientations in respect to the principal directions of the strip. This oriented structure of the shape of grains and crystal lattices is called texture.

The preferred orientations are determined from stereographic diagrams called pole-figures, which show the prevailing arrangement of normals to a particular family of crystallographic planes, such as the cubic or octahedral planes. Schmid and Staffelbach [1] [1] concluded from pole-figures of normals to the cubic and octahedral planes that there is only one preferred orientation in severely cold-rolled copper, this condition being defined when the [110] axis is parallel to the normal direction and the [1$\bar{1}$2] axis is parallel to the rolling direction. [2] A twin to this orientation, however, is indicated by the pole-figures of Schmid and Staffelbach. They undoubtedly considered the twin orientation in making their conclusion. It appears then that cold-rolling causes the lattice to rotate toward one of two preferred orientations having a twin relationship.

The texture of severely cold-rolled copper is similar to the texture of other face-centered cubic metals and alloys, such as aluminum, nickel and alpha brass. This similarity of textures has led to the belief that during cold-rolling the lattices of all face-centered cubic metals approach the same preferred orientations. Investigations [2, 3, 4] contributing information on the development of textures have indicated that preferred orientations not included in the texture of all face-centered cubic metals are sometimes attained. The purpose of the present investigation was to determine whether or not these orientations can be considered as transient or intermediate in the development of a severely cold-rolled texture in copper. This was done by cold-rolling relatively large monocrystalline specimens of copper and determining the structure after different degrees of cold work with the usual metallographic and X-ray methods.

II. PROCEDURES

1. PREPARATION, COLD-ROLLING, AND METALLOGRAPHIC EXAMINATION OF MONOCRYSTALLINE SPECIMENS

A charge of 4½ to 5 lb of tough-pitch electrolytic copper was melted in a graphite crucible to produce an ingot 1⅜ in. in diameter and 6 in. in length with the lower end tapered to a point. The melting was done in an Arsem vacuum furnace and the molten metal allowed to freeze slowly. This procedure [5] results in a monocrystalline ingot when the crucible is placed in the furnace so that the freezing begins at the pointed end and proceeds toward the top end. Ten monocrystalline ingots were made, and a typical monocrystalline ingot is shown in figure 1 (*A*).

The initial orientation of each of the 10 monocrystalline ingots was determined, using Greninger's back-reflection method [6], and, on the basis of these results, five different orientations were selected. A specimen was prepared from each of the five monocrystalline ingots by machining off its sides so as to produce two parallel surfaces, 1 in. apart, as is shown in figure 1 (*B*). The orientation of each of the five

[1] Figures in brackets indicate the literature references at the end of this paper.
[2] Throughout this paper, orientations in respect to the rolling plane and direction are defined by stating first the crystallographic axis which is parallel to the normal direction and then the crystallographic axis which is parallel to the rolling direction; thus the above orientation would be written as 110–1$\bar{1}$2.

monocrystalline specimens was determined accurately, and these orientations are shown on a stereographic diagram, figure 2, by the locations of the principal directions of each specimen in respect to the octahedral, dodecahedral, cubic, and icositetrahedral axes of a cubic crystal. The angular values for the initial orientations with respect to the [010] axis and (010) plane are given in table 1. The principal directions, X, Y, and Z, of the monocrystalline specimen coincide with the normal, rolling, and transverse directions, respectively, of the same after rolling—all rolling being done in one direction.

The monocrystalline specimens were cold-rolled to a final thickness of 0.005 in., care being taken always to keep the same side up and to

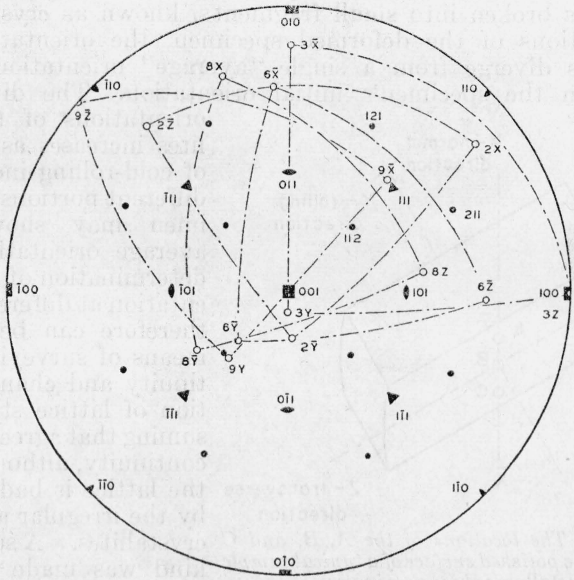

FIGURE 2.—*Stereographic diagram showing locations of principal directions of monocrystalline specimens in respect to crystallographic axes.*

enter the same end between the rolls during the entire reduction. The rolling was accomplished with a 16-in. diameter, two-high rolling mill operating at a speed of 50 to 80 rpm. This corresponds to a linear rolling speed of 3.5 to 5.6 fps. The reduction in thickness during each pass was from 0.03 to 0.05 in. Samples were cut from the end, first to enter the rolls, after each reduction of 0.15 in. until the thickness was 0.10 in. The specimens, after reduction to 0.10-in. thickness, were cold-rolled to thickness of 0.005 in. with a 5-in. diameter, two-high rolling mill operating at a speed of 50 rpm, corresponding to a linear travel of 1.1 fps. Similar samples of the strip of this thickness were cut from the end first to enter the rolls.

Metallographic examinations were made of polished and etched surfaces to show the structure of cross sections of the specimens at ¼ in. or more from the end first to enter the rolls. Samples representing 15-, 30-, and 45-percent reduction in thickness were photographed at a magnification of approximately 1½ diameters under oblique lighting. The source of light was an open window, the sample

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being tilted at the angle that revealed the structure best. These photographs are shown in figures 3, 4, and 5. They are arranged in order of increasing reduction, and the upper edge in each case corresponds to the top rolling plane.

2. DETERMINATIONS OF AVERAGE ORIENTATIONS AFTER REDUCTIONS OF 90 PERCENT AND LESS

Diffraction patterns of a monocrystalline specimen after different degrees of cold-rolling show a gradual transition from a Laue pattern to a pattern consisting of arcs, characteristic of a severely cold-rolled polycrystalline specimen. The patterns indicate that the original crystal has broken into small fragments, known as crystallites. In small portions of the deformed specimen, the orientations of the crystallites diverge from a single "average" orientation that may differ from the specimen's initial orientation. The divergence in orientations of the crystallites increases as the degree of cold-rolling increases, and different portions of the specimen may show different average orientations. The determination of average orientation at different locations therefore can be used as a means of surveying the continuity and changes in position of lattice structure, assuming that agreement means continuity, although actually the lattice is badly distorted by the irregular alinement of crystallites. A survey of this kind was made of the five monocrystalline specimens of copper after 15-, 30-, 45-, and 90-percent reductions.

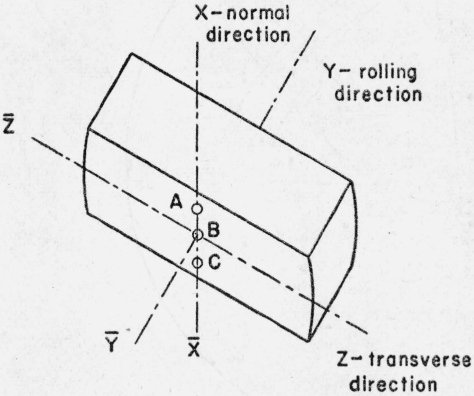

FIGURE 6.—*The locations of the A, B, and C areas on the polished surface of a typical sample used for metallographic examination.*

The method of surveying the cold-rolled specimens after reductions of 45 percent or less was as follows: in the section $XX'-ZZ'$, back-reflection X-ray patterns were made using molybdenum radiation of three locations, A, B, and C, in the line $X-X'$, as shown in figure 6. The average orientations indicated by these patterns, as well as the orientations of the undeformed specimens, then were plotted, by the location of octahedral poles, on stereographic diagrams, figures 7 and 8, using the $XX'-ZZ'$ planes as projection planes. Thus the position of the lattice at the C location, on specimen 3, after 30-percent reduction is designated as the "3–30C position." The procedure used for determining the average orientations has been described and photographs of similar patterns have been shown in a previous publication [7].

