USE OF LAMÉ MODE PROPERTIES IN THE DETERMINATION OF TEXTURE PARAMETERS ON AL PLATES

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INTRODUCTION

Texture (preferred grain orientation) characterization of polycrystalline aggregates has traditionally been done by X-ray or neutron diffraction techniques. These techniques are generally slow and destructive. Advances in ultrasonics over the last decade have made it possible to determine texture of cubic polycrystalline aggregates quickly and nondestructively [1-3]. It is known that all polycrystalline materials have some degrees of texture and, when texture is present, the materials are anisotropic, usually weakly orthotropic for rolled plates or sheets. The principle of ultrasonic characterization of texture is to infer texture by sensing and determining the material anisotropy.

The mathematical description of texture was developed over 20 years ago by Roe [4,5] and Bunge [6]. Texture is quantitatively described by the orientation distribution coefficients (ODCs) or W_{lmn} in Roe's notations. These ODCs are dimensionless parameters. Theoretically, diffraction techniques can determine W_{lmn} for l up to infinity, though in practice W_{lmn} is determined for l up to no more than 20 or 30. In principle, only W_{lmn} for l up to 4 can be determined ultrasonically. It is very fortunate that these W_{lmn} are often the most important texture parameters for formability study for cubic metals [7,8]. For these materials, there are only three independent and nonzero W_{lmn} for l up to 4; these are W_{400}, W_{420}, and W_{440}. Typical values of these W_{lmn} are on the order of 10^{-3}. These W_{lmn} are related to deep drawability and earing in the manufacturing process [8].

The key to the ultrasonic determination of texture is the set of relations between the texture parameters W_{4m0} and the elastic constants C_{ij} of the material. For rolled plates or sheets of cubic crystallites, these relations are linear and can be expressed as [9]:

$$C_{ij}=C^{o}_{ij}+C^{o}\sum \alpha_{ijm}W_{4m0} \qquad (m=0,2,4) \qquad (1)$$

where C^{o}_{ij} and C^{o} are isotropic elastic constants and an anisotropy measure, and α_{ijm} are constant coefficients. In Eq. (1), C^{o}_{ij} and C^{o} can be calculated from the elastic constants of single crystals c_{ij} via different averaging methods. The values of c_{ij}, C^{o}_{ij} and C^{o} for Al, Cu, and Fe are tabulated in Table I. The values for C^{o}_{ij} and C^{o} in the table are obtained by the Hill averaging method with the bounds corresponding to the Voigt and Reuss averaging results.

The conventional techniques for texture determination on rolled plates or sheets are the long wavelength S_0 (symmetric Lamb) and the SH_0 (shear horizontal) plate mode techniques (see Fig. 1). Using these techniques, one measures phase velocities of these two modes at 0, 45, and 90 degrees with respect to the rolling direction. The equations which calculate W_{420} and W_{440} from the S_0 or the SH_0 mode velocities can be found in Refs. 2 and 10. These

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Table I. Elastic constants of cubic materials (in GPa)

	c_{11}	c_{12}	c_{44}	C^o_{11}	C^o_{12}	C^o_{44}	C^o
Al	108.0	62.0	28.3	112.1±0.2	60.0±0.1	26.0±0.1	-10.8±0.2
Cu	169.0	122.0	75.3	200.7±9.7	106.1±4.9	47.3±7.3	-98.7±4.9
Fe	229.0	134.0	114.0	272.7±9.6	112.2±4.7	80.2±7.2	-132.1±0.9

equations use the angular variation in velocity, $V(\alpha)$, hence do not require absolute velocity measurements. The equations for the calculation of W_{400} are given below:

$$W_{400} = \frac{35\sqrt{2}}{16\pi^2 C^o}\left[\rho V^2_{SH_0}(0^o) + \rho V^2_{SH_0}(45^o) - 2C^o_{44}\right] \quad (2)$$

$$W_{400} = \frac{35\sqrt{2}}{32\pi^2[3+8(c^o_{12}/c^o_{11})+8(c^o_{12}/c^o_{11})^2]C^o}\{\rho V^2_{S_0}(0^o) + 2\rho V^2_{S_0}(45^o) + \rho V^2_{S_0}(90^o) - 4C^o_{11}[1-(c^o_{12}/c^o_{11})]^2\} \quad (3)$$

where ρ is the density of the material.

