MEASUREMENT OF THERMAL STRESS IN RAILROAD RAILS USING ULTRASONIC SH WAVES

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ABSTRACT

The use of welded joints in railroad tracks has led to problems of rail buckling brought about by the development of large compressive stresses during hot days. On cold days, tensile stresses can actually fracture the rail. In order to prevent this source of derailments, it is desirable to develop an easily used instrument to measure the level of stress in an arbitrary section of track in the field. Ultrasonic birefringence, acoustic emission and certain magnetic phenomena have all been used to attack this problem but they all suffer from the necessity for calibrating the sensor under stress-free conditions in order to correct for metallurgical structure variations. A new ultrasonic technique based on using surface skimming shear horizontal ultrasonic waves generated and detected by EMATs was investigated here because it rigorously eliminates the effects of metallurgical texture as well as unreliable coupling of the transducer to the part. Tests on sections of rail mounted in a 200,000 pound testing machine at the University of New Mexico demonstrated that the theory for the basic phenomenon is correct and that the stress level can be measured in spite of the presence of considerable texture in the rail microstructure.

INTRODUCTION

For a variety of economic and mechanical reasons, most railroad track is now welded together in long lengths before it is installed. This causes large compressive or tensile stresses to be built up as the temperature varies between the heat of the day and the cold of the night. It has been reported [1] that in 1977 alone, there were 109 train derailments resulting in over $5.5 million in damage caused by track buckle. It is clear that an instrument capable of monitoring the stress level in a section of rail by nondestructive techniques could simplify the detection of dangerous conditions and lead to the prevention of track-buckle related accidents. A recent (1982) study sponsored by the DOT and performed by the National Materials Advisory Board [1] reviewed all the possible techniques that have been studied in the past and concluded that use of the acousto-elastic effect [2] appeared promising if a better understanding of the role played by microstructure and especially texture in the steel comprising the rail could be developed.
The present research program was undertaken because there have been recent theoretical discoveries concerning the relationship between the acousto-elastic effect and the texture present in structural materials as well as developments of new ultrasonic transducers. To be more specific, it has been shown that electromagnetic acoustic transducers (EMATs) can excite shear horizontal (SH) waves that skim along the surface of a material without any errors due to coupling media \cite{3} and that measurements of the propagation velocity of these waves in certain directions can be used to directly deduce the level of stress independent of the microstructure and the texture of the material \cite{4}.

THEORETICAL BACKGROUND

Recent theoretical \cite{4} and experimental \cite{4,5} studies have shown that surface skimming SH waves can be used to measure the stress level in a material independent of the texture and metallurgical conditions. This new approach to acousto-elastic measurements is based on very general symmetry properties of the stress tensor so it does not depend on any special coefficients such as the nonlinear or third order elastic constants of the material. Specifically, the general stress-velocity equation can be written for our case of longitudinal loading of a rail as

\begin{equation}
\sigma_i = \rho \left( \frac{V_{ij}^2 - V_{ji}^2}{2V_{ij}} \right) = 2\rho V_{ij}^2 \left( \frac{V_{ij} - V_{ji}}{V_{ij}} \right)
\end{equation}  

where \(\sigma_i\) is the stress in the i (longitudinal) direction, \(\rho\) is the material density, and \(V_{ij}\) is the velocity of a shear wave propagating in the direction of the first subscript and polarized in the direction of the second subscript. The most serious restriction on the use of the equation is that directions i and j must be symmetry axes of any texture in the metal. For rails, this condition is easily met because the rolling direction is parallel to the longitudinal axis of the rail and the gross symmetry of the rail cross section puts a second symmetry direction in the plane of the web at right angles to the axis. Equation 1 can, therefore, be rewritten in a more appropriate format as

\begin{equation}
\sigma = 2G \left( \frac{t_I - t_H}{t} \right)
\end{equation}  

where \(\sigma\) = the longitudinal stress in the rail, \(G\) = the shear modulus of steel = 11 x 10^6 psi, \(t = \rho V_{ij}^2\) for shear waves in steel, \(t_I = \frac{V_{ij}^2}{V_{ij}}\) for SH waves over the fixed distance between transmitter and receiver, \(t_I - t_H = \) difference in transit time between a surface skimming SH wave propagating perpendicular and parallel to the stress.

EXPERIMENTAL APPROACH

Excitation of Surface Skimming SH Waves

The key to successful application of the texture independent ultrasonic stress measuring technique is the ability to launch and detect a shear wave whose polarization and propagation directions can be easily interchanged. This criterion can be met by surface skimming shear horizontal or SH waves excited and received by specially designed ultrasonic transducers that operate by electromagnetic induction mechanisms. There
are actually two different types of these devices available to the rail stress problem because the material is ferromagnetic and possesses magnetostrictive properties. The most commonly used SH wave transducer operates on any metal and is constructed from a periodic array of small permanent magnets with a single coil of wire sandwiched between the surface of the part and the magnets [6]. For such EMATs to be used on rails, the complete magnet array must be small enough to fit on the web of the rail and the wavelength must be smaller than the thickness of the web in order to avoid standing wave modes in the thickness dimension. These dimensional restrictions made the EMATs very sensitive to the gap between the magnets and the rail surface and thus too difficult to use on the rough surface of the web.

