

ANALYSIS OF A SEMI-AUTOMATIC SYSTEM FOR
THE ULTRASONIC MEASUREMENT OF TEXTURE

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INTRODUCTION

The texture (preferred grain orientation) of rolled metal plates influences a number of important properties. Included are their formability into complex shapes such as beverage cans, vehicle bodies, or airframe skins, and their response to static or dynamic loading when the resulting components are placed into service [1-3]. Considerable benefit would be gained from the development of instrumentation which could measure texture in real time for process control applications or which could easily establish the texture of incoming materials or finished components so that their elastic or plastic mechanical properties could be estimated. As an example of the economic benefits of such a device, it has been estimated that \$40 million could be saved by the aluminum can industry through adequate texture monitoring [4].

Neutron or x-ray diffraction techniques can provide textural information in great detail [5-7]. However, these have a number of limitations. Portable x-ray diffraction instrumentation [8] is available which could be suitable for both process control or non-destructive evaluation applications. However, analysis of the resulting pole figures to obtain quantitative texture information would be time consuming and only a very thin surface layer would be examined. In rolled plates, the properties of this layer may be quite different from those of the bulk of the material. Neutron diffraction produces bulk information. However, analysis is again time consuming and the measurements can only be made at a few specialized facilities.

It has recently been shown that ultrasonic measurements provide an attractive alternative methodology [9-11]. Relationships have been established between the macroscopic elastic constants of a rolled metal plate and the coefficients of an expansion of the crystallite orientation distribution function (CODF) in terms of generalized Legendre functions. It has also been shown that these coefficients can be determined from velocity measurements of ultrasonic plate modes. A prototype device for implementing these ideas was described in the previous volume of these proceedings [12]. In the present paper, an analysis of the performance of that system is presented.

THEORY

Details of the system operation has been discussed previously [12]. Conceptually, the system is designed to measure the velocities of ultrasonic plate modes traveling at 0° , 45° , and 90° to the rolling direction of the plate. As shown in Figure 1, two modes are utilized, the SH_0 mode and the S_0 mode of the plate. In the former, one is essentially measuring the anisotropy of the shear modulus for deformations in the plane of the plate. In the latter, one senses the anisotropy of a quantity which can be qualitatively thought of as Young's modulus. This measurement requires that the wavelength be large with respect to the plate thickness.

The original governing equations relating the texture to the velocity measurements were based on an expansion of the velocities about their single crystal values [12,13]. More recently, this has been modified to an expansion about the isotropic polycrystal moduli [10,14].

The orientation distribution coefficients (ODC's), W_{LMN} , are predicted as follows

$$W_{440} = \frac{\sqrt{35}\rho}{16\pi^2 C} [SH_0^2(45) - SH_0^2(0)] \quad (1)$$

$$W_{440} = \frac{\sqrt{35}\rho}{32\pi^2 C} [S_0^2(0) + S_0^2(90) - 2S_0^2(45)] \quad (2)$$

$$W_{420} = \frac{7\sqrt{5}\rho}{32\pi^2(1+2P/L)C} [S_0^2(90) - S_0^2(0)] \quad (3)$$

where ρ is the material density, $SH_0(\theta)$ and $S_0(\theta)$ are the phase velocities of the aforementioned modes, θ is the angle of propagation with respect to the rolling direction, C is an elastic anisotropy parameter determined by the moduli of the crystallites, and $P = \lambda$ and $L = \lambda + 2\mu$ are the elastic constants of an isotropic polycrystal expressed in terms of the Lamé elastic constants λ and μ .