The conventional techniques work satisfactorily overall except for the determination of W_{400} on Al plates, whose prediction is often found to be inconsistent with independent diffraction measurements. This discrepancy is believed to be caused primarily by the following reasons. (a) The accuracy of the prediction of W_{400} relies on the accurate measurement of phase velocities in all three different directions. The typical measurement error in velocity is about ±0.005 mm/μs for manual absolute measurement. This may be improved to ±0.0005 mm/μs or better for automated measurement. (b) Existence of second phase or alloying elements in Al samples alters the isotropic elastic moduli. The influence of second phase material or alloying elements is still unclear. Up to 5% of difference in isotropic moduli for the alloyed aluminum can be found in the literature. A paper presented recently has shown that for pure Al plates, the ultrasonic predictions and X-ray diffraction results are reasonably consistent [11]. Table II shows how each of these two reasons contributes to the errors in the prediction of W_{400}. From this table one can see clearly why Al is particularly vulnerable to the errors and uncertainty in the measurement and calculation.

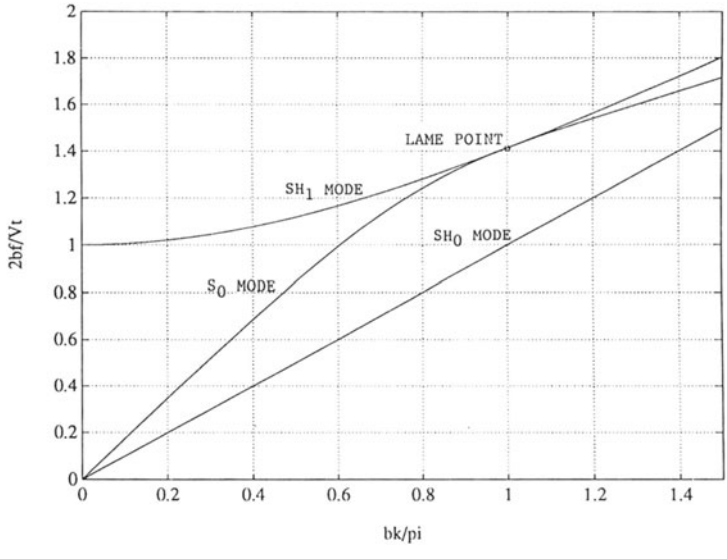

Fig. 1 Dispersion curves for the Lamb waves that are used in ultrasonic characterization of texture

Table II. Error in determination of W_{400} by the conventional ultrasonic techniques

error source	error	mode	ΔW_{400}(Al)	ΔW_{400}(Cu)	ΔW_{400}(Fe)
Velocity	0.005 mm/μs	SH_0	0.004	0.0014	0.0009
Velocity	0.005 mm/μs	S_0	0.001	0.0003	0.0002
Isotropic moduli	1%	SH_0	0.015	0.003	0.004
Isotropic moduli	1%	S_0	0.0015	0.0003	0.0003

The objective of this paper is to explore or develop a different ultrasonic method that does not rely on very precise absolute measurements or precise knowledge of the isotropic elastic moduli and density to predict W_{400}.

THEORY OF LAMÉ MODE TECHNIQUE

We have recently proposed an ultrasonic technique which utilizes Lamé mode properties to characterize texture of cubic and hexagonal polycrystalline aggregates [11,12]. It is known that, when a plate is isotropic, there is always a Lamé point where dispersion curves of the S_0 and the SH_1 modes touch each other tangentially at the wavevector $k=\pi/b$ (see Fig. 1), where b is the plate thickness. At this point, both modes have the dimensionless frequency $2bf/V_t=\sqrt{2}$, the phase velocity $V_p=\sqrt{2}V_t$, and the group velocity $V_g = V_t/\sqrt{2}$, where V_t is the plane shear wave velocity, $\sqrt{C^o_{44}/\rho}$. The S_0 Lamb mode at the Lamé point has only vertically polarized shear wave components (the longitudinal wave component is absent); the wave bounces back and fourth from the two surfaces at 45 degree angles. The SH_0 mode has only horizontally polarized shear wave components, also propagating at $\pm 45^o$ with respect to the plate surfaces.

