A. V. Clark¹ and S. R. Schaps¹

1. INTRODUCTION

Assessment of structural safety by fracture mechanics requires knowledge of the size of any defect and the stresses acting on it. There are also applications such as welding where residual stress is "locked in" during the fabrication process and will have a significant effect on structural lifetime.

Ultrasonics can be used to measure applied stress since there is a change in velocity with stress. For example, stress in a disk in diametral compression has been measured with shear waves¹ and with Rayleigh waves.² Applied stresses around a central hole in a plate in remote tension were measured in Ref. 3.

Another example is the use of ultrasonics to monitor the buildup of stresses induced by drag-braking of wheels.³ Here velocity measurements were made before braking and used as a baseline value. Changes in velocity were related to the braking-induced stresses. These changes are superimposed on those already present in the wheels due to the manufacturing process.

In these examples, the access to a reference state of the material essentially means that "applied" stress is being measured. The problem becomes more difficult when measuring residual stress. Here the influence of other factors on velocity must be accounted for; perhaps the most difficult is that of variation in microstructure.

For example, a standard method to determine stress is the acoustic birefringence method. Here the percent difference in velocities of orthogonally polarized shear waves is measured; this is the acoustic birefringence, B. When the material symmetry and stress axes coincide,⁴

\[ B = B_o + C_o D \]  

where \( B = \) birefringence, \( B_o = \) the birefringence in the unstressed state, \( C_o = \) the acoustoelastic constant, and \( D = \) the difference of principal stresses.

In general access to the unstressed state of the material may not be possible, so the usual procedure is to measure \( B_o \) at a separate "reference" location where stresses are known, and assume homogeneity of microstructure.
This technique works well in some circumstances. For example, it has been used to measure stress in drag-braked railroad wheels. Here short sections of wheels were cut out to stress-relieve them, and "baseline" measurements of $B_o$ made on these reference specimens. The birefringence was measured on stressed specimens and Eq. (1) applied to obtain stresses which agreed to within 40 MPa with destructive measurements. This agreement was possible because drag-braking did not heat the wheels above the recrystallization temperature, and so the microstructure did not change.

In other situations the microstructure may change during the process of creating the residual stress. A good example is welding of plates where the microstructure changes in the heat-affected zone (HAZ). Experiments described in Refs. 7 and 8 have demonstrated changes in $B_o$ in the HAZ; the "baseline" $B_o$ measured in the parent material is not valid in the HAZ.

Variability in microstructure manifests itself as a change in the amount of preferred orientation (texture) of the polycrystals in the material. Various theories have been developed to model the effect of texture on velocity. As a result it has been suggested by different researchers that combinations of velocities may suppress texture variability. One method uses the $R$-ratio:

$$R = \frac{V_L}{V_{S1} + V_{S2}} = R_o + C_S S$$  \hspace{1cm} (2)

where $V_L$ is the longitudinal wave velocity, $V_{S1}$ and $V_{S2}$ are shear wave velocities, and $S$ is the sum of principal stresses. It is assumed that the material symmetry and principal stress axes coincide in the above. The $R$-ratio has been measured in welded steel plates both in the baseplate and the HAZ. $R_o$ was unaffected by welding, unlike $B_o$ (Whether $R_o$ will be uneffected by welding for all cases remains to be determined; we hope to test this in future experiments.)

Equations (1) and (2) show that the principal stresses can be determined if the material under test is sufficiently homogeneous. For example in the case of welded plates, the principal stresses could be determined along an axis of symmetry at some distance away from the HAZ.

To evaluate stresses near the weld (where stresses are largest) requires suppression of variability in $B_o$. One method is to measure $B$ at locations where there is a shear stress.

For this more general case:

$$B^2 = [B_o + M_1 (\sigma_{xx} + \sigma_{yy}) + M_2 (\sigma_{xx} - \sigma_{yy})]^2 + (2M_3 \sigma_{xy})^2$$  \hspace{1cm} (4)

Here the stresses are referred to the material symmetry axes. The pure-mode polarizations are now at angle $\phi$ to the material symmetry axes:

$$\tan 2\phi = \frac{2M_3 \sigma_{xy}}{B_o + M_1 (\sigma_{xx} + \sigma_{yy}) + M_2 (\sigma_{xx} - \sigma_{yy})}$$  \hspace{1cm} (5)

Combining (4) and (5) gives

$$\sigma_{xy} = \frac{B \sin 2\phi}{2M_3}$$  \hspace{1cm} (6)

which has eliminated the effect of texture ($B_o$ is absent from the equation).

For welded plates the centerlines are lines of symmetry for stress, so the shear stress vanishes there. However, from the stress equilibrium equations

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial x} = 0$$  \hspace{1cm} (3a)

$$\frac{\partial \sigma_{xx}}{\partial y} + \frac{\partial \sigma_{xy}}{\partial x} = 0$$  \hspace{1cm} (3b)

there must be shear stresses on either sides of the centerlines since there are obviously gradients in the normal stresses. The shear stress $\sigma_{xy}$ appears in both equations. If $\sigma_{xy}$ and its gradients can be determined, the normal stresses $\sigma_{xx}$ and $\sigma_{yy}$ can be obtained by integration of the stress equilibrium equations. Measurement of $\sigma_{xy}$ and integration of the stress-equilibrium equations has been performed for several specimens with good results.

In sum, a hybrid procedure for stress determination in specimens having microstructural inhomogeneity would be:

1. Measure $B$ and $R$ along scans in principal directions in regions of microstructural homogeneity, and use the results to determine principal stresses.
2. Measure $B$ and $\phi$ in regions of varying microstructure along scan lines where the shear stress is non-zero (using Eq. (6) to determine $\sigma_{xy}$).
3. Integrate the stress equilibrium equations, starting from the boundary of the inhomogeneous and homogeneous regions. The constant of integration is just the normal stress (determined from step 1. above) at the boundary of the regions.

In this paper we examine the feasibility of implementing measurement of $B$ and $R$ to rapidly determine principal stresses in regions of microstructural homogeneity. We illustrate the validity of this procedure by performing it on a well-characterized residual stress specimen.

In performing our acoustoelastic measurements we use a swept-frequency, phase-sensitive instrument. This