ULTRASONIC CHARACTERIZATION OF RESIDUAL STRESS AND TEXTURE IN CAST STEEL RAILROAD WHEELS

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ABSTRACT

An ultrasonic technique has been used to characterize the state of residual stress and texture in the rims of cast steel railroad wheels. Orthogonally polarized shear-horizontal (SH) waves are propagated through the thickness of the rim in pulse-echo mode. The (normalized) difference of arrival times of these waves (acoustic birefringence) depends upon both texture and stress. The birefringence, B, was measured with two transducers: an electromagnetic-acoustic transducer (EMAT) and a piezoelectric transducer made of PZT.

Two wheels were tested. The first wheel had a sawcut, which locally relieved the residual (hoop) stress. Measurement of the birefringence at the sawcut allowed us to estimate the contribution of texture, which we subtracted from values of B at stressed locations. Values of hoop stress obtained with the EMAT and PZT transducer agreed to within 10 MPa, for transducers placed on the center of the back face of the rim.

The second (uncut) wheel had been heat treated and air quenched, giving a different microstructure. Measurements of B were made with both transducers at different radial and circumferential locations. We estimate that the values of hoop stress obtained with the two transducers will differ by less than 25 MPa for this wheel. Furthermore, the EMAT required less surface preparation of the rim than the PZT transducer, indicating the potential for use of EMATs for residual stress measurements in the field.

INTRODUCTION

Residual stresses can be a significant factor in railroad wheel failure. These residual stresses have two origins: (1) stress due to fabrication of the wheel and (2) in-service stress induced by drag braking.

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For cast steel wheels, fabrication stresses occur during cooling due to differential shrinkage. If these stresses are above the yield stress, inhomogeneous plastic deformation results and residual stresses are then necessary so that compatibility is satisfied.

The same process that creates residual stresses during cooling occurs (in reverse) during drag braking. The heat input into the tread of the wheel during braking causes expansion of this region of the wheel. Each volume element of the rim tries to expand but is constrained by its neighbors. If the resulting compressive stresses exceed yield stress, inhomogeneous plastic deformation results; as the wheel cools after braking, a tensile hoop stress will result to make all the regions of the rim fit together.

Residual stresses due to fabrication are compressive, while those due to drag braking are (usually) tensile. When the latter stresses exceed the former, the rim will be in a state of net tensile stress. If a crack occurs in the rim, those tensile stresses will act as crack-driving forces and that can lead to wheel failure. Therefore it is highly desirable to have a non-destructive testing method for measuring such residual stresses.

In this paper, we present results of a study on the feasibility of using ultrasonic methods to characterize residual stress state in cast steel railroad wheels.

THEORY

It can be shown, both analytically and experimentally, that the presence of stress in metals induces a small sound velocity change. For isotropic materials, the normalized difference in velocity of orthogonally polarized shear-horizontal (SH) waves is proportional to the difference of principal stresses. This normalized difference in velocities is called the acoustic birefringence, in analogy to the birefringence effect in photoelasticity, so

\[
B = \frac{V_\theta - V_r}{1/2(V_\theta + V_r)}, \quad (1)
\]

where \(V_\theta\) and \(V_r\) are velocities of SH-waves polarized in the hoop and radial directions respectively.

For anisotropic (textured) materials, birefringence depends on texture and principal stresses \([1,2]\):

\[
B = B_0 + C_A(\sigma_\theta - \sigma_r), \quad (2)
\]

where \(B_0\) is unstressed birefringence due to texture, \(C_A\) is stress-acoustic constant and \(\sigma_\theta\) and \(\sigma_r\) are principal stresses in hoop and radial directions.