The method, described above, of surveying the continuity of lattice structure was modified slightly so as to apply to specimens after 90-percent reduction. After 90-percent reduction, average orientations could be determined better from diffraction patterns of small

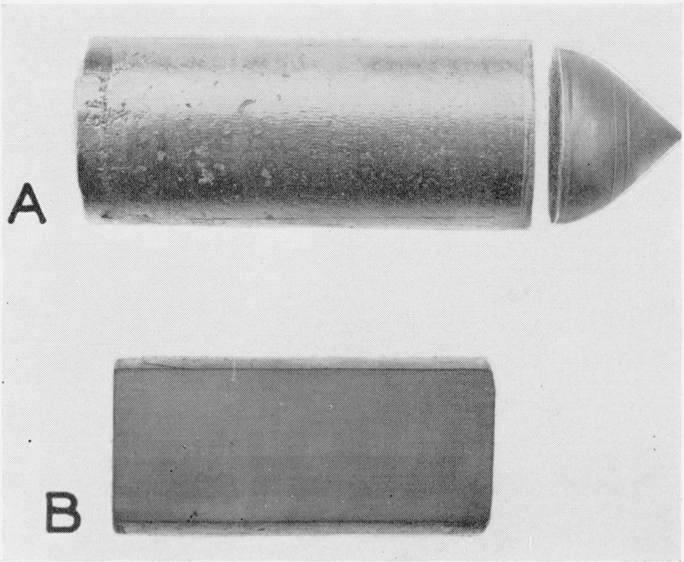

FIGURE 1.—*Monocrystalline copper.*

A, ingot, one-half actual size; surface view, with tapered end separated from body of ingot. *B*, specimen, one-half actual size; top view, showing machined surface.

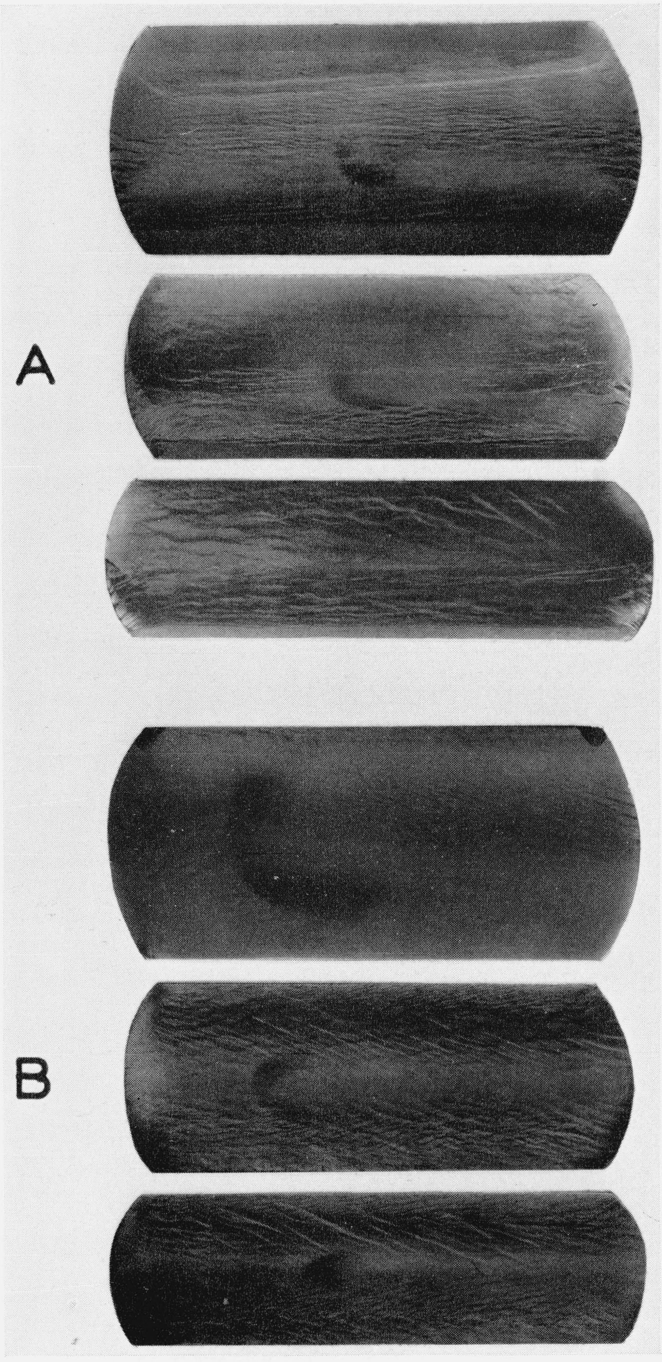

FIGURE 3.—*Macrostructure of monocrystalline copper after 15-, 30-, and 45-percent reduction by cold-rolling.*

Approximately ×1½. Cross sections: *A*, specimen 9; *B*, specimen 2. Etched with 10-percent ammonium persulfate.

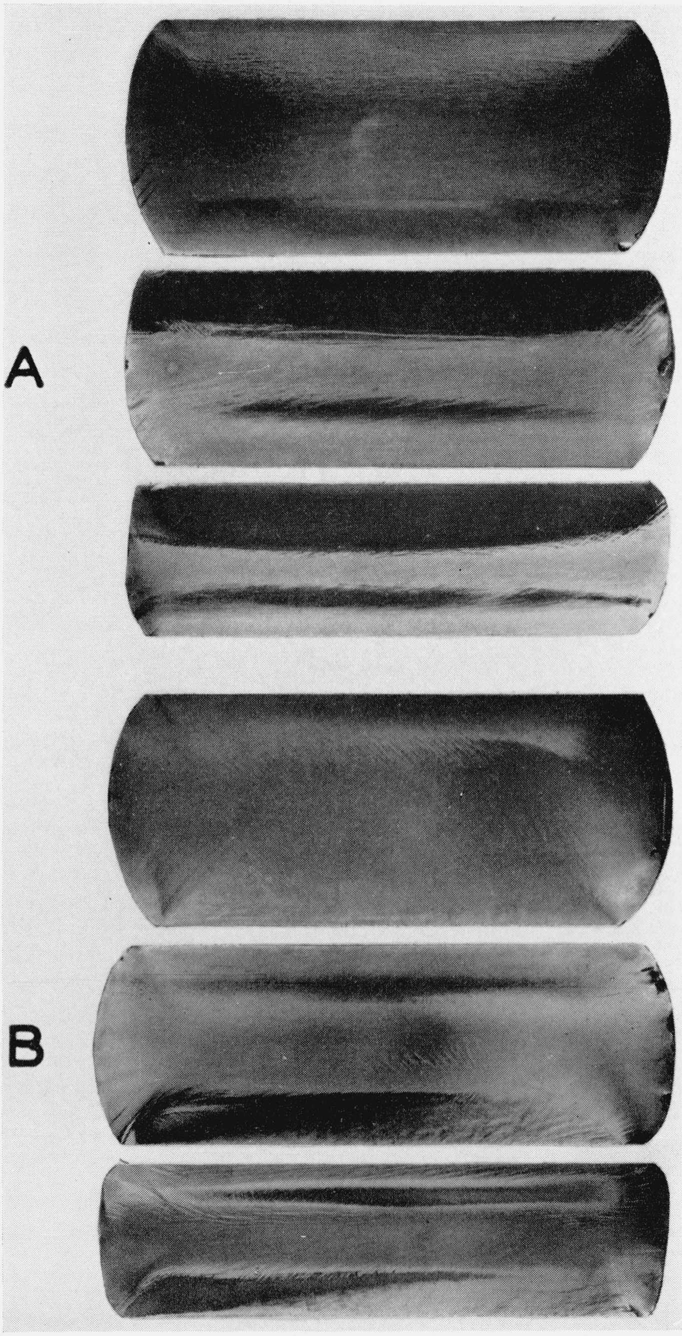

FIGURE 5.—*Macrostructure of monocrystalline copper after 15-, 30-, and 45-percent reductions.*

Approximately ×1½. Cross sections: *A*, specimen 8; *B*, specimen 6. Etched with 10-percent ammonium persulfate.