The second method of getting SH waves is to use a meander type EMAT coil and a uniform magnetic field [3]. Here, the transduction mechanism is based on the saturation magnetostriction of the material and very large \( H = 1,000 \) to 2,000 oersted, \( B = 21,000 \) to 22,000 gauss) magnetic fields parallel to the surface must be used. The EMAT coil is of the meander shape and the field is applied parallel to the long dimension of the wires in the coil. By using pulsed electromagnets, the high tangential magnetic fields could be generated by a magnet that was small enough to fit on the web of the rail between the rail head and the base. For the experiments discussed here, two pulsed electromagnets were mounted side-by-side on the web of a railroad track. Both magnets were identical so that either could be used perpendicular or parallel to the rail length for wave velocity measurements in the short or long dimensions of the web. By using two electromagnets in this way, it was possible to make a simultaneous and direct measurement of the difference in transit time over paths that were parallel and perpendicular to the rail length.

**Electronic Circuits**

The measurement objective was to accurately determine the difference in velocity of two SH waves traveling over paths parallel and perpendicular to the direction of a stress which was along the length dimension of the rail. If the separation distance between transmitter and receiver transducers is absolutely fixed, this velocity difference can be reduced to a measurement of the difference in time of travel for the two waves over two orthogonal paths. To achieve this latter objective, the two transmitter EMATs were wired in series so that they launched their SH waves at the same time and the difference in arrival time of the signals from the two receivers was accurately measured by a commercial Time Interval Counter. A block diagram of the measurement electronics is shown in Figure 1. The gate circuit following each of the receiver amplifiers was designed to separate out one of the zero crossings of the signal in the middle of the received tone burst. Usually, the two zero crossings for the two acoustic paths were chosen to be within one period of the tone burst. Each zero crossing triggered its own sharp timing pulse which was then used to start or stop the time interval counter. Thus, the counter directly registered the time difference between two adjacent cycles of the tone burst in the two receiver channels. By allowing the time interval counter to average 100 or 1,000 of these small intervals, a value for the average difference in arrival time could be displayed. This average time difference was found to have an accuracy of a few tenths of a nanosecond.

Since the separation distance between the centers of the EMAT coils was 1.75 inches and the velocity of propagation of an SH wave in steel is 0.127 inches per microsecond, the transit time was 13.8 microseconds. Thus a change of one nanosecond in the transit time represented a relative shift in velocity of sound of \( 7.2 \times 10^{-5} \). Most of the experiments were performed with ultrasonic waves at a frequency of 2 MHz so the time between zero crossings within one tone burst signal was 250 nanoseconds and the maximum
time separation between adjacent positive-going zero crossings in the two receiver channels was 500 nanoseconds.

EXPERIMENTAL RESULTS

Stress-Strain Relations

A large mechanical testing machine at the University of New Mexico was used to apply both compressive and tensile loads to especially prepared rail samples picked from a set of 35 rails available to Magnasonics. Tensile samples were prepared by cutting the rail to a 48-inch length. Compression specimens were cut to a length of 12 inches and their end faces were ground flat and parallel so that they would sit exactly square on flat anvils attached to the testing machine. Electrical resistance strain gages were attached to the center of the web and to the center of the base at the center of the rail samples so that both the transverse and longitudinal strains could be directly measured as a function of the load applied by the machine. The samples used were cut from a 136 pound/yard sample made of standard carbon steel and had a cross sectional area of 13.3 square inches. Therefore, at a 200,000 pound load the stress level was 15 ksi. The strain readings observed in directions parallel and perpendicular to the stress direction were quite consistent with what would be expected from calculations based on the Young's Modulus and Poisson's ratio for carbon steel. Thus, the mechanical testing machine and grip arrangement was applying a simple, axial load to the rail and the transverse stresses could be assumed to be zero or negligible.

Tests with Fixed EMATs

In order to test the validity of the stress-velocity equation, the two pulsed magnets were held against the web of the rails with a simple clamp when the rails were mounted in the mechanical loading machine. One magnet and its EMAT pair were mounted such that the SH wave would propagate over a path that was parallel to the direction of stress while the other was mounted nearby in a manner to allow the SH wave to propagate perpendicular to the stress direction. Although the two paths involved different physical locations, the difference in transit time when the load was applied should still measure the stress level.
Figure 2 shows the difference in transit time between the SH waves propagating parallel and perpendicular to the tensile stress while the mechanical testing machine increased and decreased its applied load in steps over a period of time. The data taken during the approximately 20 seconds required to change the load has been omitted in order to make the data taken at fixed load more clear. Obviously, the effects of application or removal of 3-3/4 ksi load increments are quite clear and the general drift of the time difference over the approximately 400 seconds (7 minutes) required to complete the loading and unloading is small compared to the stress effects. Note that the application of a tensile load caused the transit time for the SH wave propagating parallel to the stress direction to be decreased and the time difference \( t_1 - t_u \) to be reduced. When the time interval counter was reversed to measure the time interval \( t_u - t_1 \) the opposite change in the time difference was observed.