Combining equations (1) and (2) we have

\[
\frac{V_\theta - V_r}{1/2(V_\theta + V_r)} = B_0 + C_A(\sigma_\theta - \sigma_r). \quad (3)
\]

From equation (3) it is possible to calculate the difference in principal stresses if the unstressed birefringence and velocities of orthogonally polarized shear waves are known.
Instead of measuring velocities $V_\theta$ and $V_r$, we actually measure arrival times $T_\theta$ and $T_r$ of shear waves polarized in hoop and radial directions. Since the SH-waves propagate through the same thickness,

$$\frac{V_\theta - V_r}{1/2(V_\theta + V_r)} = \frac{T_r - T_\theta}{1/2(T_r + T_\theta)},$$

so that the equation for calculating the difference in principal stresses is given by

$$\frac{T_r - T_\theta}{1/2(T_r + T_\theta)} = B_0 + C_A(\sigma_\theta - \sigma_r).$$

Problems arising in using equations (5) for obtaining the difference in principal stresses are: (1) the influence of texture and (2) the small value of stress-acoustic constant $(C_A \sim 10^{-5}/\text{MPa})$. The value of $B_0$ can be obtained by measurements on unstressed reference samples (provided that the wheels are sufficiently homogeneous). Because of the small value of the stress-acoustic constant, we use electronics capable of measuring arrival times within $\pm 1$ ns.

EXPERIMENTS

Fukuoka et al. used conventional piezoelectric SH-wave transducer to measure the residual stress state in rolled steel wheels [3,4]. They measured birefringence in the as-received state (residual stress due to rolling), after drag braking, and after cutting into blocks (stress relieved). The total residual stress measured ultrasonically was compared with destructive measurements and agreed within 40 MPa [3,4].

In our work, we investigated the feasibility of using electromagnetic-acoustic transducers for measurements in the field. The EMAT has the advantage that it requires no acoustic couplant to generate sound in a metal. Consequently, an EMAT can be scanned and rotated over the rim of the wheel with ease. Being noncontacting, an EMAT may require less preparation of the surface (where the sound is generated) than a piezoelectric device.

To determine whether these potential advantages could be realized in practice, we performed a series of experiments on two cast steel wheels (one sawcut and one uncut) which had been removed from service. We measured the birefringence with an SH-wave EMAT in pulse-echo setup using a simple velocity measurement system (described elsewhere [5]). We also measured the birefringence using the same piezoelectric transducer used in Refs. 3 and 4. The birefringence method using this piezoelectric transducer has been successful in determining residual stresses in rolled wheels [3,4]. Consequently, we used results obtained with this transducer as a benchmark against which our EMAT measurements were compared.

The first set of measurements was made on a sawcut wheel. The measurements were made from the back face of the rim, 19 mm from the inner edge of the rim. This corresponds to the centerline of the front face (see Fig. 1).

Six different regions of the back face of the rim were milled in preparation for using both PZT and EMAT transducers (see Fig. 2). We measured the birefringence near the center of each milled region at least three times with both transducers. The values of birefringence thus obtained are plotted in Fig. 3. The error bars represent the standard deviation of the measurements of birefringence at each of the milled regions.
Fig. 1. Cross-section of rim, of cast steel railroad wheel. Transducers placed on back face; center of ultrasonic beam shown as broken line.

Fig. 2. Top view of sawcut wheel. Shaded regions correspond to areas where back face of rim was milled.

We were able to measure $B_0$ for the wheel as the mean value of the birefringence measured on both sides of the sawcut. Knowing $B_0$ we could convert the birefringence measurements to stress. We used the same value for the stress-acoustic constant $C_A (-7.6 \times 10^{-6} / \text{MPa})$ that was used in Refs. 3,4 and subtracted $B_0$ from $B$ to obtain $\sigma \varphi - \sigma_n$ (see equation 2). Results obtained are shown in Fig. 4 for both transducers.
Fig. 3. Birefringence as function of circumferential position.

Fig. 4. Principal stress difference as function of circumferential position.

There are several interesting features in this figure. First, there is good agreement between EMAT and PZT results. In fact, the difference of peak stress measured with the different transducers is less than 10 MPa.

