ILLUSTRATION OF TEXTURE WITH ULTRASONIC POLE FIGURES


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INTRODUCTION

Materials are most often used in the form of polycrystalline aggregates. Preferential orientation of the grains or crystallites within such an aggregate is known as "texture", and almost all methods of fabrication will tend to develop a texture to some degree. To differentiate among textures, it is desirable to describe and quantify them. One technique for doing this is the "pole figure".

Figure 1 illustrates how a pole figure is developed with diffraction techniques [1]. As illustrated, the source and detector are fixed to detect some selected diffraction maximum such as a (200), (110), or (111) reflection. The sample is positioned in the focus of the beam and the reference axes of the sample are moved through a variety of positions to cover a large fraction of the relevant solid angle. At each position, the diffracted intensity is measured and is proportional to the number of grains whose normals define the pole P. The angular relation between the direction of the pole P and the reference axes of the sample defines the relative orientation of this number of reflecting grains with respect to the sample axes. Intensities may be measured at a thousand or more different orientations, and projection of the intensities at the various pole orientations produces the pole figure.

X-RAY POLE FIGURES

Figure 2 illustrates the differences in texture of a copper plate after a series of rolling reductions. This figure shows (200) pole figures; the contour lines connect positions of equal intensity. It is obvious that the degree of texture increases with increasing rolling reduction. For quantitative evaluation, an orientation distribution function may be generated, or more simply, a numerical measure of the level of texture can be made by evaluating the ratio of the intensity value at the point
of maximum intensity to the average intensity value for the entire pole figure. Figure 3 shows plots of such intensity ratios for (111) and (200) pole figures from a series of copper samples that have undergone differing degrees of rolling reduction. It is evident that, for either (111) or (200) pole figures, the intensity ratio increases monotonically with percent rolling reduction.

X-ray pole figures sample only a thin layer near the surface, require a sample to be cut from the material of interest, and require appreciable time. Pole figures from neutron diffraction are an improvement to the extent that sampling is through the thickness of the test piece, but again a sample must be cut, and low beam intensities require even greater periods of time than do x-rays. In contrast, ultrasonic measurements sample the bulk material, can be made nondestructively on the material of interest, and can be made rapidly. On the negative side, ultrasonic evaluation of texture involves a considerably more limited base of datum points so the precision of textural definition is necessarily more limited. However, the following treatment for rolled material gives some indication of the level of textural information that can be garnered from ultrasonic measurements.

ULTRASONIC POLE FIGURES

This treatment utilizes the work of Sayers [2] who developed ultrasonic pole figures by projecting crystallite orientation distribution functions [3-5] onto a reference plane of interest which, in the present instance, is the rolling plane. The normalized orientation distribution function, \( W(\epsilon, \psi, \phi) \), satisfies the condition:

\[
\int_0^{2\pi} \int_0^{2\pi} \int_{-1}^1 W(\epsilon, \psi, \phi) \, d\epsilon \, d\psi \, d\phi = 1
\]  

Fig. 1. Schematic representation of the development of a pole figure from diffraction data.
Fig. 2. (200) x-ray pole figures for a copper plate after a series of rolling reductions.

Fig. 3. Intensity ratios for (111) and (200) x-ray pole figures for several copper samples (differentiated by symbol) after various rolling reductions.
where $\theta$, $\psi$, and $\phi$ are the Euler angles relating the crystallite axes to the reference axes of the sample and $\varepsilon = \cos \theta$. The distribution function can be expressed as a convergent series

$$W(\varepsilon, \psi, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \sum_{n=-\ell}^{\ell} W_{\ell mn}(\varepsilon) Z_{\ell mn}(\psi) \exp(im\psi) \exp(-in\phi)$$

where $Z_{\ell mn}$ are generalized Legendre functions and $W_{\ell mn}$ are the expansion coefficients. Symmetry arguments [6] for cubic crystallites reduce the number of independent coefficients, $W_{\ell mn}$, so that, to fourth order, only $W_{400}$, $W_{420}$, and $W_{440}$ are required.

In the present development of ultrasonic pole figures, only three of the nine independent orthotropic elastic constants of the polycrystalline aggregate were evaluated. Sayers [2], with the orthotropic approximation for the polycrystalline aggregate and with Voigt averaging, has developed the following relationships between these three elastic constants and the $W_{\ell mn}$,

$$c'_{44} = c_{44}^0 + c_{55}^0 [1/5 - 16/35 \sqrt{2} \pi^2 (W_{400} - \sqrt{5/2} W_{420})]$$

$$c'_{55} = c_{55}^0 [1/5 - 16/35 \sqrt{2} \pi^2 (W_{400} + \sqrt{5/2} W_{420})]$$

$$c'_{66} = c_{66}^0 + c_{44}^0 [1/5 + 4/35 \sqrt{2} \pi^2 (W_{400} - \sqrt{70} W_{440})]$$

where the primed constants are the constants of the aggregate and $c_{44}^0$, $c_{55}^0$, $c_{66}^0$, and $c^0 = c_{11}^0 - c_{12}^0 - 2c_{44}^0$ are the single crystal elastic constants. $W_{420}$ may be evaluated directly from the difference between $c'_{44}$ and $c_{55}^0$ but, in the present work, evaluation of $W_{400}$ and $W_{440}$ required the additional assumption that the single crystal constants of the crystallites in the aggregate were unchanged from those of a macro-single crystal. Hirao et al. [6] have developed alternative relationships between the orthotropic elastic constants and the $W_{\ell mn}$ with both Reuss averaging and Voigt-Reuss-Hill averaging.