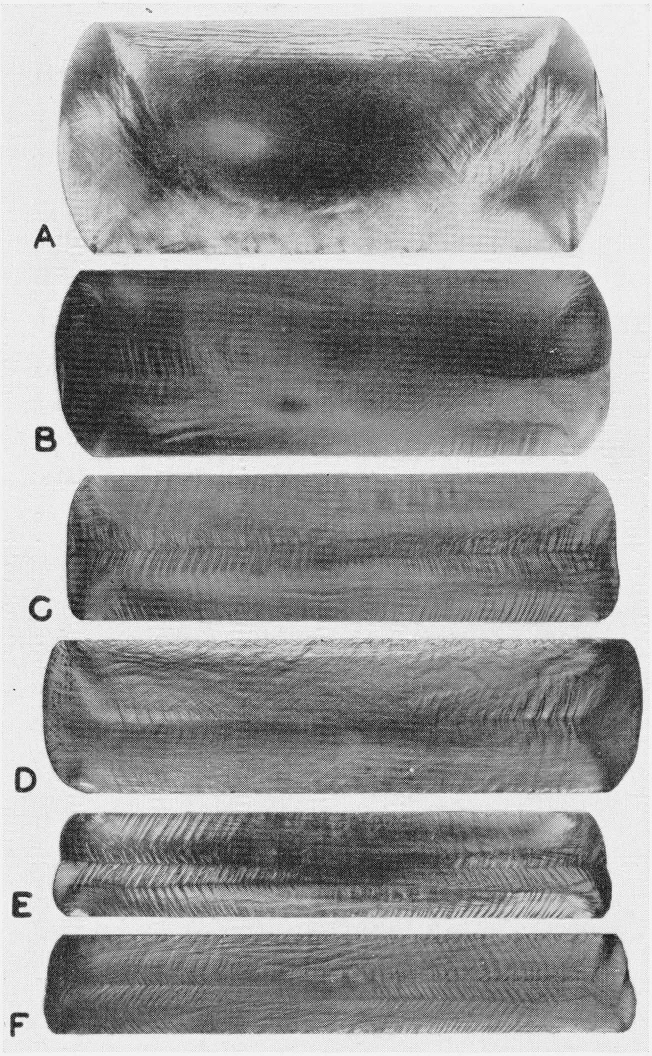

FIGURE 4.—*Macrostructure and end of monocrystalline copper, specimen 3.*

Approximately ×1½. *A*, *B*, *C*, and *E*, cross sections after 15-, 30-, 45-, and 60-percent reductions, respectively. Etched with 10-percent ammonium persulfate. *D* and *F*, photographs of the end first to enter the rolls, after 45 and 64 percent, respectively.

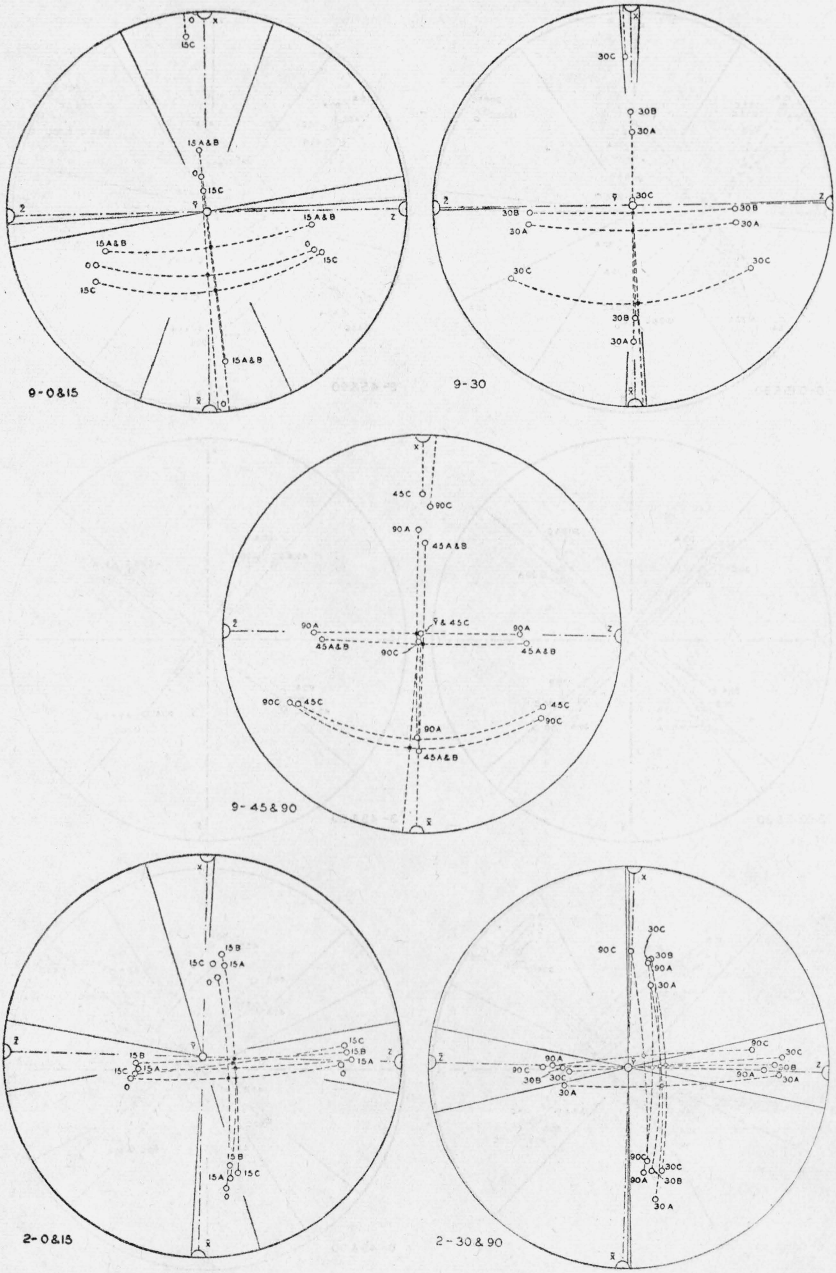

FIGURE 7.—*Stereographic diagrams showing initial orientations and positions of the lattice after 15-, 30-, 45-, and 90-percent reductions of specimens 9 and 2.*

areas located on the top and bottom rolling planes rather than on the line $X—X'$, as shown in figure 6. The locations on the top and bottom rolling planes are referred to as A and C, respectively, because of their

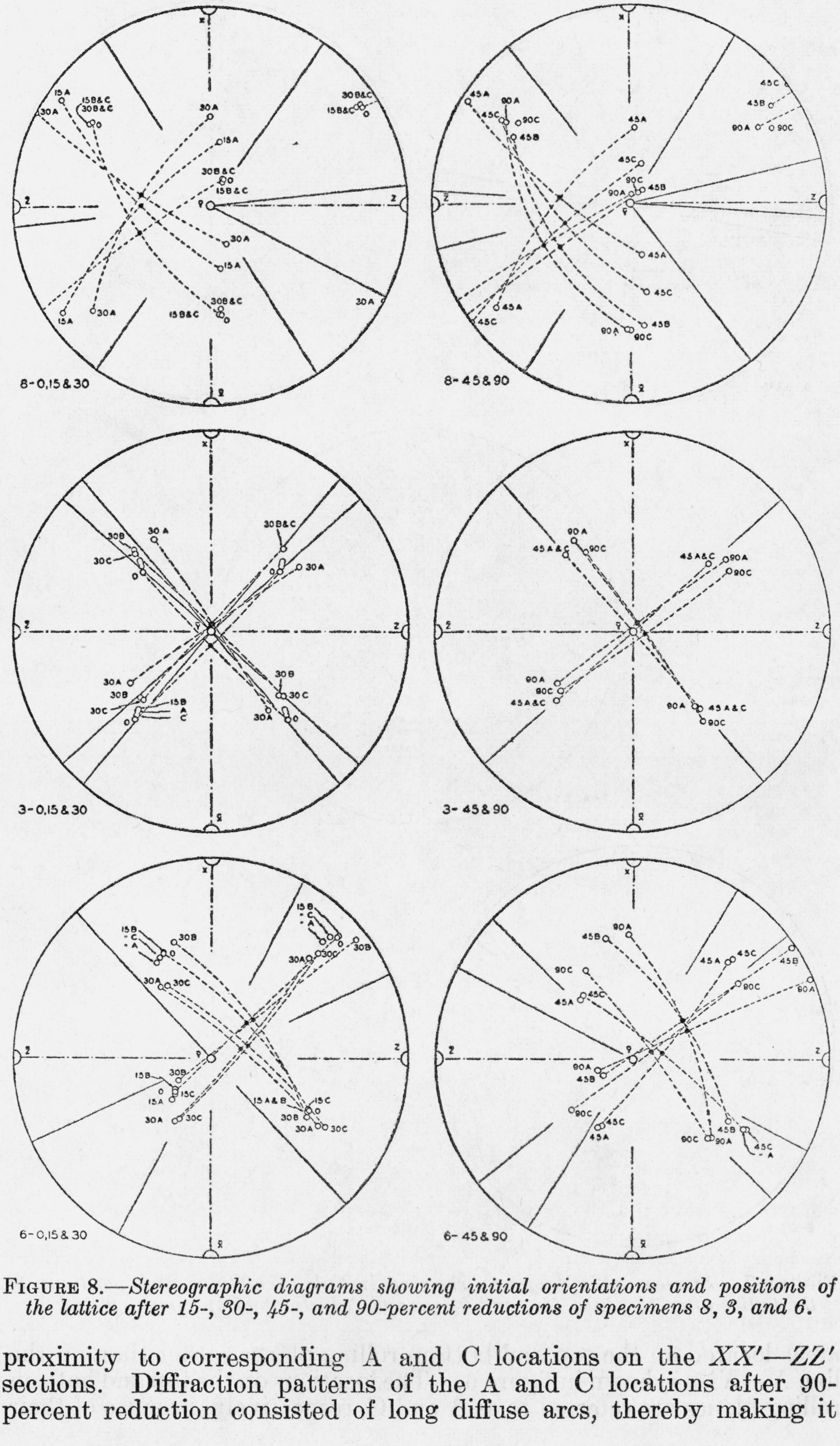

FIGURE 8.—*Stereographic diagrams showing initial orientations and positions of the lattice after 15-, 30-, 45-, and 90-percent reductions of specimens 8, 3, and 6.*

proximity to corresponding A and C locations on the XX'—ZZ' sections. Diffraction patterns of the A and C locations after 90-percent reduction consisted of long diffuse arcs, thereby making it