When the plate is anisotropic, Lamé modes do not exist any more. Instead, the S_0 and the SH_1 modes may cross over or split in the vicinity of the Lamé point. The amount of cross-over and splitting, which is sensitive to the weak anisotropy induced by the texture in the metal sheets, is related to the texture parameters by:

$$\Delta k=\frac{k\pi^2 C^o}{35C^o_{44}}(25\sqrt{2}W_{400}-4\sqrt{5}W_{420}\cos 2\alpha+6\sqrt{35}W_{440}\cos 4\alpha) \qquad (4)$$

where $\Delta k \equiv k(SH_1)-k(S_0)$, $k(SH_1)$ and $k(S_0)$ are the wave numbers of the SH_1 and the S_0 modes of the anisotropic materials at the Lamé frequency ($f=V_t/\sqrt{2}b$), $k=\pi/b$ is the wave number at the Lamé point, and α is the wave propagation angle. By measuring Δk at 0, 45, and 90 degree directions, estimates of all three W's can be made based on this equation.

SAMPLES AND EXPERIMENT

We have used ten Al sheets in this study. All the samples are about 0.1" (2.5 mm) thick. One of these samples is a pure Al sample (99.99%) and all of the others are alloys with different heat treatments and rolling histories. Neutron diffraction measurements have been made on six samples and results of five samples have been reported [13]. X-ray diffraction has also been done on the pure Al sample on the top and the bottom surfaces as well as in the middle plane [14]. Of all the samples, none of them are fully flat -- local curvature exists irregularly on all the plates.

The experiments have been done using EMATs. The Lamé mode transducers have 5.1 mm period for the S_0 mode and 5.4 mm for the SH_1 mode. These enable the waves to be excited close to the Lamé point. For comparison purpose, we have also made measurements using the conventional S_0 technique.

The measurement method used in this study is the Fourier-phase method. Because both the S_0 and the SH_1 modes are strongly dispersive near the Lamé point, the commonly used

zero-crossing velocity measurement method is not suitable. Using the Fourier-phase method, one takes waveforms at two different transducer separation distances and uses deconvolution technique to obtain the wave number information or phase velocity information. The typical change of separation distance is about 100 mm in this study. For each measurement, there are three repetitions and the averaged value is used in the final computation.

RESULTS AND DISCUSSIONS

Using the Fourier-phase measurement method, we can construct dispersion curves from the experiments. Because the ultrasonic pulses are bandlimited, the constructed dispersion curves are also bandlimited. Figure 2 shows the experimentally constructed dispersion curves and the dispersion curves generated theoretically based on the ODCs obtained from the conventional ultrasonic technique (the long wavelength S_0 mode). These dispersion curves are for one set of measurements only. They are obtained for wave propagation in the rolling direction on one specific sample. One can see from this figure that the dispersion curves from experiments are in very good agreement with the theoretical ones, indicating a mathematical consistency in the computations.

Unfortunately, the ultrasonic results are different from the neutron diffraction results. To see this, we enlarged the portion of Fig. 2 near the Lamé point. Figure 3 shows the zoomed-in portion with two added curves. The two additional curves are the S_0 and the SH_1 dispersion curves produced using the ODCs from the neutron diffraction analysis. One sees clearly from this figure that the S_0 and the SH_1 mode dispersion curves from the ultrasonic techniques cross over near the Lamé point while those from neutron diffraction split there. The reason for this is that the value for W_{400} are significantly different between ultrasound and neutron diffraction. As will be seen later, of the six samples for which we have neutron diffraction data, all exhibit such kind of disagreement.

When using the Fourier-phase method, there exists an ambiguity of a multiple of 2π in the phase computation. Figure 4 shows how much of shift in the dispersion curves may occur if a plus/minus 2π phase error is introduced in the dispersion curve construction process. We have paid very careful attention to this problem and convinced ourselves that we have selected correct multiples of 2π in our study.

