INTRODUCTION

The preferred orientation of grains in a polycrystalline material is referred to as crystallographic texture. There are two broad categories of textures commonly known as sheet and fiber textures. To describe a sheet texture requires determining the crystallographic plane aligned in the rolling plane of the sheet and the direction in that crystallographic plane aligned into the direction of rolling. A fiber texture is completely described by the definition of the crystallographic direction aligned parallel to the fiber axis.

The results of x-ray measurements of texture in metallic materials are usually represented graphically employing the crystallographic pole figure and/or the inverse pole figure. In a crystallographic pole figure, the orientation of a grain is plotted on the specimen processing axial system producing a description of the distribution of crystal orientations. The same texture data can be depicted to form the inverse pole figure. In this case the specimen orientation of each grain is plotted on the crystal axial system creating a description of the distribution of the specimen orientations.

In a crystallographic pole figure, the density of \( <hkl> \) normals (poles) are plotted on a polar grid with coordinates based on the specimen processing coordinate system (e.g. rolling direction, transverse direction and normal to the sheet surface). In the case of a sheet texture, two directions 90° apart on the perimeter of the polar grid are selected as the rolling and the transverse directions and the center of the pole figure is the direction normal to the plane of the sheet. In the case of a fiber texture, the center of the polar plot is the fiber axis direction.
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To successfully satisfy the material requirements in many engineering applications, a specific crystallographic texture has to be formed in a controlled manner. Thus, the texture existing at all stages of processing should be quantified in a condensed and quickly understood manner. In a majority of these cases, a sufficient degree of texture characterization consists of the fractions of the three major crystallographic poles representing the orientations of grains in the surface. These fractions are frequently sufficient texture characterization for applications involving fiber textured cubic metals. Two procedures to arrive at such a partial description of a fiber texture will be considered; one based on the crystallographic pole figure ($\theta/2\theta$ method) and the other based on the inverse pole figures (IPF method). Fiber textures are quantified, employing both methods in two processing sequences, the compressive deformation of cold drawn copper rod and the annealing of a copper plate produced by cold upsetting and clock rolling.

$\theta/2\theta$ Method

Consider the $<100>$, $<110>$ and $<111>$ pole figures of a fiber textured metal with the projection plane normal to the fiber axis. The center positions of the pole figures are the locations of the $<hkl>$ poles parallel to the fiber axis. These grains are oriented for diffraction in Bragg-Brentano specimen geometry. Therefore the diffracted intensity of the (h00), (hh0) and (hhh) Bragg peaks in a $\theta/2\theta$ scan contains information concerning the densities of $<100>$, $<110>$ and $<111>$ poles parallel to the fiber axis.

The fractions of poles of the three orientations are computed from the intensity data by assuming that the deviations of the ratios of the heights of the Bragg peaks from that observed from a random sample correspond to the strength of the texture. This method of fiber texture characterization was suggested by Junginger and Elsner (1) and expanded on by Rhode et al. (2). The $\theta/2\theta$ method is consists of collecting x-ray diffractometer $\theta/2\theta$ patterns from random and texture samples. Examples of $\theta/2\theta$ patterns containing the (111), (200) and (220) peaks for textured and random polycrystalline copper are shown in Fig. 1. Notice the intensities are normalized such that the $<111>$ peak intensity is one hundred in both patterns. In cases where the random sample is not available the random peak intensities are taken to be those reported in the JCPDS-ICDD database; e.g. the reported intensities for copper for the (111):(200):(220) are 100:46:20 as shown in Fig. 1.
Fig. 1. X-Ray Patterns from Textured and Random Copper Showing the (111), (200) and (220).
The texture quantities, the fraction of grains in a specific orientation, are arrived at by calculating the ratios of the peak intensities of the textured material to the peak intensities of the random material. Here $i_{\text{hkl}}$ is the intensity of the (hkl) Bragg peak from the textured metal and $I_{\text{hkl}}$ is the intensity of the (hkl) reflection from the random material. The fraction of grains with $<200>$ poles parallel to the fiber axis, $P_{<200>}$, is:

$$P_{<200>} = \frac{i_{200}}{I_{200} + i_{220} + i_{111}}$$

and the fraction of grains with $<220>$ poles parallel to the fiber axis, $P_{<220>}$, is:

$$P_{<220>} = \frac{i_{220}}{I_{200} + i_{220} + i_{111}}$$

Inserting the values of $i_{111}$ and the $I_{111}$, Eqs. (1) and (2) reduce to the following for the fraction of grains of $<200>$ and $<220>$ orientation.