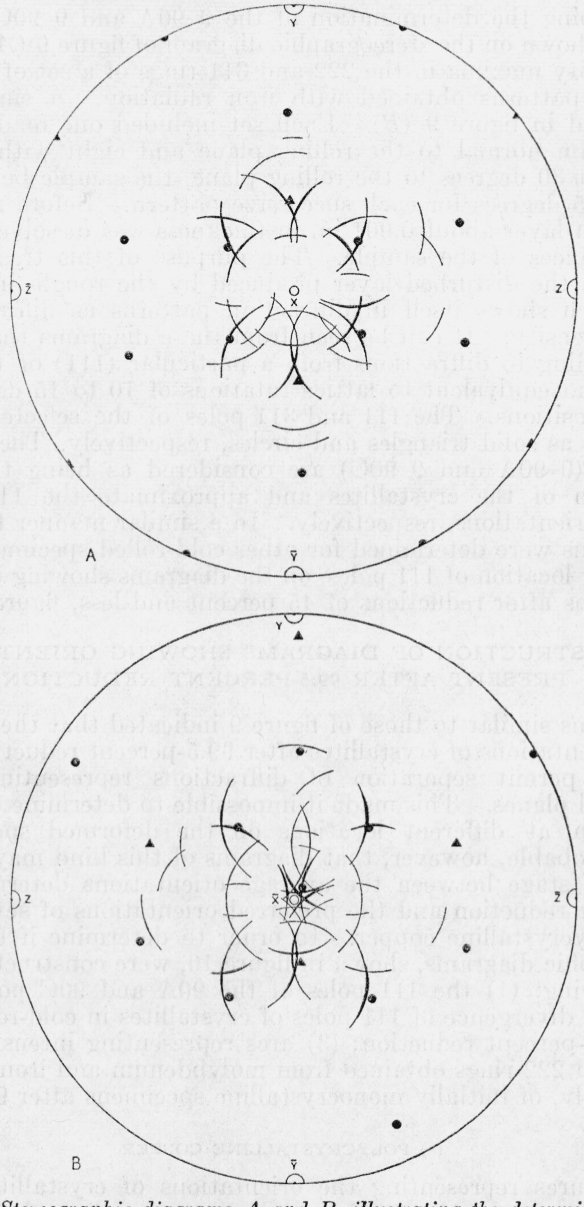

FIGURE 9.—*Stereographic diagrams A and B, illustrating the determination of the 9–90A and 9–90C positions, respectively.*

The arcs of large and small circles represent the arcs of intensity maxima in the 311 and 222 rings, respectively, from iron radiation. The solid circles and triangles are 311 and 111 poles, respectively.

impossible to determine the average orientation from a single pattern as was done for reductions of 45 percent and less.

The procedure used for determining the average orientations at different locations on specimens after 90-percent reduction is given by describing the determination of the 9–90A and 9–90C positions. The arcs shown on the stereographic diagram of figure 9 (*A*) represent the intensity maxima in the 222 and 311 rings of a set of nine back-reflection patterns obtained with iron radiation. A similar set is represented in figure 9 (*B*). Each set included one made with the X-ray beam normal to the rolling plane and eight with the beam inclined at 30 degrees to the rolling plane, the sample being rotated through 45 degrees for each successive pattern. Before making the patterns, a layer about 0.001 in. in thickness was dissolved from the rolled surfaces of the sample. The purpose of this treatment was to remove the disturbed layer produced by the rough finish on the rolls, which shows itself in diffraction patterns as diffuse rings of uniform density. It can be seen from these diagrams that the area corresponding to diffractions from a particular (111) or (311) plane is large and equivalent to lattice rotations of 10 to 15 degrees from selected positions. The 111 and 311 poles of the selected positions are shown as solid triangles and circles, respectively. These selected positions (9–90A and 9–90C) are considered as being the average orientation of the crystallites and approximate the 110–001 and 112–$\bar{1}\bar{1}$1 orientations, respectively. In a similar manner the average orientations were determined for other cold-rolled specimens and are plotted by location of 111 poles, on the diagrams showing the average orientations after reductions of 45 percent and less, figures 7 and 8.

3. CONSTRUCTION OF DIAGRAMS SHOWING ORIENTATIONS PRESENT AFTER 99.5-PERCENT REDUCTION

Diagrams similar to those of figure 9 indicated that the divergence of the orientations of crystallites after 99.5-percent reduction was too great to permit separation of diffractions representing different octahedral planes. This made it impossible to determine the average orientation at different locations on the deformed specimen. It is very probable, however, that diagrams of this kind may indicate a transitory stage between the average orientations determined after 90-percent reduction and the preferred orientations of severely cold-rolled polycrystalline copper. In order to determine if this is true, stereographic diagrams, shown in figure 10, were constructed to show the following: (1) the 111 poles of the 90A and 90C positions; (2) maximum divergence of 111 poles of crystallites in cold-rolled copper after 99.5-percent reduction; (3) arcs representing intensity maxima in 111 and 222 rings obtained from molybdenum and iron radiations, respectively, of initially monocrystalline specimens after 99.5-percent reduction.

(a) POLYCRYSTALLINE COPPER

Pole-figures representing the orientations of crystallites in polycrystalline metals after different degrees of rolling show that the divergence of orientations is less when the degree of rolling is more. A pole-figure of polycrystalline copper that had been subjected to the same degree of cold-rolling as the initially monocrystalline specimens therefore is necessary in order that the maximum divergence of 111 poles of crystallites may be located accurately on the diagrams shown in figure 10.

A piece of oxygen-free hot-rolled copper,[3] 1 by 4 by 8 in., served as a

[3] The oxygen free copper was "Oxygen-Free-High-Conductivity" copper obtained from Revere Copper & Brass, Inc.

