ULTRASONIC CHARACTERIZATION OF TEXTURE

Y. LI AND R. B. THOMPSON
Ames Laboratory, Iowa State University, Ames, IA 50011

ABSTRACT

This paper will propose a new technique to characterize texture of rolled plates of cubic crystallites. This technique uses information from ultrasonic velocities of high order plate mode to improve the estimation of orientation distribution coefficients (ODC's), especially W_{400}. Also discussed will be the generalization of this technique to the case of hexagonal crystallites.

INTRODUCTION

It is well know that the texture (preferred grain orientation) of a polycrystalline metal sheet or plate strongly influences the formability of the material. Traditionally, texture is determined destructively through X-ray or neutron diffraction techniques. Recently, ultrasonic techniques have shown the promise of being able to characterize texture quickly and nondestructively in polycrystals of cubic crystallites [1,2]. Present techniques are generally based on the information from velocities of S_o and SH_o plate waves. This paper presents two extensions to the current theory and techniques. In one extension, higher order plate modes are utilized to make better estimations of the orientation distribution coefficients. The second extension is made to polycrystals of hexagonal crystallites. Included are discussions on the similarities and differences in applying the present and newly proposed theory and techniques.

The texture or preferred grain orientation of a plate is often described by the crystallite orientation distribution function (CODF) expressed as a series of spherical harmonics with weightings W_{LMN} (Roe's notation) [3,4] or $C_\ell^{\mu\upsilon}$ (Bunge's notation) [5] known as the orientation distribution coefficients (ODC's). The texture is characterized quantitatively by the ODC's. Although the complete specification of texture requires knowledge of all W_{LMN} for $L \geq 0$, it has been shown that the formability of polycrystalline metals is most strongly influenced by the lowest order coefficients, W_{LMN} for $L \leq 4$. Of this order, W_{400}, W_{420}, and W_{440} are the only nonzero and independent coefficients for cubic materials such as Fe, Al, and Cu. For hexagonal materials such as Ti and Zr, W_{200} and W_{220} are also nonzero and independent [6,7].

PRESENT TECHNIQUE FOR CUBIC MATERIALS

The presence of texture gives rise to anisotropy in the polycrystalline metal and hence influences the ultrasonic wave speed. Ultrasonic measurement of texture relies on the information from ultrasonic wave speeds in different propagation directions. In a technique which has received considerable recent attention [8,9], use is made of S_o and SH_o modes of plate waves. Through the measurements of S_o and SH_o wave velocities at 0°, 45°, and 90° with respect to the rolling direction, W_{400}, W_{420}, and W_{440} for cubic materials can be calculated from following equations:

$$SH_o: \quad W_{400} = \frac{35\sqrt{2}\,\rho}{16\pi^2 C}\left(V_{SH_o}^2(45) + V_{SH_o}^2(0) - \frac{2T}{\rho}\right);$$

$$W_{440} = \frac{\sqrt{35}\,\rho}{16\pi^2 C}\left[V^2_{SH_o}(45) - V^2_{SH_o}(0)\right] \;;$$

$$S_o: \quad W_{400} = \frac{35\sqrt{2}\,\rho}{32\pi^2 C(3 + 8\,P/L + 8\,P^2/L^2)}\left[V^2_{S_o}(0) + V^2_{S_o}(90) + 2V^2_{S_o}(45) - 4\left(\frac{L - P^2/L}{\rho}\right)\right] \;; \tag{1}$$

$$W_{420} = \frac{7\sqrt{5}\,\rho}{32\pi^2 C(1+2P/L)}\left[V^2_{S_o}(90) - V^2_{S_o}(0)\right] \;;$$

$$W_{440} = \frac{\sqrt{35}\,\rho}{32\pi^2 C}\left[V^2_{S_o}(0) + V^2_{S_o}(90) - 2V^2_{S_o}(45)\right] \;.$$

In the above equations, T, P, and L are elastic moduli for the corresponding isotropic material (texture free), and C is the elastic anisotropy constant. Depending on the averaging scheme employed, these constants are related differently to the single crystal elastic constants and compliances [10].

Theoretically, the S_o velocities in Eqs. (1) should be the long wave length limit of the S_o mode velocities due to the dispersive nature of S_o plate wave. However, the difference between the two is in general small as long as the plate thickness is relatively small with respect to the wave length.