Figures 5~7 show the comparisons between the ODC values inferred from ultrasonic techniques (both the conventional S_0 and the Lamé mode techniques) and neutron diffraction. Six sets of data for each of the six samples on which neutron measurements were made are shown in each of the figures. Separate symbols are used to denote the correlations between the conventional S_0 and the Lamé mode ultrasonic measurements and the neutron diffraction with the straight lines being the loci of perfect agreement. Figure 5 is the comparison for W_{420} and Fig. 6 is the comparison for W_{440}. Agreements are generally to within $\pm 1 \times 10^{-3}$, with two exceptions. This is the order of accuracy obtained in previous studies [10]. Considering the nonsmooth surfaces on all the samples, the correlations in Figs. 5 and 6 are satisfactory. Figure 7, however, shows very poor agreement between the ultrasonic and neutron predictions of W_{400}. We do not understand this major disagreement at this stage.

We have also made a comparison for the two different ultrasonic techniques. Figure 8 shows how the Lamé mode results on W_{400} compare to those obtained by the conventional S_0 technique. Relatively good agreement can be observed in this figure.

Despite the poor agreement between the ultrasonic and neutron diffraction predictions of W_{400} on the alloys, reasonably good agreement was obtained on the pure Al sample, which was studied by X-ray rather than neutron diffraction. This sheet was studied before with the conventional S_0 technique using the zero-crossing method and the comparison between the results from ultrasound and X-ray was found satisfactory [11]. Figure 9 shows, in addition to the results from the previous study, the comparison of X-ray results with the Lamé mode and the S_0 mode results from the current study. One can see from this figure that W_{400}'s estimated from both the Lamé mode and the S_0 mode methods fall within the range given by X-ray results on the surfaces and mid-plane. The estimates for W_{420} and W_{440} are not bad either, even though they are not always within the X-ray limits.