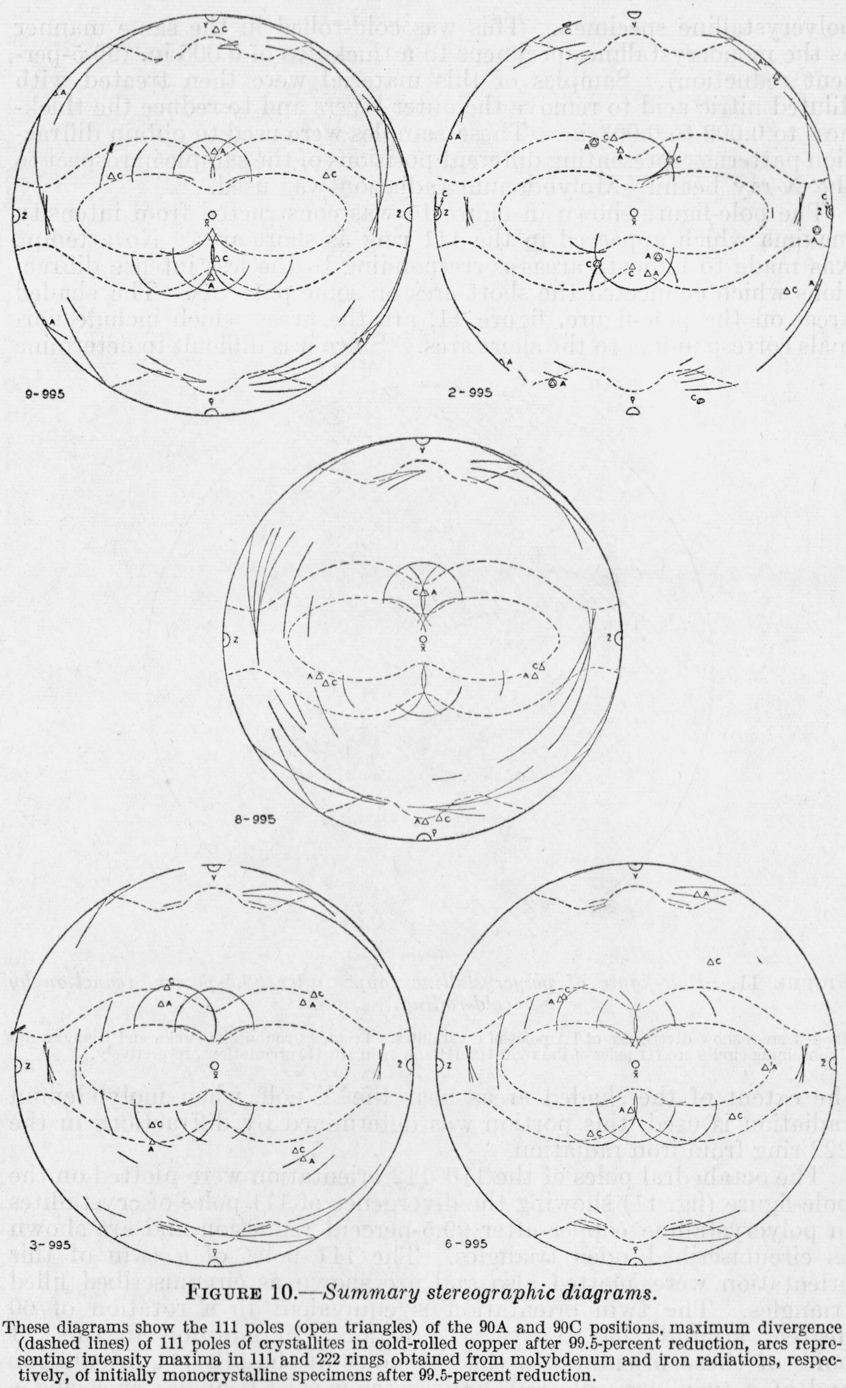

FIGURE 10.—*Summary stereographic diagrams.*

These diagrams show the 111 poles (open triangles) of the 90A and 90C positions, maximum divergence (dashed lines) of 111 poles of crystallites in cold-rolled copper after 99.5-percent reduction, arcs representing intensity maxima in 111 and 222 rings obtained from molybdenum and iron radiations, respectively, of initially monocrystalline specimens after 99.5-percent reduction.

polycrystalline specimen. This was cold-rolled in the same manner as the monocrystalline specimens to a thickness of 0.005 in. (99.5-percent reduction). Samples of this material were then treated with diluted nitric acid to remove the outer layers and to reduce the thickness to 0.002 to 0.003 in. These samples were used to obtain diffraction patterns representing different positions of the sample in respect to the X-ray beam. Molybdenum radiation was used.

The pole-figure shown in figure 11 was constructed from intensity maxima which appeared in the 111 ring as short arcs. No attempt was made to indicate areas corresponding to the less intense diffractions which connected the short arcs on some patterns. The shaded areas on the pole-figure, figure 11, are the areas which include normals corresponding to the short arcs. Since it is difficult to determine

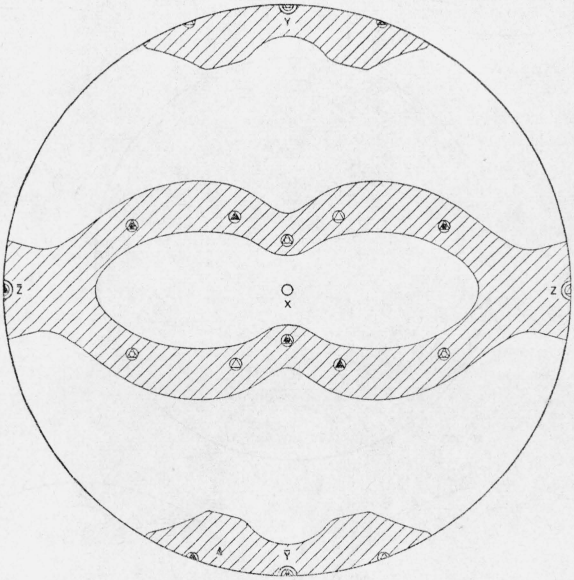

FIGURE 11.—*Pole-figure of polycrystalline copper after 99.5-percent reduction by cold-rolling.*

Shaded areas show divergence of 111 poles of crystallites. Triangles containing circles and triangles not containing circles are 111 poles of the twin 112–$\bar{1}\bar{1}$1 and twin 110–1$\bar{1}$2 orientations, respectively.

the extent of the shaded areas near the *X* pole when molybdenum radiation is used, this portion was determined by diffractions in the 222 ring from iron radiation.

The octahedral poles of the 110–1$\bar{1}$2 orientation were plotted on the pole-figure (fig. 11) showing the divergence of 111 poles of crystallites in polycrystalline copper after 99.5-percent reduction and are shown as circumscribed open triangles. The 111 poles of a twin of this orientation were plotted also and are shown as circumscribed filled triangles. The twin orientation is equivalent to a rotation of 60 degrees around the transverse direction. In addition to the 111 poles of these orientations, the 111 poles of the 112–$\bar{1}\bar{1}$1 orientation and of a twin were plotted, and are shown as triangles enclosing a circle. The twin orientation is equivalent to a rotation of 60 degrees around the rolling direction. From the evidence summarized in this diagram, it was concluded that the preferred orientations of severely cold-rolled polycrystalline copper are twin 110–$1\bar{1}2$ and twin 112–$\bar{1}\bar{1}1$ orientations.

(b) MONOCRYSTALLINE COPPER

Transmission and back-reflection diffraction patterns from molybdenum and iron radiation, respectively, were obtained from small areas on samples of the initially monocrystalline specimens. The samples were initially etched slightly with diluted nitric acid to remove the surface layers, whose structure is not always representative of the rolling process. Each pattern represented a different position of the sample in respect to the X-ray beam. Arcs representing intensity maxima in the 111 ring from molybdenum radiation and in the 222 ring from iron radiation are shown in the stereographic diagrams of figure 10. The back-reflection patterns from iron radiation are caused by crystallites near the surface, whereas the transmission patterns from molybdenum radiation are caused by crystallites making up the body of the sample. Therefore, the patterns from iron radiation indicate changes in the 90A or 90C positions and the patterns from molybdenum radiation indicate changes in the 90A and 90C positions. The triangles in the diagrams of figure 10 are 111 poles corresponding to the 90A and 90C positions, and the dashed lines correspond to the shaded areas in figure 11.

III. RESULTS

Specimen 9.—The initial orientation of this specimen was such that the angle between an octahedral plane and the rolling plane was about 3 degrees and between an octahedral axis and the rolling direction about 20 degrees.

The macrostructure of cross sections of specimen 9, figure 3 (*A*), shows that rolling caused bands to develop within the metal. These bands were easily identified and occupied nearly the same relative cross-sectional areas after 60- and 75-percent reduction. After 90-percent reduction, the macrostructure was similar to that after smaller reductions, but the bands could not be identified with certainty. Therefore it can be concluded that these bands represent layers with the boundary between them nearly parallel to the rolling plane, during moderate reductions (75 percent).

After 15-percent reduction (9–15A and 9–15B positions, fig. 7) the lattice of the upper layer had rotated anticlockwise[4] about 15 degrees around an axis approximately parallel to the transverse direction, whereas the lattice of the bottom layer (9–15C position) had rotated clockwise about 8 degrees around the same axis. It is evident, therefore, that the initial 15-percent reduction by cold-working caused specimen 9 to divide into two layers differing in orientation by a rotation of 23 degrees about an axis approximately parallel to the transverse direction.

Further reductions, 30, 45, and 90 percent, by cold-rolling continued the rotation of the lattice of the upper layer until the cubic axis, whose locations are shown in figure 7 as filled circles, was approximately parallel to the rolling direction. Likewise, the lattice of the bottom layer continued to rotate until an octahedral axis was approximately

[4] The position of an axis of rotation for a clockwise (positive) rotation and anticlockwise (negative) rotation is with the negative pole toward the eye of the observer.

parallel to the rolling direction. Therefore, after 90-percent reduction by cold rolling, specimen 9 consisted of two layers, the orientation of one of which corresponded closely to the 110–001 orientation and of the other to the 112–$\bar{1}\bar{1}1$ orientation.

Orientations of the crystallites, as indicated by diffractions from octahedral planes (diagram 9–995, fig. 10), in specimen 9 after 99.5-percent reduction included the twin 110–$1\bar{1}2$ orientations as well as those represented by the 9–90A and 9–90C positions. The long arcs near the circumference of the diagram indicated intermediate orientations. It appears, therefore, that further cold-rolling after 90-percent reduction caused specimen 9 to attain orientations similar to those present in severely cold-rolled polycrystalline copper. If rolling could be continued indefinitely, all orientations not included in the cold-rolled texture would presumably disappear.

Specimen 2.—The initial orientation of this specimen was such that the angle between a cubic plane and the rolling plane was about 40 degrees and between a cubic axis and the rolling direction about 20 degrees.

The macrostructure of specimen 2 after 15-, 30-, and 45-percent reductions, figure 3 (*B*), was similar to the top layer of specimen 9 after corresponding reductions. The initial orientation of specimen 2, figure 2, corresponded approximately to the 110–001 orientation. This orientation has a $\bar{1}10$ axis parallel to the $\bar{Z}$ direction. It is noteworthy that the traces of two octahedral planes which make acute angles with the transverse direction (Z–$\bar{Z}$) correspond approximately to the slopes of the wavy lines seen in the macrostructure of specimen 2 and in the top layer of specimen 9.