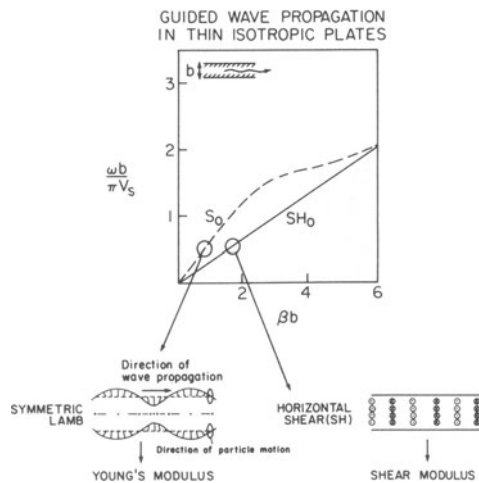


Figure 1. Guided modes used in the measurement

To fourth order, the texture of cubic polycrystals is defined by the ODC's W_{400} , W_{420} , and W_{440} . Whereas W_{420} and W_{440} can be determined from relative velocity measurements, W_{400} requires an absolute measurement. Problems associated with this approach are discussed in detail elsewhere [14].

THE MEASUREMENT SYSTEM

In its previously described form [12], the system was able to make reasonable predictions of W_{440} , but results for W_{420} and W_{400} were not satisfactory. A detailed evaluation of the system revealed several non-idealities which contributed to these problems. Included were clock-noise in the digitizer, randomly varying cable inductance and errors in EMAT magnet arrays. Corrections of these problems led to significantly improved signal fidelity and decreased noise levels and was the basis for the performance reported below.

ERROR ANALYSIS

An error analysis of the system performance was conducted. In its present implementation, the time delay of the signal is determined by the maximum value of the cross-correlation of the signals detected at two receivers. Since the signals can only be shifted by multiples of the sampling interval, delays are also defined to this precision (although more sophisticated interpolative procedures could be envisioned in the future.) Hardware limitations on data storage and transfer define this sampling interval to be 5nsec. Inserting this time error, along with the separations of the EMAT's and the elastic constants and density of aluminum, into Eqs. (1-3) leads to the estimated errors.

$$\delta W_{440} = 3.72 \times 10^{-5} (SH_0 \text{ Data}) \quad (4)$$

$$\delta W_{440} = 2.38 \times 10^{-4} (S_0 \text{ Data}) \quad (5)$$

$$\delta W_{420} = 1.47 \times 10^{-4} (S_0 \text{ Data}) \quad (6)$$

This is a worst case estimate, i.e. it has been assumed that the time errors have the signs which will maximize the ODC error rather than considering the velocity errors to be statistically independent.

It will be noted that the error in W_{440} as determined by S_0 data is 6.4 times that as determined by SH_0 data. This can be understood by noting that the factors in brackets in Eqs. (1-3) have the essential form $[2V\Delta V]$ where V is either the S_0 or SH_0 velocity and ΔV is the difference in its values at the angles indicated. For receivers separated by a distance L , this factor becomes approximately $[2V^3\Delta T/L]$ where ΔT is the relative time delay of the two received signals. Assuming that the time errors are the same for the two modes, the error in W_{440} should be proportional to the cube of the velocity. For aluminum, this implies that the error for S_0 measurements would be 5.2 times that of SH_0 measurements. Different values of L account for the small discrepancy between this number and the aforementioned 6.4 error ratio. The error in the prediction of W_{420} is intermediate between these cases. Figure 2 illustrates this same conclusion

by plotting the SH_0 and S_0 velocities as a function of angle in a particular copper plate [14]. It can be seen that for the same value of W_{440} , there is a much greater anisotropy in the SH_0 velocity. Consequently, measurement of that velocity has a greater leverage on the prediction of W_{440} .

An obvious consequence of this discussion is the fact that uncertainties in times lead to additive errors in the ODC's. We do not believe that it is useful to discuss percentage errors in the ODC's since these will be strongly influenced by the absolute value of the coefficient being estimated.

It should also be emphasized that the above error estimates are for the particular case of aluminum. Because of its low elastic anisotropy, as reflected by a small value of C , the errors will be much worse for this material than for some other cubic metals. The formulas presented herein do not apply to the polycrystals of other crystal classes such as hexagonal.

It is well known that the velocity of the \dot{S}_0 mode is frequency dependent [15]. The estimation of delay from correlation processing and its use in the prediction of velocity rests on the assumption of non-dispersive wave propagation. More detailed analysis is required to fully estimate errors introduced in those estimates by small amounts of dispersion.

