INTRODUCTION

The use of ultrasonic waves to measure stress is an old technique whose extensive application has been retarded by the fact that texture or preferred orientation in the grain structure within the material introduces anisotropy that cannot be distinguished from the effects of stress. During the past few years, a new approach to this problem has emerged since a technique based on the use of shear horizontal (SH) waves has been demonstrated to overcome the effects of texture. In particular, it has been shown that the symmetry of the stress tensor demands that in a stress free solid the velocity of propagation of a shear wave along a principal symmetry axis is the same when the polarization and propagation directions are interchanged no matter how much anisotropy may be present due to texture. More important, if there is a difference in these two velocities, its magnitude is a direct measure of any uniaxial stress that may be present. Thus, it appears that one can measure the level of stress in a body by finding the principal symmetry axes of the material and then measuring the difference in wave velocities of two properly chosen shear waves.

Since the introduction of welded rail, the railroad industry has been faced with the problem of monitoring the magnitude of thermally induced stresses in railroad tracks that can fracture the rail on cold nights and give rise to buckling on hot days. It would appear that the SH wave method should be able to measure thermal stresses in rails because the method of fabrication imposes easily recognized principal symmetry axes on a normal rail. In fact, it was reported last year [1] that surface skimming SH waves propagating on the web of rails subjected to compressive and tensile loads in a laboratory testing machine could be used to make a quantitative measurement of the sign and magnitude of the stress. This paper describes an extension of that work toward the development of an instrument and probe to be used to monitor thermal stresses in railroad tracks after they have been installed in the field.
THEORETICAL AND EXPERIMENTAL BACKGROUND

It has been shown both experimentally \( \{2\} \) and theoretically \( \{2,3\} \) that surface skimming SH waves propagating along symmetry axes of the texture have velocities that differ in proportion to the magnitude of any stress that lies along one of the symmetry axes. Specifically, the stress is directly proportional to the relative velocity difference through the equation

\[
\sigma_i = 2G \left( \frac{V_{ik} - V_{ki}}{V_{ik}} \right)
\]

where \( \sigma_i \) is the stress in the direction \( i \), \( G \) is the shear modulus and \( V_{ik} \) is the velocity of an SH wave propagating in the \( i \) direction and polarized in the \( k \) direction. This rather simple relationship is particularly useful because the constant of proportionality involves only the well known shear modulus and the velocity term can be measured directly by observing the transit time shift when a transmitter-receiver pair of SH wave transducers are rotated through 90 degrees on the surface of the part.

Experimentally, Equation (1) was tested on the web of railroad rails which had been loaded by a 200,000 pound mechanical testing machine \( \{1\} \). The method of exciting and detecting the necessary surface skimming SH waves used electromagnetic acoustic transducers (EMATs) that operated through a magnetostrictive mechanism at high magnetic fields \( \{4\} \). Wave velocities parallel and perpendicular to the axis of the rail on the web differed by the amount predicted by Equation (1) to an absolute accuracy of 30 percent in the worst case. This result was taken as reasonable agreement with the theory since the geometry of a rail is complex and there are no adjustable parameters in the equation.

CURRENT RESULTS

Since the previous results were in the nature of a feasibility test to see how well the theory would apply to an actual steel part whose texture was ill-defined and whose shape was far from a flat plate, the present studies were undertaken to improve the accuracy of the measurement system and to develop a more compact and easily maneuvered EMAT probe. The electronic measurement concept described previously \( \{1\} \) was not changed significantly although a personal computer was added to make the data collection more convenient and a more stable clock/oscillator was installed to improve stability.

The EMAT probe, however, was changed completely from using pulsed electromagnets to an array of permanent magnets \( \{5\} \). This latter design was chosen in order to escape the heating effects of the pulsed electromagnets and to make the transducer itself into a more compact unit. Figure 1 shows a diagram of the bottom face of the improved EMAT. It was designed to excite and detect surface skimming SH waves by the periodic permanent magnet technique \( \{5\} \) and was in the shape of a square with EMATs all around the perimeter in order to be sure that the two SH waves would always propagate in orthogonal directions while interrogating identical volumes of the rail. Each magnet in the array was 0.06" wide so the system excited waves with a wavelength of 0.12 inches and operated at a frequency of 1 MHz. There are 320 neodymium-iron-boron magnets in the complete transducer.
Figure 1. Schematic drawing of the array of periodic permanent magnets used to launch and detect surface skimming SH waves over orthogonal propagation paths.

