APPLICATION OF SURFACE SKIMMING SH WAVES TO STRESS
AND TEXTURE MEASUREMENT IN STEEL

G. A. Alers, R. A. Chesebrough and D. T. MacLauchlan
Magnasonics, Inc.
215 Sierra Drive, SE
Albuquerque, New Mexico 87108

INTRODUCTION

During the past five years, there has been a resurgence of activity in the area of stress measurement by ultrasonic techniques because new methods of accounting for texture effects have been developed [1]. In fact recent review article by Sayers [2] outlines several different ways of separating stress and texture effects so that each can now be measured separately and the information used for a variety of practical applications. The work described in this paper is aimed at using shear horizontal (SH) waves to measure the thermal stresses developed in railroad tracks during the usual day/night temperature cycle [3]. To accomplish this, a hand held probe that can operate on the web or base of the rail was fabricated and procedures that minimize sources of error were developed.

BASIC APPROACH

In order to increase the durability of a railroad line, the individual rails are welded together to form a continuous "ribbon" of steel that extends for thousands of feet. Because of the mechanical constraints imposed by the ties and the ballast, this length is essentially fixed so that an increase in temperature will subject the rail to a compressive load and a decrease in temperature will develop tensile loads. These thermally induced stresses can cause the rail to buckle on a hot summer day or break in tension on a cold winter night. Since the length dimension is fixed, the longitudinal strain is zero so stress detection techniques that depend on measurements of a displacement (such as strain gages or X-ray diffraction) cannot be used directly. Hence the interest in measuring the stress in a section of installed rail by a field worthy, ultrasonic method that does not depend on detecting a mechanical displacement.

The important feature of the recent theoretical and experimental developments is that in textured polycrystalline aggregates such as common structural steel and aluminum, the symmetry of the stress tensor dictates that the velocity of a shear wave propagating along a symmetry axis will be invariant to an interchange of the polarization and propagation directions if no stress is present. Thus, a surface skimming shear
horizontal (SH) wave \{4\} propagating on the web or base of a rail in the length dimension (i.e., the rolling direction) will have the same velocity as the same wave propagating at right angles to this dimension. More practically, if one places a transmitter/receiver pair of SH wave transducers on the web of a rail such that the transit time \(T\) for a wave to travel between them can be measured, the same transit time will be observed when the acoustic path is parallel and perpendicular to the length of the rail. In fact, an equation for the dependence of the transit time on the orientation of the acoustic wave path relative to the long axis of the rail will have the form \{5\}:

\[
\tau = \tau_0 + T \cos 4\theta
\]  

(1)

where \(\theta\) is the angle relative to the rail axis and \(T\) is a coefficient determined by the texture in the rail. If a longitudinal stress is present (such as a thermally generated stress), this four fold symmetry is modified by a term that depends on the cosine of \(2\theta\) so that the general form is:

\[
\tau = \tau_0 + S \cos 2\theta + T \cos 4\theta.
\]  

(2)

Theory \{2\} shows that the coefficient \(S\) is a linear function of the stress that depends only on the shear modulus \(G\) of the material and not on any third order elastic constants of the material. To be specific,

\[
S = \tau_0 \sigma / 4G
\]  

(3)

where \(\sigma\) is the axial stress. Therefore, by simply making a graph of the transit time as a function of \(\theta\), the coefficients \(S\) and \(T\) can be determined and the effects of stress and texture can be separated without any reference to calibration experiments that determine the metallurgical state of the specific rail being tested.

The experimental problems with this approach are: (1) the transducers must be able to excite and detect a clean surface skimming SH wave, (2) the coupling between the transducer and the surface cannot introduce any phase shifts as the transducer pair is rotated and (3) the separation distance between the transducers must be held constant to an accuracy of a few parts in \(10^4\) during the rotation.

**TRANSUDER DESIGN**

The electromagnetic acoustic transducer or EMAT \{6\} is the only transducer that can easily excite and detect surface skimming SH waves. In fact, it can do so by two different mechanisms \{7,8\} that are distinguished by the orientation and magnitude of the magnetic field required by this class of transducer. Both designs were investigated for this application to stress measurement in rails but only one gave results that satisfied Eqn. 3. This transducer operates by applying a very high magnetic field to the rail in a direction parallel to the surface of the rail. SH waves are induced by a meander coil oriented with its long wires parallel to the magnetic field through a magnetostrictive mechanism \{8\}. The high, tangential magnetic field was supplied by a spiral wound coil of copper wire that was powered by a pulsed current source capable of delivering 300 amperes in a pulse with a duration of about 1/2 millisecond. Figure 1 shows a diagram of this transducer. Note that the meander coils are positioned along a radius of the magnetizing coils where the magnetic field is essentially parallel to the long dimension of the meander. Four meander coils are available for directly measuring the
transit time difference along two orthogonal paths although only two diametrically opposed coils are needed to produce the time versus angle data called for by Eqn. 3. Fig. 2 shows how the amplitude of the SH wave generated by this EMAT varied with the current in the magnetizing coil along with an approximate measurement of the tangential field in the gap between the coil and the steel surface where the EMAT coil is located.