The above procedure makes consistently accurate prediction of W_{420} and W_{440}, which depend on relative velocities. However difficulties have been encountered in the prediction of W_{400} in aluminum. This is believed to be a consequence of the need for an absolute rather than a relative measurement, the strong dependence of the prediction on the isotropic moduli L, P, and T, and the small anisotropy of aluminum plates.

USE OF HIGHER ORDER PLATE MODES IN CUBIC POLYCRYSTALS

An improved technique for determining W_{400} takes advantage of higher order plate modes [11]. It is known that, for an isotropic free plate, there always exist infinite Lamé modes, occurring at $K = \frac{\pi}{b}\,n$. The lowest order Lamé mode occurs at the point where the S_o and SH_1 modes touch each other tangentially on the dispersion curves, as depicted in Fig. 1. At the tangency point, the S_o mode consists of pure SV partial waves polarized in the sagittal plane and propagating at ±45° with respect to the plate surfaces. The SH_1 mode is polarized perpendicularly to the sagittal plane and also consists of partial waves propagating at ±45° with respect to the plate surfaces. In the presence of texture (weak anisotropy), the dispersion curves of S_o and SH_1 modes have been shown to cross over one another or split at the Lamé point as shown in Fig. 2 [12]; therefore, information on texture can be inferred from the differences between these two wave speeds. In other words, W_{400}, W_{420} and W_{440} all can be determined through relative measurement of S_o and SH_1 wave velocities. Although computation of the W's from S_o and SH_1 velocities based on exact solution is not mathematically feasible, perturbation technique is readily available to accomplish this inversion process. Using the formula developed by Auld [13], we find the difference in wave numbers for SH_1 and S_o modes are:

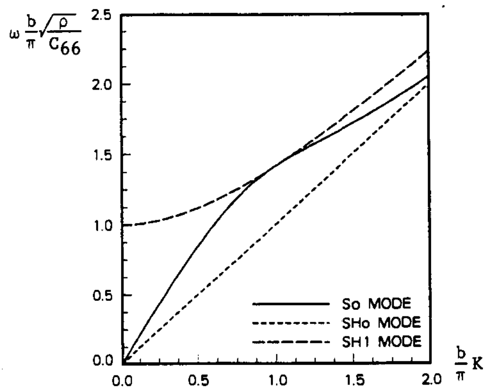

Fig. 1: SH_o, S_o, and SH_1 mode dispersion curves in an isotropic plate

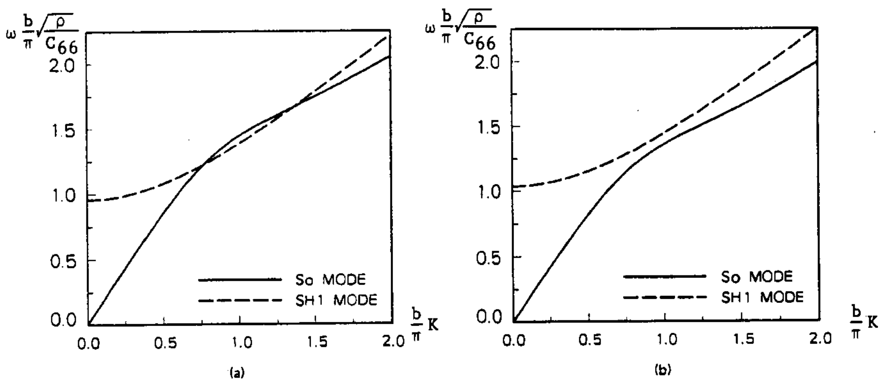

Fig. 2: S_o and SH_1 mode dispersion curves in an anisotropic plate. (a) SH_1 and S_o cross over; (b) SH_1 and S_o split.

$$\Delta K = \frac{K\pi^2 C}{35\ T}\left(25\sqrt{2}\ W_{400} - 4\sqrt{5}\ W_{420} \cos 2\alpha + 6\sqrt{35}\ W_{440} \cos 4\alpha\right) \tag{2}$$

where $K = \frac{\pi}{b}$, and α is the wave propagation direction with respect to rolling direction. Therefore, explicit expressions for W's can be easily derived and expressed in terms of velocity differences at 0°, 45°, and 90° propagation directions. This technique has been evaluated using exact solutions for wave propagation in orthotropic free plates of polycrystalline Cu material [11] and found to work satisfactorily [12]. Table I shows the comparison of true W's and W's obtained from Eq. (2) .