Cold-rolling, producing an initial reduction of 15 percent (2–15A, 2–15B, and 2–15C positions, fig. 7), caused the lattice of the specimen as a whole to rotate around an axis nearly parallel to the transverse direction. After 30-percent reduction the condition was approximately the same as in the top layer of specimen 9. An increase in reduction to 90 percent caused little change from the lattice positions after 30-percent reduction. During the 90-percent reduction the changes in the position of the lattice did not proceed along great circles to a closer approximation of the 110-001 orientation as expected. The changes brought the lattice to a closer approximation of the 110–001 orientation only insofar as it could be accomplished by a rotation about an axis approximately parallel to the transverse direction.

Diffraction data representing the metal after 99.5-percent reduction, obtained from small areas in the top and bottom rolling planes, respectively, could be represented by two average orientations in the top plane and by one in the bottom plane, the latter one being the same as one of the average orientations in the top plane. An inspection of the summarizing diagram (diagram 2–995, fig. 10) shows that the 111 poles of these orientations (circumscribed triangles) nearly correspond to the twin 110–$1\bar{1}2$ orientations. The diagram as a whole indicates that further cold-rolling after 90-percent reduction caused the lattice of certain layers (2–90A position) to rotate anticlockwise while the lattice of other layers (2–90C position) rotated clockwise around axes nearly parallel to the normal direction. It is important to note that no orientations corresponding to the twin 112–$\bar{1}\bar{1}1$ orientations were present. This has been interpreted as indicating that further cold-rolling after the 110-001 orientation has been approximated will not produce the complete cold-rolled texture of polycrystalline copper.

Specimen 8.—The initial orientation of this specimen was such that the angle between a cubic plane and the rolling plane was about 22 degrees and between an octahedral axis and the rolling direction about 15 degrees.

Cross sections of specimen 8, figure 5 (*A*), after 30-percent reduction showed bands in the macrostructure approximately parallel to the rolling plane. Their boundaries, however, were too irregular to suggest traces of crystallographic planes. As in specimen 9, these bands could be identified after larger reductions and therefore can be considered as cross sections of layers whose boundaries were approximately parallel to the rolling plane.

During the initial 15-percent reduction (8–15A position, fig. 8) the lattice of the top layer of specimen 8 rotated anticlockwise about 20 degrees around an axis nearly parallel to the transverse direction. This position corresponds approximately to the 100–011 orientation. The lattices of the central and bottom layers (8–15B and 8–15C positions) did not change their positions. Additional cold-rolling to 30-percent reduction caused the lattice of the top layer to rotate about 12 degrees more, but after 45-percent reduction, it has apparently rotated back about 7 degrees. The 8–30B and 8–30C positions were nearly the same as the 8–15B and 8–15C positions. These lattice positions represent the white areas shown in the macrostructure, figure 5 (*A*), which are considered as constituting the bottom layer. The dark area within the white area had approximately the same lattice position as the top layer. Cold-rolling to 45-percent reduction caused the lattice of the portion of the bottom layer represented by the 8–45B position to rotate clockwise about 5 degrees around an axis nearly parallel to the transverse direction (fig. 8), whereas the lattice of the portion represented by the 8–45C position rotated anticlockwise about 7 degrees. It cannot be stated with certainty, however, that the 8–45C position represents the bottom layer. Probably it represents the dark area within the bottom layer and thus indicates a possible lattice position of the top layer. The 8–90A and 8–90C positions (fig. 8) approximate the 112–$\bar{1}\bar{1}$1 orientation and are nearly twins of the 9–30C position, figure 7. It appears that cold-rolling to a reduction of 90 percent caused specimen 8 to develop layers having different lattice rotations. The lattice of the top layer rotated to a position approximating the 100–011 orientation, then rotated in the opposite direction along with the lattice of the bottom layer, each to a position approximating the 112–$\bar{1}\bar{1}$1 orientation.

Orientations of crystallites in specimen 8 after 99.5-percent reduction indicated (diagram 8–995, fig. 10) that orientations represented by the 8–90A and 8–90C positions persisted, but during the reduction from 90 to 99.5 percent some of the crystallites attained orientations characteristic of severely cold-rolled polycrystalline copper.

Specimen 3.—The initial orientation of this specimen was such that the angle between a cubic plane and the rolling plane was about 9 degrees and between a cubic axis and the rolling direction about 9 degrees.

Cross sections of specimen 3 (fig. 4) showed in the macrostructure a "herringbone" condition, largely confined to the sides, one side of the cross section being nearly a mirror image of the other side. The herringbone structure when fully developed (micrograph *E*) consisted of parallel bands projecting from the top and bottom rolling planes toward intermediate layers and from these toward the top and bottom rolling planes, respectively. In the fully developed stage the bands projecting from the top and bottom rolling planes met the bands projecting from the intermediate layer and the parallel bands made an angle of approximately 60 degrees with the rolling plane. The herringbone structure was very evident after 75- and 90-percent reductions. It appears that the herringbone structure represents sections of small parallel layers, whose sides increased progressively during reduction by rolling, from the top and bottom rolling planes and from the central layer of the specimen. Initially, the small parallel layers were nearly perpendicular to the rolling plane and parallel to the rolling direction, but in later stages they were inclined to the rolling plane but still parallel to the rolling direction.

The bands in the macrostructure had their counterpart in the wrinkled surface of the ends of the rolled specimens. Figure 4 (*D*) shows a wrinkled end of the specimen after 45-percent reduction. This is the reverse side of the sample whose macrostructure is shown by figure 4 (*C*), the two surfaces being approximately ½ inch apart. After 30-percent reduction the end was flat and perpendicular to the direction of rolling. Figure 4 (*F*) shows the end wrinkling that occurred between reductions of 60 and 64 percent. Examination of the wrinkled surface at higher magnification (fig. 12) after 45-percent reduction showed, near the lower ends of the ridges, slip lines in two directions; but on opposite slopes of the ridges the slip lines had only one direction. The two directions of the slip lines at the end of a ridge corresponded approximately to the directions on the two slopes of the ridge. These slip lines on the end surface of the specimen indicated that adjacent layers, shown as parallel bands in the macrostructure, and the portion near the sides which increased progressively during reduction by rolling, distorted by three different combinations of slip systems and therefore would approach three different orientations.

Specimen 3 initially approximated the 100–001 orientation, figure 2. Cold-rolling to a reduction of 90 percent produced little change in lattice position in the central portion of the specimen (fig. 8). The fine lines seen in the macrostructure were parallel to the traces of the octahedral planes, which indicated that they were formed as slip lines. After 99.5-percent reduction, orientations of crystallites (diagram 3–995, fig. 10) indicated that the twin 112–$\bar{1}\bar{1}$1, the twin 110–1$\bar{1}$2, and the 100–001 orientations were present. As in specimens 9, 2, and 8, the orientations present in the metal after rolling beyond 90-percent reduction proceeded to change to orientations identified with the texture of cold-rolled polycrystalline copper.

Specimen 6.—The initial orientation of this specimen was such that the angle between a cubic plane and the rolling plane was about 20 degrees and between a cubic axis and the rolling direction about 30 degrees.

The macrostructure of specimen 6, figure 5 (*B*), was unlike the structure of the preceding specimens. After 15-, 30-, and 45-percent