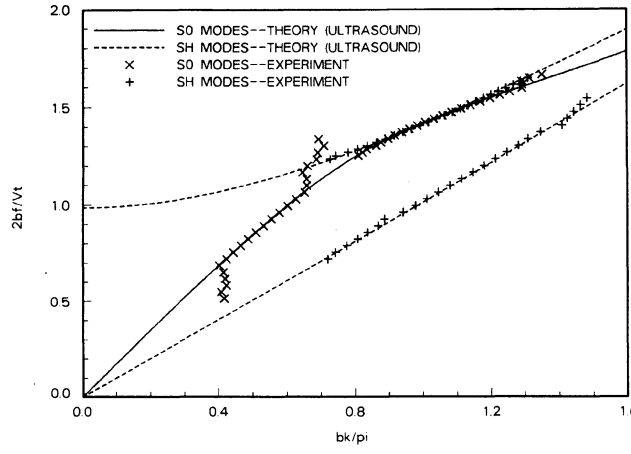

Fig. 2. Theoretical and experimental dispersion curves

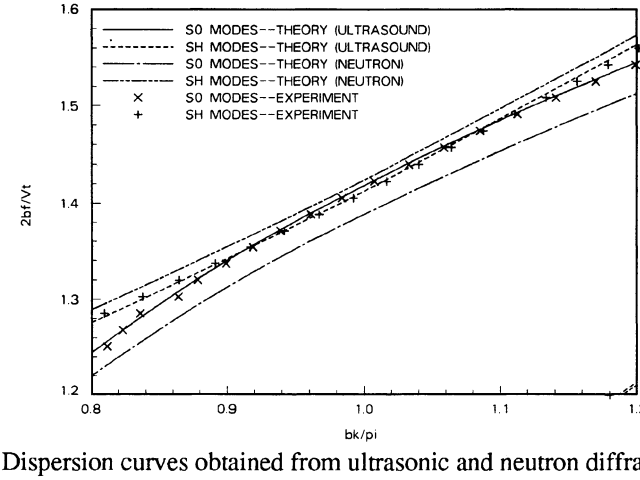

Fig. 3. Dispersion curves obtained from ultrasonic and neutron diffraction data

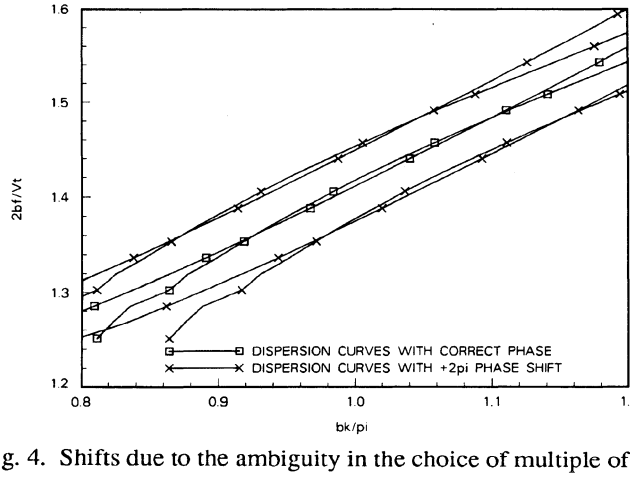

Fig. 4. Shifts due to the ambiguity in the choice of multiple of 2π

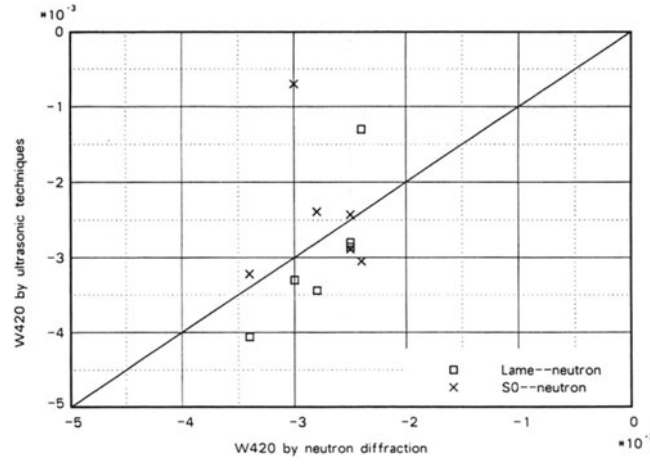

Fig. 5. Correlation between ultrasonic and neutron diffraction results (W_{420})

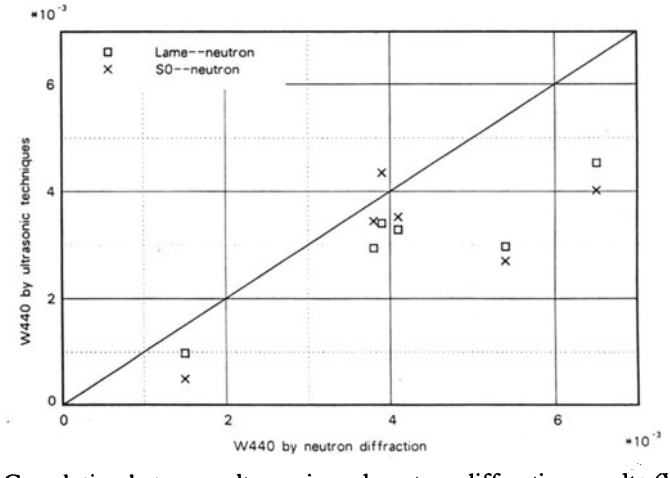

Fig. 6. Correlation between ultrasonic and neutron diffraction results (W_{440})

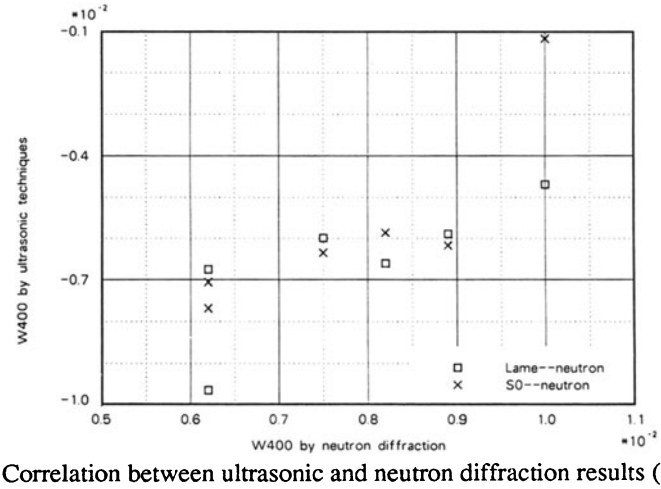

Fig. 7. Correlation between ultrasonic and neutron diffraction results (W_{400})