In contrast to the techniques mentioned earlier, this technique eliminates the need for absolute measurement of velocities and reduces the sensitivity to the average isotropic moduli.

Table I. Comparisons of exact W's and their estimations from Eq. (2) ($\times 10^{-3}$)

	W_{400}	W_{420}	W_{440}
Exact	1.00	1.00	1.00
Voigt	1.12	1.33	1.13
Hill	1.02	1.21	1.03
Reuss	0.91	1.08	0.91

CHARACTERIZING TEXTURE OF HEXAGONAL POLYCRYSTALS

For materials with hexagonal crystallites, there are five nonzero and independent ODC's. W_{200}, W_{220}, W_{400}, W_{420}, and W_{440}. As for cubic crystallites, one again can express the elastic constants and wave speeds in terms of the ODC's and then solve for the latter. The result is

$$SH_o: \quad B\, W_{400} - \sqrt{5}\, A_3\, W_{200} = \frac{105\sqrt{2}\,\rho}{16\pi^2}\left[V_{SH_o}^{\,2}(45) + V_{SH_o}^{\,2}(0) - \frac{2T}{\rho}\right];$$

$$W_{440} = \frac{3\sqrt{35}\,\rho}{16\pi^2 B}\left[V_{SH_o}^{\,2}(45) - V_{SH_o}^{\,2}(0)\right];$$

$$S_o \quad : \quad [3+8\,P/L + 8\,P^2/L^2]\,B\,W_{400} + 2\sqrt{5}\,\{[1-2\,P^2/L^2]\,A_1 - P/L\,A_2\}W_{200}$$

$$= \frac{105\sqrt{2}\,\rho}{32\pi^2}\left[V_{S_o}^{\,2}(0) + V_{S_o}^{2}(90) + 2V_{S_o}^{2}(45) - \frac{4(L-P^2/L)}{\rho}\right]; \qquad (3)$$

$$(1 + 2\,P/L)\,B\,W_{420} + \sqrt{3}\,[A_1 + (P/L)A_2]W_{220}$$

$$= \frac{21\sqrt{5}\,\rho}{32\pi^2}\left[V_{S_o}^{\,2}(90) - V_{S_o}^{\,2}(0)\right];$$

$$W_{440} = \frac{3\sqrt{35}\,\rho}{32\pi^2 B}\left[V_{S_o}^{\,2}(0) + V_{S_o}^{\,2}(90) - 2V_{S_o}^{\,2}(45)\right],$$

where L, P, T are elastic constants for the corresponding isotropic material. A_1, A_2, A_3, and B are elastic anisotropy constants. These constants are related to the elastic moduli of single crystals and, depending on the averaging scheme, the relations vary [7,14]. Regardless of the averaging scheme, there always exists the relation $A_1 + A_2 + A_3 = 0$.

One can see that the situation is considerably more complex than for the cubic case. The determination of W_{440} is very similar, being possible from the angular dependence of either the S_o or SH_o mode velocities. Absolute velocity measurements are necessary to determine W_{200} and W_{400}. The required algorithms are sensitive to the values of the isotropic moduli, and one must further solve a pair of linear equations involving SH_o and S_o mode data to separately determine W_{200} and W_{400}. The stability of this further inversion has not yet been investigated, but the erratic predications from cubic case imply questionable reliability for doing so.. Furthermore, there is insufficient information to separately determine W_{220} and W_{420}, although the indicated linear combination depends only on a relative measurement and should be determined with high precision.