In order to test this EMAT, a 12-inch long section of rail (140 lb/ft) was mounted in a mechanical testing machine capable of delivering a 200,000 pound compressive load along the rail axis. Electronic circuits described previously [9] were used to simultaneously generate two 1 MHz SH waves propagating in the surface of the web along orthogonal paths. A Hewlett-Packard Model 5335A Universal Counter was used to measure the difference in transit time of these two waves across the face of the two-inch square area between transducers shown in Fig. 1. This counter also averaged together 100 readings so its output was a statistically significant quantity. Eqns. 2 and 3 predict that the difference in transit time should be a linear function of the stress in the rail and should have a magnitude of 1.2 nsec/ksi. By loading the rail in the mechanical testing machine to known stress levels and by plotting the transit time difference as a function of stress, the actual value of the time/stress coefficient was determined. It was found that this experimental value was in agreement with the theoretical value only at high values of the magnetic field as if the material had to be magnetically saturated before it would obey the symmetry arguments used to derive Eqn. 3. This result was anticipated because the alternate method of generating SH wave with a periodic array of small permanent magnets gave results in disagreement with Eqn. 3 whenever a large biasing field was not present [9]. Such a result might also be anticipated from the fact that the arguments that yield Eqn. 3 require coincidence of the texture symmetry axes with the polarization and propagation directions. In a magnetic material, the direction of magnetization should probably be aligned and held along a symmetry axis in order to minimize magnetic contributions to the shear wave velocity.
RESULTS

The EMAT probe shown in Fig. 1 has a flat face and is best used on flat surfaces so it was not tested on railroad rail webs because they have a marked curvature. Instead three common structural steel shapes with wide flat surfaces were obtained. These shapes were an eight inch web I beam, a six-inch square tube and a 4-1/2 inch by 2-3/4 inch rectangular box that was fabricated out of four pieces of flat plate welded together at the corners. Each was cut to a 12-inch length and the cut ends ground flat and parallel so that the loading platens of the compression machine would fit well and apply a uniform load. The EMAT diagrammed in Fig. 1 was mounted on a frame that attached to the sample with a magnetic clamp. Fig. 3 shows the angular variation of the transit time across the two-inch space between EMATs. Thus, $\tau$ in Eqns. 1-3 is 16 $\mu$s. A least squares fit to these curves by Eqn. 2 shows that they are dominated by the $\cos 4\theta$ term arising from the texture and that the coefficient of the $\cos 2\theta$ term is small as would be expected for the case of zero applied stress.

Fig. 4 shows the changes in the angular dependence that occurred when various levels of compressive stress were applied to the rectangular box sample. When Eqn. 2 is used to analyze these data, it was found that the coefficient of the $\cos 2\theta$ term was a linear function of the stress as predicted by Eqn. 3. Since there are no adjustable parameters in Eqn. 3, it can be used to calculate the stress level present. The top graph in Fig. 5 shows a comparison between the stress predicted by Eqn. 3 and the actual stress as deduced from the applied load and the cross sectional area of the box and the tube sections.

Since the $\cos 4\theta$ term caused by texture should not change during the application of the stress and since the orthogonal EMATs in the probe (see Fig. 1) allow the transit time at $\theta = 0^\circ$ and $\theta = 90^\circ$ to be measured simultaneously, it is a simple modification of the apparatus to directly measure the transit time difference between sound wave paths at $\theta = 0^\circ$ and $\theta = 90^\circ$. Solving Eqns. 1-3 for this case leads to a simple, linear
Fig. 3. Angular dependence of the transit time over a two-inch path on the flat face of three commonly used structural steel shapes. The horizontal axis covers 180 degrees. The vertical axis is marked at 20 ns/division.

Fig. 4. Changes introduced to the angular dependence of the transit time when a compressive stress was applied to the square tube structural element.
Fig. 5. Comparison of the stress induced from the ultrasonic measurements via Eqns. 2 and 3 with the actual applied stress. Top curve: deduced from the coefficient of the cos2θ term. Bottom curves: deduced from the transit time difference over two orthogonal paths.

relationship between the transit time difference and the stress which allows the stress to be predicted. The bottom curves in Fig. 5 compare the stress level predicted from the measured transit time difference with the actual stress level as deduced from the applied load and cross sectional area of the box and tube samples.

Because Fig. 5 shows very good agreement between theory and experiment for the case of compressive, static loads, it is important to verify that the theory also applies to thermal stresses. To test this case, the angular dependence of the transit time was recorded for one face of the box sample at room temperature and with no load applied. These data are shown as the circle points on Fig. 6. The box was then heated by an electric heater on the inside of the box and a load was applied by the compression machine to keep the length of the box fixed. (Dial indicator gages to measure changes in the length of the box were used for this purpose.) At a temperature of 84°C, the angular dependence of transit time was again measured and these data are shown as the triangles
Fig. 6. Change in the angular dependence of the transit time when the box beam sample was heated to $84^\circ C$ while constrained to prevent thermal expansion.

In Fig. 6. By calculating the thermally induced stress expected to be generated by such an experiment (20 ksi) and inserting it into Eqn. 3, a 15 nanosecond shift in the angular dependence curve at $\theta = 90^\circ$ would be predicted. Such a shift is marked on Fig. 6 and is quite consistent with the experimental data.

REFERENCES

3. SBIR Contract DTRS-57-86-C-00125, "Longitudinal Stress (Force) Measurement of Rail Under Operating Conditions."