Calibration tests of this EMAT design as well as the improved electronics were carried out on an aluminum block 6-1/2" wide by 2-1/4" thick by 10" long loaded in compression to controlled stress levels between 0 and 13 ksi. Figure 2(a) shows the observed variation of the difference in transit time between two SH waves propagating parallel and perpendicular to the stress direction. This difference was both linear and reproducible as predicted by Equation (1) and the slope of the line was found to be 3.30 nanoseconds per ksi. Inserting the known value for the shear modulus into Equation (1), the theory predicted a slope of 3.16 nanoseconds per ksi in excellent agreement with the observations. An additional test of the theory was to measure the transit time between a transmitter/receiver pair as a function of angle relative to the edge of the aluminum plate. Such a test exposes the texture in the sample and defines the symmetry axes as extrema in the angular dependence curve. Figure 2(b) shows this transit time versus rotation angle data. These results not only agree with the theoretical expectations by showing that the effects of texture are much larger than the effects of stress but they demonstrate that a 90 degree rotation of the SH wave propagation direction returns the sound velocity very nearly to its original value. The small difference in sound velocity at 0 and 90 degrees implies the existence of a residual stress and, indeed, the application of a 3 ksi compressive stress brought the two velocities into agreement as if the sample had a permanent, residual stress in its surface of 3 ksi.

A detailed analysis of the theory shows that symmetry in the angular dependence of the velocity such as that shown in Figure 2(b), is a very strict requirement of the theoretical model. Thus, if the 0 and 90 degree velocities are far from equal in a practical case, the stress cannot be reliably deduced through the use of Equation (1). Figure 3 shows just such a case for a sample railroad rail when it was examined with the new, permanent magnet EMAT shown in Figure 1. When the older, pulsed electromagnet, SH wave transducer was used, the required symmetry was observed. Thus, it appears that the method of exciting the SH wave plays an important role in determining the applicability of the stress measuring technique.
Figure 2. Results of tests using the periodic permanent magnet EMAT probe shown in Figure 1 on a block of aluminum. (a) Effect of applied stress on the transit time difference. (b) Angular dependence of the velocity of a surface skimming SH wave on an aluminum block.

Figure 3. Angular dependence of the velocity of propagation of a surface skimming SH wave on a railroad rail using two different EMATs.
Another manifestation of the apparent breakdown of the theory for the periodic magnet EMAT can be seen in Figure 4 where the difference in transit time between the 0 and 90 degree SH waves generated by the permanent magnet probe is plotted as a function of applied stress. Although the data fell on a straight line and were reproducible, the slope of the line was more than a factor of five higher than the prediction of Equation (1). As mentioned previously, measurements made with the pulsed electromagnet EMAT were in essential agreement with Equation (1) and fell along the dashed line marked theory in the figure.

Since the two EMAT types differ in the direction and magnitude of the magnetic field they use to excite and detect the SH waves, it is reasonable to blame the different results on an unexpected magnetic effect. Such a conclusion is not surprising because the theory makes extensive use of symmetry arguments and restricts the applicability of Equation (1) to cases where the waves and stresses lie along symmetry axes. A magnetic material adds another vector quantity (the magnetization) whose orientation must also be taken into account. In order to control this additional vector quantity, and to empirically study its effects, a large electromagnet was mounted on a railroad rail sample so that the material in the web could be magnetized parallel to the long axis of the rail. Thus, a texture axis and an acoustic axis could be aligned with the magnetization. The lines labeled with different $H_T$ values in Figure 4 were obtained with this electromagnet activated. A Hall probe gaussmeter was used to measure the magnetic field parallel to the steel surface in an axial direction and the parameter $H_T$ is the value of the tangential magnetic field used during the test. Since the tangential field is continuous across a boundary and the magnetic induction $B$ is the permeability times this field, the $B$ field inside the rail can be estimated. Examination of Figure 4 shows that at very low fields ($H_T = 0$) the discrepancy between theory and experiment is very large, while at higher fields the difference is reduced, as if it would vanish in a saturating magnetic field. The pulsed electromagnet EMAT can only operate under saturation conditions so its data agreed with theory.

Figure 4. Effect of stress on the difference in velocity of two orthogonal SH waves placed on the web of a rail while the rail was loaded in compression. The parameter $H_T$ is the level of tangential magnetic field applied parallel to the rail axis.
CONCLUSIONS

1. The surface SH wave method of measuring stress in a solid describes the observations very well in aluminum.

2. Periodic permanent magnet SH wave transducers are strongly influenced by the level of magnetization in steel.

3. Pulsed electromagnet SH wave transducers naturally operate at magnetic field levels close to saturation and hence exhibit minimal errors in the measurement of stress caused by magnetic interactions.

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REFERENCES