Even more than in the cubic case, important additional information appears to be in the behavior of the Lamé modes. At the first point of tangency, one finds that

$$\begin{aligned}
\Delta K(SH_1) &= \frac{K\pi^2}{105T} [(\sqrt{10}\, A_3 W_{200} + 6\sqrt{2}\, B W_{400}) + \\
&\quad + (2\sqrt{15}\, A_3 W_{220} + 8\sqrt{5}\, B W_{420}) \cos 2\alpha + 4\sqrt{35}\, B W_{440} \cos 4\alpha]; \\
\Delta K(S_o) &= -\frac{K\pi^2}{105T} [(2\sqrt{10}\, A_3 W_{200} + 19\sqrt{2}\, B W_{400}) + \\
&\quad + (4\sqrt{15}\, A_3 W_{220} - 12\sqrt{5}\, B W_{420}) \cos 2\alpha + 2\sqrt{35}\, B W_{440} \cos 4\alpha]; \qquad (4) \\
\Delta K = \Delta K(SH_1) - \Delta K(S_o) &= \frac{K\pi^2}{105T} [(3\sqrt{10}\, A_3 W_{200} + 25\sqrt{2}\, B W_{400}) + \\
&\quad + (6\sqrt{15}\, A_3 W_{220} - 4\sqrt{5}\, B W_{420}) \cos 2\alpha + 6\sqrt{35}\, B W_{440} \cos 4\alpha].
\end{aligned}$$

It is clear that there is now ample basis to separately determine various linear combinations of W_{220} and W_{420} from angular dependences of the velocities. Hence these constants can be uniquely determined. Furthermore, one can obtain one combination of W_{200} and W_{400} from relative measurements of the shifts of the SH_1 and S_o modes. Further measurements must be sought to obtain a second linear combination from relative rather than absolute data since the shifts $\Delta K(SH_1)$ and $\Delta K(S_o)$ are defined with respect to the Lamé mode point of an isotropic polycrystal material. Thus it can not be expected that the angle independent part of these quantities will be a basis for accurate predictions for W_{200} amd W_{400}.

CONCLUSIONS

Use of higher order mode information to improve the accuracy of determination of W_{400} in cubic materials is first discussed. In particular, it is shown how this ODC can be obtained from the relative shift of the lowest order Lamé modes. In addition, new equations are then presented for the characterization of texture in hexagonal materials. Based on measurements of the velocities of the SH_o and S_o plate modes, it is shown that W_{440} can be determined from relative angular variations, W_{400} and W_{200} can be determined from absolute measurements, and only a linear combination of W_{220} and W_{420} can be determined from relative measurements. The use of higher order Lamé mode behavior is proposed to gain additional information. It is shown that W_{220} and W_{420} can now be separated from angular variations and one linear combination of W_{200} and W_{400} can be determined from relative measurements.

ACKNOWLEDGMENTS

Ames Laboratory is operated for the U. S. Department of Energy by Iowa State University under contract no. W7405-ENG-82. This work was supported by the Office of Basic Energy Sciences, Division of Materials Sciences.

REFERENCES

1. R. B. Thompson, S. S. Lee and J. F. Smith, J. Acoust. Soc. Am. 80, 921 (1986).
2. R. B. Thompson, S. S. Lee and J. F. Smith, Ultrasonics 25, 133 (1987).
3. R.-J. Roe, J. Appl. Phys. 36 (6), 2024 (1965).
4. C. M. Sayers, J. Phys. D: Appl. Phys., 15, 2157 (1982).
5. H.-J. Bunge, Texture Analysis in Materials Science, Translated by P. R. Morris (Butterworths, Berlin, 1982).
6. R.-J. Roe, J. Appl. Phys. 31 (5), 2069 (1966).
7. C. M. Sayers, Ultrasonics 24 (5) 289, (1986).
8. S. S. Lee, J. F. Smith and R. B. Thompson, in Nondestructive Characterization of Materials, edited by J. F. Bussiere (Plenum Press, New York, 1987), p.155.
9. S. J. Wormley, R. B. Thompson and Y. Li in Review of Progress in Quantitative Nondestructive Evaluation 7B, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1988), p. 1639.
10. M. Hirao, K. Aoki, and H. Fukuoka, J. Accoust. Soc. Am., 81 1434 (1987).
11. Y. Li and R. B. Thompson, in Review of Progress in Quantitative Nondestructive Evaluation 8, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, in press).
12. Y. Li and R. B. Thompson, in Review of Progress in Quantitative Nondestructive Evaluation 8, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, in press).
13. B. A. Auld, Accoustic Fields and Waves in Solids, Vol. II (John Wiley and Sons, 1973).
14. Y. Li, Notes on relationship between C_{ij} for hexagonal polycrystallites and W_{LMN}. Unpublished, (1987).