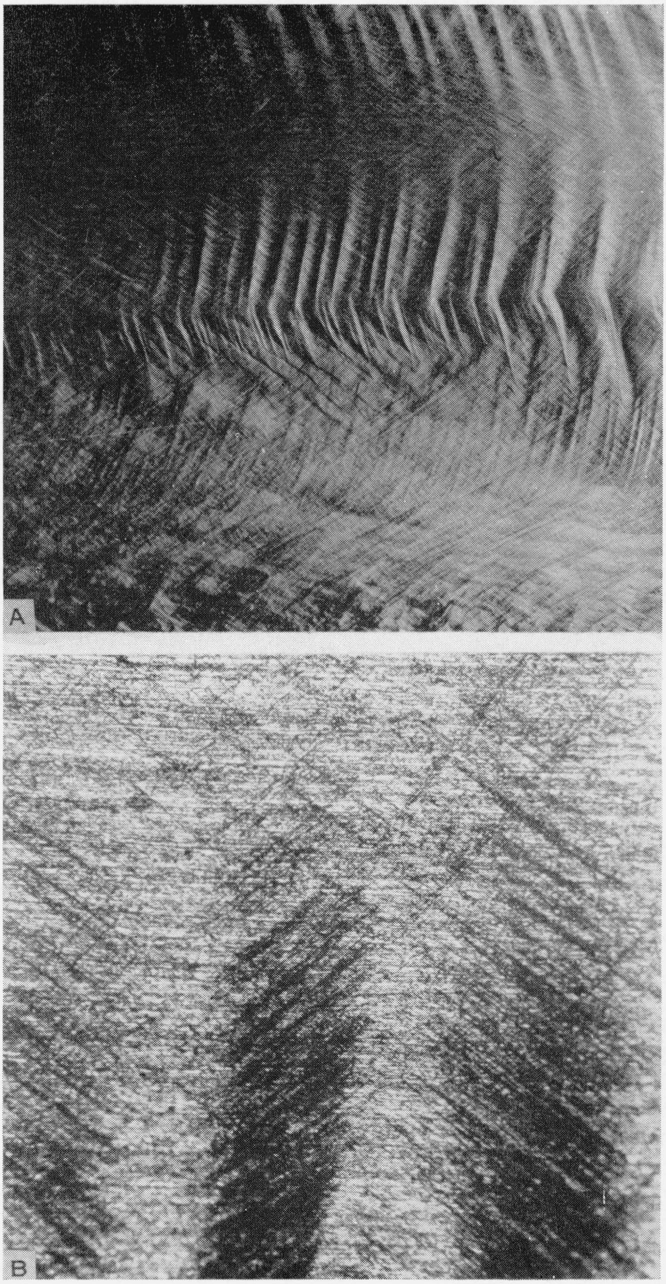

FIGURE 12.—*Appearance of the end first to enter the rolls, of specimen 3 after cold-rolling from 30- to 45-percent reduction.*

A, ×5; *B*, ×50.

reduction the specimen showed three bands in the structure, which persisted after larger reductions by cold-rolling. These bands were cross sections of layers approximately parallel to the rolling plane.

Cold-rolling to 15-percent reduction changes the initial orientation very little (fig. 8). However, further rolling to 30-percent reduction caused the lattice of the top and bottom layers (6–30A and 6–30C positions) to rotate clockwise about 15 degrees around an axis nearly parallel to the transverse direction. This rotation brought a cubic axis nearly into the rolling plane. The lattice of the center layer (6–30B position) rotated clockwise about 6 degrees around the octahedral axis in the lower right quadrant of the diagram. Further rolling to 45-percent reduction changed the top and bottom layers very little. However, the lattice of the center layer rotated 5 degrees more around the octahedral axis, which brought an octahedral axis nearly perpendicular to the rolling direction and an icositetrahedral axis [112] nearly parallel to the rolling direction. After 90-percent reduction the lattice of the bottom layer (6–90C position) approximated the 100–001 orientation. Inasmuch as changes in lattice position usually show a rotation to a preferred orientation, it is probable that the 6–90A position did not represent a lattice position of the top layer but one of the center layer and should be written as 6–90B. On this assumption, then, the lattice of the center layer after 90-percent reduction had rotated clockwise 11 degrees around an axis nearly parallel to the rolling direction. Continued rotation around the rolling direction to a position where the octahedral axis, which is nearly perpendicular to the rolling direction, became nearly parallel to the transverse direction, would approximate the 110–$1\bar{1}2$ orientation. The macrostructure and changes in lattice positions of specimen 6 indicate that cold-rolling to 90-percent reduction produced layers, in some of which the lattices rotated to a 100–001 orientation and in others to a 110–$1\bar{1}2$ orientation.

Orientations of crystallites in specimen 6 after 99.5-percent reduction by rolling (diagram 6–995, fig. 10) included the twin 110–$1\bar{1}2$ orientations. There appeared to be very few, if any, crystallites having the 100–001 orientation. A small number of crystallites having the twin 112–$\bar{1}\bar{1}1$ orientations was indicated by faint diffractions on the patterns obtained with molybdenum radiation. The diffraction patterns obtained after 99.5-percent reduction from specimen 8, as well as specimen 3, indicated that if the average orientation approximated the 100–001 orientation, additional rolling would cause a small number of crystallites to attain the twin 112–$\bar{1}\bar{1}1$ orientations and a much larger number to attain the twin 110–$1\bar{1}2$ orientations.

IV. DISCUSSION

1. BEHAVIOR OF MONOCRYSTALLINE SPECIMENS DURING COLD-ROLLING

It has been shown that the preferred orientations best representing the texture of cold-rolled polycrystalline copper after 99.5-percent reduction are the twin 110–$1\bar{1}2$ and twin 112–$\bar{1}\bar{1}1$ orientations. No attempt has been made to estimate the relative amounts of fragmented metal having the twin orientations. The presence of the twin 112–$\bar{1}\bar{1}1$ orientations is in disagreement with the conclusion of Schmid and

Staffelbach [1], who concluded that the texture of severely cold-rolled copper was represented only by twin $110\text{–}1\bar{1}2$ orientations. Their published pole-figures indicate the presence of small amounts of crystallites having the twin $112\text{–}\bar{1}\bar{1}1$ orientations. This is particularly true of their pole-figure of normals to octahedral planes, which definitely indicates that a large number of crystallites have octahedral axes nearly parallel to the rolling direction. Crystallites having the twin $112\text{–}\bar{1}\bar{1}1$ orientations have octahedral axes parallel to the rolling direction.

In initially monocrystalline specimens after 99.5-percent reduction, the relative number of crystallites having the twin $110\text{–}1\bar{1}2$ and twin $112\text{–}\bar{1}\bar{1}1$ orientations appeared to vary depending upon the initial orientation. The results indicated that a large number of crystallites had attained the twin $110\text{–}1\bar{1}2$ orientations in all specimens. No crystallites in specimen 2 had attained the twin $112\text{–}\bar{1}\bar{1}1$ orientations, a small number in specimens 6 and 3, and a slightly larger number in specimens 8 and 9. The results obtained after increasing degrees of cold-rolling indicated that these final orientations are attained in two stages, the first being usually complete after reduction of approximately 90 percent, and the second nearly complete after 99.5-percent reduction.

During the first stage, the lattices of adjacent layers tend to rotate in opposite directions around axes nearly parallel to the transverse direction. Sections of these layers were observed in specimens 9, 8, and 6. The lattice rotations around the transverse direction resulted in what might be termed intermediate orientations. The intermediate orientations approximated were 110–001, $112\text{–}\bar{1}\bar{1}1$, 100–011, 100–001.

The intermediate $110\text{–}1\bar{1}2$ orientation was not attained in the monocrystalline specimens described in this paper by a rotation about an axis nearly parallel to the transverse direction. However, it was attained in this manner by Pickus and Mathewson [7] under conditions of deformation simulating the rolling process. Their method consisted in compressing monocrystalline specimens of alpha brass between two parallel surfaces and restricting the flow to a direction perpendicular to the axis of compression.

The second stage, which occurs only during extremely severe deformation, consists in rotations of lattices from intermediate orientations to the final twin $110\text{–}1\bar{1}2$ and twin $112\text{–}\bar{1}\bar{1}1$ orientations. It was not possible to determine directly if a portion of the specimen which had attained an intermediate orientation developed new layers whose lattices had rotated to one of the two pairs of final orientations. This manner of attaining the final orientations, however, appears the most probable, as any alternative would necesssitate rotation by means other than those resulting from slip on crystallographic planes.

The results described in this paper show that during rolling the lattices of different layers of specimen 2 rotated in opposite directions around the normal direction, from a position approximating the 110–001 intermediate orientation to the twin $110\text{–}1\bar{1}2$ orientations. It appears then that the resistance to slip on the combination of slip systems necessary to maintain the 110–001 intermediate orientation had become sufficient to require other combinations of slip systems to operate. The new combinations were those which resulted in rotations around axes nearly parallel to the normal direction. The results also show that during the later stages of the rolling, most of the rotation of the lattice of the central layer in specimen 6 took place around an axis nearly parallel to the rolling direction. This has been interpreted as indicating that when certain initial orientations are unfavorable to rotations around an axis nearly parallel to the transverse direction, the distortion proceeds by combinations of slip systems which result in a rotation around an axis nearly parallel to the rolling direction. A possible conclusion from these results is that during cold-rolling the lattice in portions of a monocrystalline specimen always tends to rotate around the principal directions, that is, the transverse, normal, and rolling directions. The primary tendency, which usually occurs during the first stage, is rotation around an axis nearly parallel to the transverse direction. The secondary tendency, usually occurring in the second stage, is rotation around an axis nearly parallel to the normal direction or to the rolling direction.

On the basis of this conclusion, it is possible to designate those rotations which are necessary to convert the five intermediate orientations into the final twin 110–11̄2 and twin 112–1̄1̄1 orientations. These rotations are shown in table 1.

TABLE 1.—*Orientations produced in monocrystalline specimens of copper by cold-rolling*

[The angular values for the initial orientations were obtained from the stereographic diagram of figure 2 (*A*). The angle θ is the angle between the 010 pole and principal direction; the angle ϕ is the azimuth on the (010) plane measured from the 1̄00 pole. The intermediate and final orientations show the locations of normal and rolling directions, respectively, after cold-rolling when referred to the crystallographic poles on the diagram of figure 2.]