EXPERIMENTAL EVALUATION OF ERRORS

In principle, the evaluation of the system should consist of an analysis of the propagation of the errors based on relationships which predict formability in terms of the ODC's [16]. In practice, however, other sources of errors in these relationships are not yet sufficiently quantified to render such a comparison meaningful. Consequently a more heuristic measure

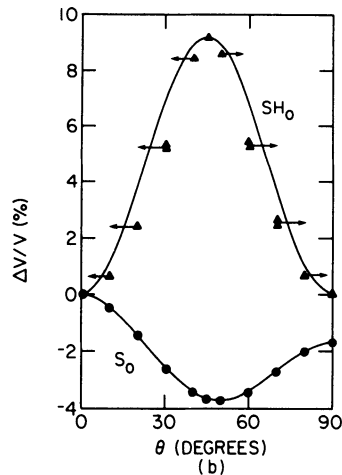


Figure 2. Angular dependence of SH_0 and S_0 mode velocities in copper plate. Solid line is theoretical predictions of phase velocity. Triangles and circles are data points and arrows indicate corrections associated with distinctions between group and phase velocities [9].

of system performance will be adopted. It will be assumed that the semi-automatic system is sufficiently accurate when the difference of its predictions from more precise manual ultrasonic measurements [17] are less than the difference between those more precise measurements and x-ray or neutron diffraction results. The latter difference is taken to define the systematic errors inherent in the ultrasonic measurement of the ODC's.

Figure 3 presents a comparison of these ultrasonic and diffraction (either neutron or x-ray) predictions of W_{440} as obtained by the authors or published by others in the literature [14]. The numbering of the data points refers to the samples examined and techniques employed, as defined elsewhere [14]. Similar comparisons have been obtained for W_{420} . Satisfactory comparison between ultrasonic and diffraction based predictions of W_{400} have not yet been obtained and hence this coefficient will not be considered further on this paper.

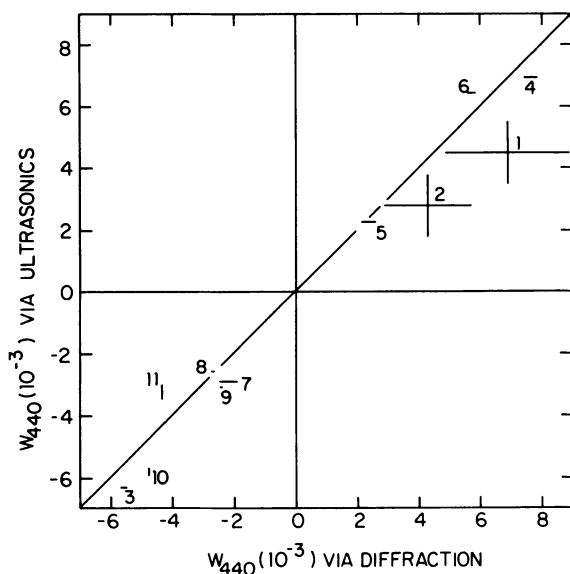


Figure 3. Comparison of ultrasonic and X-Ray or neutron determination of W_{440} . Finite length of lines corresponds to errors quoted in literature.

Figure 4 presents the results of comparison of values of W_{440} obtained with the semi-automatic and manual systems. Included are results obtained from both the SH_0 and S_0 data. Also shown are the theoretical limits of accuracy as discussed in the previous section. For the SH_0 case, those limits were so closely spaced as to be indistinguishable from the ideal line. Figure 5 presents the corresponding results obtained for W_{420} from the S_0 data.

Comparison of Figure 4 and 5 to Figure 3 illustrates two conclusions. First, the errors of the semi-automatic system are of the order of, but generally somewhat greater than, the theoretical limit. This result indicates the presence of other systematic measurement errors but establishes that they are not too severe. Second, the errors of the semi-automatic system are less than the systematic difference in ultrasonic and diffraction measurement of the ODC's. Further research is required to fully establish the sources of those errors. However, it can be concluded that the accuracy of the ultrasonic system does not limit the ability to predict formability, which depends on these ODC's.