The values of $c'_{44}$, $c'_{55}$, and $c'_{66}$ were measured with $SH_n$ modes in the manner of Smith et al. [7] and Armstrong et al. [8] who measured a series of resonances parallel and transverse to the rolling direction in copper plates with EMAT transducers. These resonances satisfy the equations

$$4 \rho \frac{f^2}{f_{n,R}} = (n/b)^2 c'_{55} + (1/D)^2 c'_{66}$$

and

$$4 \rho \frac{f^2}{f_{n,T}} = (n/c)^2 c'_{44} + (1/D)^2 c'_{66}$$

where $\rho$ is the density, $b$ is the plate thickness, $D$ is the magnet spacing in the EMAT, and $R$ and $T$ refer, respectively, to rolling and transverse
directions. Within the precision of measurement, anisotropic stresses were shown to be absent by the equality [9] of measured values of $C'_{66,R}$ and $C'_{66,T}$. Because the modulus difference, $C'_{44} - C'_{55}$, is a direct measure of $W_{420}$, this modulus difference should give some measure of the texture. Figure 4 shows this modulus difference as a function of rolling reduction, and, like the intensity ratios of Fig. 3, there is indeed a monotonic trend with rolling reduction. For some applications this difference may be a sufficient measure of texture.

However, there is more information in the ultrasonic pole figures. Sayers [2] converted his orientation distribution functions to pole figures by projecting onto a plane of interest—in the present instance this is the rolling plane. His expression for the pole densities on this plane is

$$4\pi q(\zeta, \eta) = 1 + 4 \pi S\left\{ (3/8 \sqrt{2})(35\zeta^4 - 30\zeta^2 + 3)W_{400} \right\}$$

$$+ \frac{9}{2} \sqrt{5}(1-\zeta^2)[1 - 7/6(1-\zeta^2)]W_{420} \cos 2\eta$$

$$+ \frac{3}{8} \sqrt{35}(1-\zeta^2)^2W_{440} \cos 4\eta \right\}$$

![Fig. 4. Modulus difference, $C'_{44} - C'_{55}$, for the same copper samples as in Fig. 3.](image-url)
Fig. 5. (100) ultrasonic pole figures for the same copper plate after the same series of rolling reductions as in Fig. 2.

Fig. 6. Comparison of x-ray (left) and ultrasonic (right) pole figures for the same annealed sample after initial recrystallization.
where $\zeta$ is the cosine of the angle between the normal to the rolling plane and a crystallite pole of interest and $\eta$ is the angle of rotation in the rolling plane from the axis that is chosen as the reference direction. The last term in brackets involving $W_{400}$, $W_{420}$, and $W_{440}$ describes the projected pole density with respect to the reference axes of the sample, and the term $S$ describes the pole orientation with respect to the crystallite axes and is fixed by the choice of the pole to be projected.

Figure 5 shows (100) ultrasonic pole figures for the same sample and same rolling reductions as the x-ray pole figures of Fig. 2. It should be noted that (100) poles and (200) poles are parallel so that (100) ultrasonic pole figures and (200) x-ray pole figures are equivalent projections and comparison should illustrate how much detail is lost by using the truncated number of expansion coefficients for the orientation distribution function that result from the ultrasonic data. The ultrasonic pole figures in Fig. 5 are shown as quadrants because symmetry requires mirroring across both rolling and transverse directions. A close look at the contour lines in Fig. 5 shows that they, like their counterparts in Fig. 2, indicate higher pole densities along the rolling direction than along the transverse direction. Thus, there is a qualitative correspondence between corresponding ultrasonic and x-ray pole figures. Further, the ultrasonic pole figures, like the x-ray pole figures, show intensity changes that track the level of rolling reduction. This tracking of sample history is also evident in textural changes accompanying annealing. The copper sample that was rolled to 84% reduction was given a series of anneals at successively higher temperatures. Negligible differences were observed in the pole figures until temperature was raised to near 300°C. Both x-ray and ultrasonic pole figures are shown in Fig. 6 for the sample after 0.5 hr anneal at that temperature. The difference between this pole figure and the pre-anneal 84% reduction figure in Fig. 5 is interpreted as representing the effects of the beginning stages of recrystallization. A final pole figure in Fig. 7 shows a very low level of texture that was produced by inadvertently taking a copper plate in "as received" condition to the very high temperature of 1050°C for 3 hr with no rolling reduction; this is only $\sim 30^\circ$ from the melting point.

CONCLUSIONS

Overall it appears that ultrasonic data correlate with texture and, since ultrasonic data can be acquired relatively rapidly, ultrasonic techniques should be usable for textural inspection and quality control. A first-order quantitative evaluation of textural change with rolling reduction is evident in the modulus difference, $C_{44}' - C_{55}'$, of the present copper data. However, somewhat more detail is apparent in the ultrasonic pole figures that were generated from the ultrasonic measurements. In these figures, the pole positions and intensities vary with the textural changes that result from the changing history of a sample.

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Fig. 7. Comparison of x-ray (left) and ultrasonic (right) pole figures showing a very low level of texture after the copper sample was almost melted.

REFERENCES