Specimen	Initial orientation of specimen with respect to the [010] axis and (010) plane (degrees)						Intermediate orientations approximated	Possible rotations around principal directions from intermediate orientations (degrees)			Final orientations
	X-X̄		Y-Ȳ		Z-Z̄			X	Y	Z	
	θ	ϕ	θ	ϕ	θ	ϕ					
9	42	134	116	65	49	0	110-001	±35	-----	-----	110-11̄2, 110-1̄12
							112-1̄1̄1	-----	60	-----	21̄1-1̄1̄1
								-----	-----	-----	112-1̄1̄1
2	52	167	109	92	44	23	110-001	±35	-----	-----	110-11̄2, 110-1̄12
8	22	44	112	53	84	141	010-1̄01	-----	-----	-----	
								-----	60	-----	112-1̄1̄1
								-----	-----	-----	1̄21-1̄1̄1
								-----	30	-----	
							1̄21-1̄1̄1	20	-----	-----	011-2̄11
								-----	−30	-----	
								−20	-----	-----	1̄10-1̄12
3	9	90	99	90	90	180	010-001	-----	45	-----	
								±35	-----	-----	110-11̄2, 110-1̄12
								45	-----	-----	
								-----	-----	±35	1̄21-1̄1̄1, 1̄2̄1-1̄11
6	19	76	110	70	92	160	1̄10-1̄12	-----	-----	60	1̄01-1̄2̄1
								-----	-----	-----	1̄10-1̄12
							010-001	−45	-----	-----	
								-----	-----	±35	1̄21-1̄1̄1, 1̄2̄1-1̄11

2. DEFORMATION BANDS

The bands observed in the macrostructure of cross sections of specimens 9, 8, and 6 after rolling are similar to the deformation bands frequently observed within crystals of polycrystalline metal after deformation. Adjacent bands observed in these specimens were shown to be layers whose lattices had rotated in different directions, and thus permitted the deformation of a single crystal to result in more than one orientation. The origin and behavior of deformation bands with respect to deformation of the parent crystal therefore become important in the study of the development of texture by cold-working.

The results obtained with specimens 9, 8, and 6 showed that the boundaries between bands were not initially straight and did not correspond to any particular plane. The lattices of layers corresponding to adjacent bands in these specimens rotated around an axis in the boundary plane. Recent researches by Barrett and Levenson have shown that the boundaries between deformation bands are straight in the early stages of deformation and correspond to traces of cubic or octahedral planes in iron crystals after deformation by drawing [9] and to traces of cubic planes in aluminum crystals after deformation by compression [10]. According to Barrett, the lattices of layers corresponding to adjacent deformation bands rotated around an axis perpendicular to the boundary plane. This was shown to be the case when a monocrystalline specimen of aluminum was deformed plastically by compression. It is reasonable to conclude that the position of the axes of rotation in layers shown as adjacent bands determines the kind of boundary between bands and that during deformation by drawing or compression, these axes tend to be perpendicular to the boundary plane, whereas in cold-rolling the axes of rotation tend to be in the boundary plane.

Deformation bands similar to those found in cross sections of specimen 3 have been observed by Samans [11] on a plane, parallel to the rolling plane, in his study on cold-rolling of a monocrystalline specimen of alpha brass. His specimen, as well as specimen 3 in this work, initially had 100–001 orientation. Samans showed that the orientations of adjacent bands differed by a rotation of 60 degrees around an octahedral axis and concluded that the bands had been produced by mechanical twinning. The results obtained with specimen 3 in this investigation suggest that the bands observed by Samans were sections of layers that were parallel to the rolling direction and grew in width during rolling. Slip lines observed on the end of specimen 3 indicated that adjacent layers approach different orientations during reduction by rolling. The explanation is offered that the bands observed by Samans were not sections of mechanical twins but that the 60 degrees' difference in rotation around an octahedral axis was attained by progressive rotation.

3. DEVELOPMENT OF TEXTURE IN POLYCRYSTALLINE COPPER

If the shape of individual crystals in a polycrystalline specimen during a reduction by cold-rolling changes exactly in accordance with dimensional changes of the specimen, then the results obtained with monocrystalline specimens could be used, without question, to describe the development of texture. The nonconformity of changes in shape of crystals with external changes of a specimen was demonstrated by Barrett [10]. In his experiments the inner faces of two compression blocks of polycrystalline aluminum became roughened by the deformation resulting from 22-percent reduction. The roughened surface can be explained by the initial orientations of some crystals being able to conform more easily to dimensional changes of the specimen than others. In a previous investigation [7] it was shown that the crystal in a bicrystalline copper rod having a cubic axis nearly parallel to the rod axis conformed more nearly to dimensional changes resulting from swaging than the other crystal having an octahedral axis nearly parallel to the rod axis. In this case the crystal having the cubic orientation tended to flow around the crystal having the octahedral orientation. The nonconformity of changes in shape of crystals with dimensional changes of the specimen probably diminishes as the deformation proceeds and becomes negligible after severe reductions. This contention assumes that the resistance of an individual crystal to further deformation increases as the deformation proceeds, so that in time the crystals undergoing the most deformation will offer the same resistance as those that initially offered more resistance. When this condition is realized, the dimensional changes of all crystals should conform to the external changes of the specimen. Evidence that such a conformity is approached is given by metallographic examinations of severely cold-rolled specimens of polycrystalline copper. These examinations showed that in general all grains are elongated in the direction of rolling, shortened in the normal direction, and almost unchanged in the transverse direction. From the above consideration it is concluded that the interactions of neighboring crystals in polycrystalline specimens may result, during early stages of deformation by rolling, in lattice rotations which are not consistent with the behavior of monocrystalline specimens, but these inconsistencies are greatly reduced in later stages.

The development of texture in polycrystalline copper by cold-rolling, based on the behavior of monocrystalline specimens during cold-rolling, appears to be as follows: During moderate reductions, a crystal may develop layers by the rotation of the lattice in different directions. The lattice rotation of a crystal or of a layer within a crystal, during moderate reductions, tends to be around an axis nearly parallel to the transverse direction and ends at a position approximating one of five intermediate orientations, as follows: 110–$1\bar{1}2$, 112–$\bar{1}\bar{1}1$, 110–001, 100–001, and 100–011. Additional rolling causes the crystals or layers within crystals that approximate the 110–001 intermediate orientation to develop new layers. The lattices of some of the newly developed layers rotate to one of the twin 110–$1\bar{1}2$ orientations, and the lattices of the remaining layers rotate to the other. Crystals or layers within crystals approximating other intermediate orientations develop new layers whose lattices rotate in a similar manner to the twin 110–$1\bar{1}2$ and twin 112–$\bar{1}\bar{1}1$ orientations. The rotations required to attain one of the final orientations from an intermediate orientation appear to be only around axes that are nearly parallel to the normal or rolling directions.

V. SUMMARY

Five monocrystalline specimens differing in their initial orientation and one polycrystalline specimen were cold-rolled without intermediate annealing from 1-in. to 0.005-in. thickness. Care was taken to keep the same rolling surface up and to enter the same end between the rolls during the entire reduction. After 15-, 30-, 45-, 90-, and 99.5-percent reductions, samples were cut from the ends of the monocrystalline specimens first to enter the rolls. These samples were

used for metallographic examinations of the cross sections and the determination of lattice orientations. Samples from the polycrystalline specimen after 99.5-percent reduction were used to obtain data for constructing a pole-figure of normals to the octahedral planes.

The pole-figure of a polycrystalline specimen of severely cold-rolled copper indicated that the preferred orientations were twin 110–1$\bar{1}$2 and twin 112–$\bar{1}\bar{1}$1 orientations. The behavior of five monocrystalline specimens during cold-rolling showed that three specimens developed layers whose lattices rotated to positions approximating two of five orientations. These five orientations have been called intermediate because they are approached during moderate reductions and appear to be the starting positions for the development of the texture characteristic of severely cold-rolled polycrystalline copper. The five intermediate orientations are 110–1$\bar{1}$2, 112–$\bar{1}\bar{1}$1, 110–001, 100–001, and 100–011. The lattice of the other two monocrystalline specimens as a whole rotated to a position approximating one of the five intermediate orientations. After additional rolling all specimens showed more than one orientation. The final orientations approached were twin 110–1$\bar{1}$2 or twin 110–1$\bar{1}$2 and twin 112–$\bar{1}\bar{1}$1 orientations, which are characteristic of cold-rolled polycrystalline copper.

The lattice rotations resulting in positions approximating the intermediate orientations tend to be around axes nearly parallel to the transverse direction. Other rotations tend to be around axes nearly parallel to the normal or rolling directions.

An explanation of the development of texture in severely cold-rolled polycrystalline copper, based on the behavior of monocrystalline specimens, is given.

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