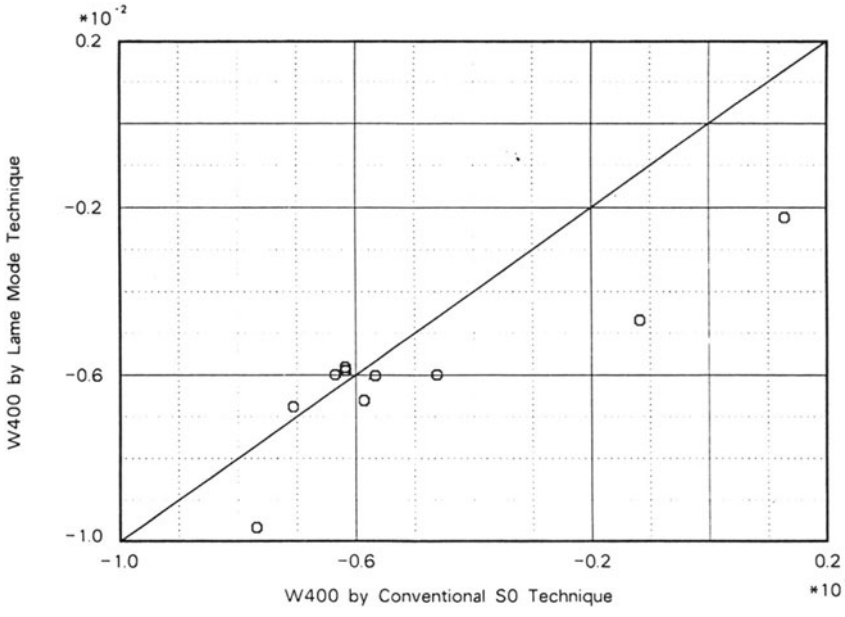

Fig. 8. Comparison of two different ultrasonic techniques (W_{400})

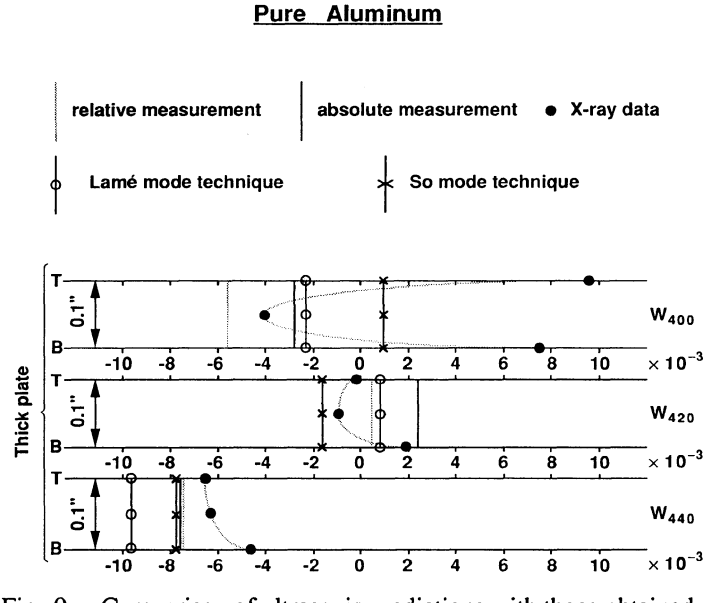

Fig. 9. Comparison of ultrasonic predictions with those obtained from X-ray diffraction measurement on the pure Al sample (see Ref. 11 for definition of previously used relative and absolute measurements). The symbols "T" and "B" denote the top and bottom of the sheet. The curve connecting X-ray values, at those points and mid-plane, denote an estimate of the texture profile.

SUMMARY AND CONCLUSION

We have shown in this paper that the Lamé mode properties can be utilized to determine texture in plates (sheets) of cubic polycrystalline aggregates. In principle, this method has the advantage of requiring relative rather than absolute measurements in the determination of W_{400} and being not sensitive to the measurement error or the error in isotropic moduli. Experimental results on the pure Al samples have shown that estimates by the Lamé mode technique are in good agreement with estimates by the X-ray diffraction method. On the other nine alloy samples, we have found that the results from the conventional techniques are consistent with those from the Lamé mode technique. However, for the six samples on which we have neutron diffraction data, ultrasonic results for W_{400} are significantly different from those obtained by the diffraction method. Further work is needed to understand this disagreement.

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