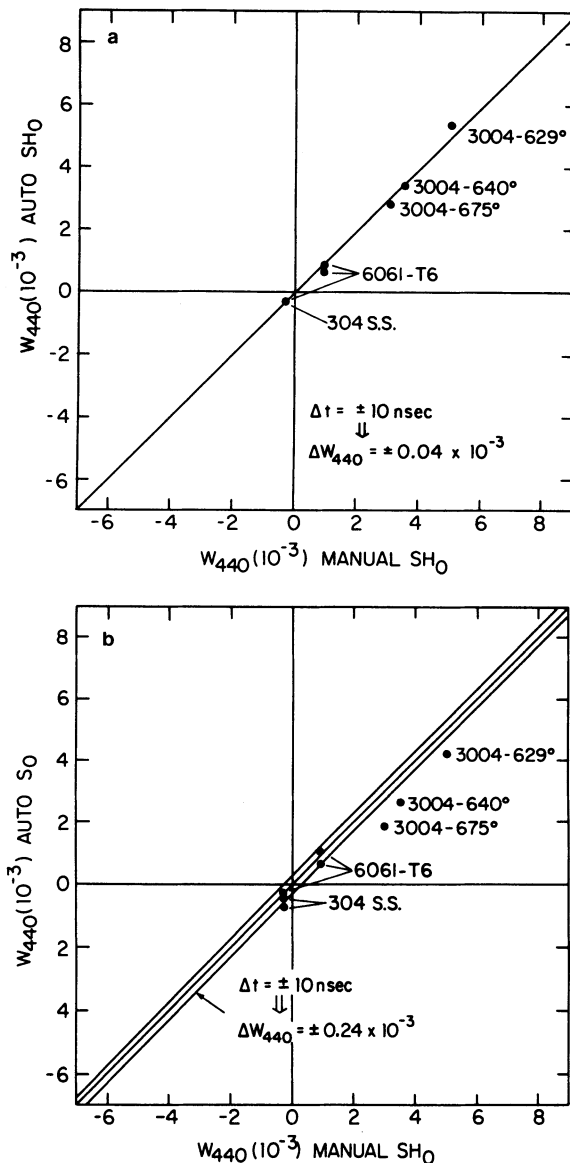


Figure 4. Comparison of predictions of W_{440} from semi-automatic and manual measurements.
a. From semi-automatic SH_0 data
b. From semi-automatic S_0 data

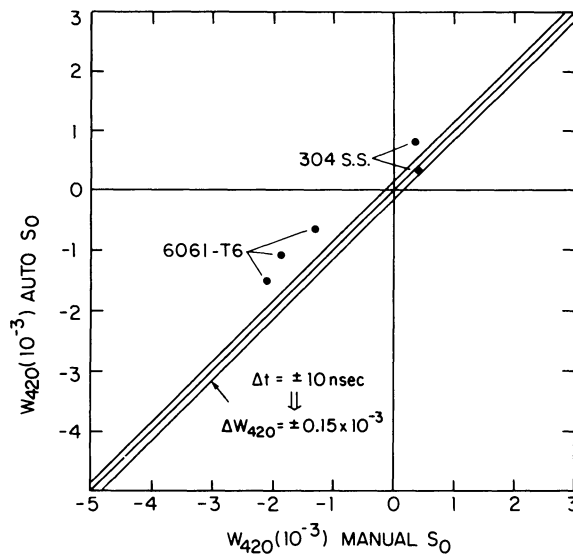


Figure 5. Comparison of predictions of W_{420} from semi-automatic and manual measurement.

SUMMARY

The errors in a semi-automatic system for the measurement of texture have been analyzed. These have been found to be on the same order, but somewhat greater than, fundamental limits based on the time sampling procedure employed. Comparison to evaluation of the systematic errors between ultrasonic and diffraction determinations of ODC's establish that the accuracy of the semi-automatic system does not limit the implementation of techniques to predict formability.

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