The changes in time difference produced by a compressive load were also measured in the same way. Here the transit time for the SH wave propagating parallel to the stress was increased and the time difference \( t_1 - t_u \) increased. This response was opposite to that observed in the tension case as would be predicted by the theory when the direction of the stress is reversed. In order to obtain these compression data, it was more convenient to hold the EMATs against the base of the rail and to use a surface that had been cleaned of its oxide layer by a grinding wheel. Thus the compression data were obtained under somewhat different conditions from the tensile data but yielded very similar results.

Figure 3 shows how well quantitative agreement could be obtained with the predictions of Eqn. 2. The values for the time shifts were read from data like that shown in Figure 2 and the stress levels were calculated from the load and cross sectional area of the rail. The dashed line was calculated from Eqn. 2 using the shear modulus of steel and the transit time for an SH wave between the EMAT used in these tests (13.8 usec). There are no adjustable parameters or calibration constants for the materials involved. There appears to be a systematic difference between the tension case and the compression case which may arise from the fact that the compression data was taken on the base of the rail after it had been cleaned of its oxide layer by a grinding wheel. Thus the compression data were obtained under somewhat different conditions from the tensile data but yielded very similar results.

**Tests with EMAT Motion**

The tests described above demonstrate that the stress-velocity relationship provided by Eqns. 1 and 2 can be used to measure the stress if a value for \( t_1 - t_u \) is known at the zero stress condition or at any other initial stress level. Thus, it is an improvement over the methods that require an a priori knowledge of the texture in the part because no acousto-elastic constants need be known. In order to improve the technique even further by eliminating the need for knowing the texture, a measurement procedure should be developed that utilizes the fact that the symmetry of the stress tensor demands that the absolute values of the SH wave velocity be identical parallel and perpendicular to the rail axis in the absence of a stress. The optimum procedure for exploiting this fact would be to physically interchange the parallel and perpendicular acoustic paths by rotating the EMAT pairs through 90 degrees. This method could cancel effects caused by path length and temperature difference but it could still be affected by inhomogeneities in the steel if the acoustic paths did not exactly coincide. Unfortunately, this method could not be demonstrated clearly in the present study because both of the two pulsed electromagnets would have to be rotated simultaneously and the resulting measurements could still be different because different volumes of metal were measured by each EMAT.
Figure 2. Changes in the transit time difference caused by tensile loads being applied to a rail sample.

Figure 3. Comparison between observed transit time shifts (solid lines and points) and shifts calculated from Eqn. 2 (dashed line) as a function of stress in the rail.
Nevertheless, such measurements were made to assess the degree to which inhomogeneities in the velocity of sound on a dimensional scale comparable with the spacing of the EMATs could change the data. It was observed that simply translating one EMAT relative to the other along the web caused fluctuations of approximately 10 nanoseconds in one quarter of an inch when the surface was in its oxidized state. When the surface had been cleaned by grinding off the oxide, the velocity was observed to change randomly by a few nanoseconds in an inch. There were also some variations that correlated with the general rail geometry as would be expected from local variations in texture caused by the different degrees of working required to fabricate the rail shape. Another source of error was traced to the fact that the pulsed magnets heated the metal in the vicinity of each magnet so that translation or rotation of the EMATs changed the temperature distribution in the rail and therefore changed the local values of the sound velocity.

The overall amount of texture in the base of a rail was measured by observing the changes in $t_\parallel - t_\perp$ when one EMAT pair and its electromagnet were rotated relative to the other on the base of a rail. The results of these variations corroborated the initial assumption that the surface skimming SH wave has the same velocity when propagating either parallel or perpendicular to the long axis of the rail. Thus a rigorous adherence to measuring the shear wave velocities only in the directions parallel and perpendicular to the rail axis should eliminate the gross effects of texture. By also being careful to make sure that the two shear waves sample the same volume of material, local variations in sound velocity can be averaged out and eliminated from the measurements.

CONCLUSIONS

1. Although texture in the microstructure of a rail is large, the difference in wave velocity of SH waves propagating parallel and perpendicular to the rail axis is small as expected from arguments based on the symmetry of the stress tensor.

2. The magnitude of the difference in SH wave velocity between the parallel and perpendicular directions is a linear function of the level of stress and changes sign between compression and tension states.

3. The theoretical value of the coefficient relating the stress to the velocity difference involves only well known quantities and agrees with the experimental observations for compressive stresses. It may be in disagreement for tensile stresses but the origin of this discrepancy may be related to the condition of the surface oxides.

4. Successful prediction of the stress level in an arbitrary rail using only measurements of the difference in SH wave velocities appears to be practical if precautions are taken to insure a constant EMAT separation and wave paths that interrogate identical volumes of materials from the two orthogonal directions.

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REFERENCES