$$P_{<200>} = \frac{i_{200} * I_{220}}{(I_{200} * I_{220}) + (i_{220} * I_{200}) + (i_{200} * I_{220})}$$

And:

$$P_{<220>} = \frac{i_{220} * I_{200}}{(I_{200} * I_{220}) + (i_{220} * I_{200}) + (i_{200} * I_{220})}$$

The fraction of grains with $<111>$ parallel to the fiber axis is obtained from the condition that the sum of the three $P_{<\text{hkl}>}$ are set to unity.

$$P_{<111>} = 1.0 - P_{<200>} - P_{<220>}$$

**INVERSE POLE FIGURE METHOD**

The inverse pole figure of the plane normal to the axis of a fiber textured metal describes the locations of all of the $<\text{hkl}>$ pole orientations parallel to the fiber axis. The fraction of poles in an angular range in the vicinity of an $<\text{hkl}>$ orientation is determined by integrating the pole densities existing in the angular range. A numerical technique for accomplishing this integration for $2.5^\circ$, $7.5^\circ$ and $12.5^\circ$ around the $<100>$, $<110>$ and $<111>$ poles has been developed by Hosford et al. (3). This method provides a means to calculate the fractions of grains in the
selected angular range encircling the \(<100>\), \(<110>\) and \(<111>\).

The fraction of grains on the surface that are not in the angular range encircling the three major crystallographic poles is given by;

\[
F_{NO} = (1.0 - F_{<111>} - F_{<100>} - F_{<110>})
\]

where the \(F_{<hkl>}\) are the fractions of grains in the selected angle encircling an \(<hkl>\) orientation. If the distribution of grain orientations is ideally random the \(F_{<hkl>}\) values for the \(<111>\), \(<100>\) and \(<110>\) orientations for encirclement angles of 12.5°, 7.5°, 2.5° and are listed in Table I. Also included in Table I are the values \(F_{NO}\), the fraction of grains that are non-oriented in the specific angular spread around the three major \(<hkl>\) poles. The fraction of grains data from any specimen can be expressed in units of times random simply by normalizing the fractional values by the ideally random values of \(F_{<hkl>}\) given in Table I.

It is important to note the ability of the IPF method to provide the value of \(F_{NO}\) which is lacking in the \(θ/2θ\) method (see Eq.(5)). Another advantage of the IPF method is by extending the times random normalization the texture distribution can be described. Data from a specimen is normalized to times random at 2.5°, 7.5° and 12.5° angles using the fraction of grains data from the ideal random grain orientation given in Table I. This method probes the texture distribution at three angular values about the \(<111>\), \(<100>\) and \(<110>\).

Table I: Values of \(F_{<hkl>}\) for an Ideally Random Fiber Texture

<table>
<thead>
<tr>
<th>Encirclement Angle</th>
<th>(F_{&lt;111&gt;})</th>
<th>(F_{&lt;100&gt;})</th>
<th>(F_{&lt;110&gt;})</th>
<th>(F_{NO})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 Degrees</td>
<td>0.0050</td>
<td>0.0034</td>
<td>0.0079</td>
<td>0.9837</td>
</tr>
<tr>
<td>7.5 Degrees</td>
<td>0.0351</td>
<td>0.0290</td>
<td>0.0576</td>
<td>0.8783</td>
</tr>
<tr>
<td>12.5 Degrees</td>
<td>0.0965</td>
<td>0.0715</td>
<td>0.1428</td>
<td>0.6892</td>
</tr>
</tbody>
</table>

To compare the texture quantification results from the \(θ/2θ\) and the IPF methods requires that the sum of the \(P_{<hkl>}\)s equals the sum of the \(F_{<hkl>}\)s. To accomplish this the value of \(F_{NO}\) is set to zero.

EXPERIMENTAL

A 0.375 inch thick eight inch diameter copper plate was produced from a one inch thick pancake by cold rolling, employing a clockwise rotation of 135° between each pass. The copper pancake was manufactured by upset forging a three inch diameter, three inch long cylinder cut normal to the surface of a three inch thick hot rolled slab. This production sequence produces a plate with a largely fiber texture. Nine x-ray diffraction specimens were machined from the plate at 1/4, 3/4 and 4/4 radial positions. The numbered specimens and their positions in the plate are shown.
in Fig. 2. The specimens were located in the half section of the plate along radial center lines of zero degrees (specimens numbered 1, 3 and 5), forty five degrees (specimens numbered 8, 10 and 12) and ninety degrees (specimens numbered 13, 15 and 17) to the cut surface. These nine specimens and the specimen from the center of the plate (specimen number 7) were the ten locations in the plate where texture determinations were made. These ten samples were split near to mid-plane and milled flat. The exposed midplane surface was prepared for x-ray investigation by metallographically polishing and etching. The <111>, <200> and <220> pole figures were collected from the midplane surface of each specimen. The pole figure data was converted to ODFs and projected onto an inverse pole figure employing popLA (4) and Siemens (5) software.

Fig. 2. Specimen Layout in the 0.375 inch Thick Cold Worked Copper Plate.

The ten matching half specimens were vacuum annealed at 300°C for one hour. The matching exposed mid plane surfaces were prepared as described above and the <111>, <200> and <220> pole figures were determined on the ten annealed specimens. The ODFs of the annealed specimens were calculated from the pole figure data and the values of F<sub>hkl</sub> were determined from the inverse pole figures. θ/2θ scans were collected from all twenty specimens employing a Siemens diffractometer. Intensity data from the θ/2θ scans was utilized with Eqs. (3-5) to obtain the values of P<sub>hkl</sub>.

Similar determinations of texture were made on compression specimens of OFC copper. Thirteen compression specimens 0.3 inch diameter by 0.3 inches long were prepared from a half hard cold drawn copper bar. The original bar material contained a very strong [111] and [200] combination fiber texture. The specimens were compressed to logarithmic strains between -0.051 and -0.792. Specimens subjected deformations in the higher range of strains were remachined to a constant diameter after -0.275 and -0.541 strains. The textures of the as received rod and thirteen compressed specimens were quantified by both the IPF and the θ/2θ methods.
RESULTS

The comparisons of the IPF and theθ/2θ methods for quantifying texture in the cold worked copper plate specimens at zero, forty five and ninety degree radial orientations as a function of radial position are shown in Figs. 3 to 5. The results from the two methods are in excellent agreement. Similar comparisons of the two methods for quantifying texture in the annealed copper plate specimens at zero, forty five and ninety degree radial orientations as a function of radial position are shown in Figs. 6 to 8. The differences between the results of the two methods are significantly greater in the annealed plate than in the cold worked data. However, in general the results obtained from the IPF and theθ/2θ methods agree very favorably.

Fig. 3. Texture Fractions for the Copper Plate in the Cold worked Condition at Zero Degrees.

Fig. 4. Texture Fractions for the Copper Plate in the Cold worked Condition at 45 Degrees.
Fig. 5. Texture Fractions for the Copper Plate in the Cold worked Condition at 90 Degrees.

Fig. 6. Texture Fractions for the Copper Plate in the Annealed Condition at Zero Degrees.
In the cold worked plate the $<220>$ texture component increases from 0.4 to 0.8 at radial distances between 1.5 to 2.5 inches and remains relatively high out to a 4 inch radius. The fraction of $<200>$ poles in the surface of the cold worked plate decreases from 0.5 in the center to less than 0.2 at radial distances of 2 to 3 inches and increase back to 0.4 at a 4 inch radial position. The $<111>$ component is almost completely absent from the texture of the cold worked plate at all radial positions.
After annealing, the cold worked plate samples show diminished texture variation with radial position and angular position. The texture strength data as a function of radial position for the zero, forty five and ninety degree radial positions are almost indistinguishable (see Figs. 6 to 8). Annealing the cold worked plate has the effect of reducing the strengths of the $<200>$ and $<220>$ texture components and increases the strength of the $<111>$ component substantially.

The texture data obtained on the copper compression employing the $\theta/2\theta$ and the IPF methods are shown in Figs. 9 and 10. The fractions of the $<111>$, $<110>$ and $<100>$ poles are plotted versus the total amount of logarithmic compressive strain experienced by the specimen. The data obtained by the $\theta/2\theta$ method compares very favorably to the data acquired by the IPF method. The agreements between the two methods for the $<111>$ and $<200>$ poles are extremely good. In the case of the $<220>$ the agreement at low and high strains is excellent, however the IPF method transitions from low to high values at a lower compression strain than observed in the data obtained by the $\theta/2\theta$ method. Overall the agreement between the two methods for the compression data is considered to be very good.

Fig. 9. Texture Fractions for Copper Compression Specimens by the $\theta/2\theta$ Method.
CONCLUSIONS

1. The $\theta/2\theta$ method provides a rapid and easy mean to quantify fiber textures in cubic materials.
2. The IPF method is a more complete technique to quantify fiber textures in cubic materials because the inverse pole figure is a description of the orientations of all grains diffracting.

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REFERENCES