Second, the peak stress occurs at 180° circumferentially around the wheel from the sawcut. This is in qualitative agreement with results obtained by researchers at Transportation Test Center [6]. They found that sawcutting relieved the stress near the cut but left the stress 180° from the cut almost unchanged.
Third, the EMAT results are almost symmetric about 180° (the line opposite the sawcuts). In fact, if the residual stresses and the degree of texture were homogeneous, one would expect \( \sigma_0 - \sigma_r \) to display this symmetry after sawcutting. The symmetry of the EMAT results is encouraging, since it does indicate that the residual stresses and the texture were axisymmetric prior to sawcut. This reduces the number of required measurements around the rim of the wheel.

With the EMAT we made measurements not only on the milled regions, but also at other locations where we used various surface preparation treatments. The results obtained using the EMAT on these variously prepared surfaces are indicated by different symbols in Fig. 4. Qualitatively, it appears that the degree of surface preparation is not particularly significant for EMAT measurements.

A second set of birefringence measurements was made with both an EMAT and PZT transducer on an uncut cast steel wheel which had been heat treated and air quenched. This process results in a grain structure which is finer than in cast steel wheels and consequently shows a better signal-to-noise ratio in ultrasonic measurements. Measurements were performed on the front face of the wheel, which is the side accessible in the field.

To characterize the effect of surface preparation we made measurements at the center of the front face of the rim and for varying degrees of surface preparation. Results of these measurements at different circumferential locations are shown in Fig. 5. For comparison we also have shown results obtained by the PZT transducer on a milled surface at the same locations. There is a good agreement between results obtained by EMAT and the PZT transducer. The difference in EMAT birefringence measurements for different surface preparations is usually less than 2 x 10^-4. This is equivalent to a stress uncertainty of about 25 MPa, assuming a value of -7.6 x 10^-6/MPa for the stress-acoustic constant, C_A.

The good agreement between EMAT measurements on surfaces with varying degrees of surface preparation is quite encouraging. From a practical point of view, it minimizes the amount of time or labor necessary to prepare the surface.

![Fig. 5. Effect of surface preparation on birefringence measurements.](image-url)
We were also interested in determining whether there is a radial variation of birefringence. (In fact, a radial dependence of birefringence was found by Fukuoka, et al. [3,4] on rolled steel wheels, using the PZT transducer). We measured the birefringence at 5 different radii, at 4 different circumferential positions (marked as 0°, 90°, 180° and 270°). Both EMAT and PZT measurements were made after the wheel was milled.

The results of the birefringence measurement at different radii are shown in Fig. 6. The data points are the mean value of measurements at 4 circumferential positions, and the error bars represent the standard deviation. The birefringence has a gradient, becoming increasingly negative as the outer edge of the rim is approached. The gradient as measured by the EMAT is almost linear and, assuming a constant texture, it has value of about 6 MPa/mm.

In the ideal case, both the texture and residual stress would be axisymmetric. If this is the case, then the standard deviations of B shown in Fig. 6 would vanish. The presence of the standard deviations (which are larger than experimental errors) implies that there is some asymmetry in the birefringence. To show this asymmetry better, we have plotted the birefringence as a function of circumferential position in Fig. 7, with the radial distance (from center of the rim) as a parameter.

![Fig. 6. Radial variation of birefringence.](image)

![Fig. 7. Birefringence as function of circumferential position, for radii of +6 mm, -3 mm. Radial position measured outward from center of front face of rim.](image)
For axial symmetry, the birefringence would be a straight line with zero slope (constant as function of circumferential position). The data in Fig. 7 for the radius -3 mm from center of the rim show a departure from axial symmetry with a minimum algebraic value of B in the region about 180° (with good agreement between an EMAT and a PZT measurements). On the other hand, the values of B for +6 mm from the center of the rim show not only good agreement for both transducers measurements but also a behavior which is very close to axial symmetry.

CONCLUSIONS

We have performed proof-of-concept experiments which show that EMATs can be used to characterize residual stress in cast steel railroad wheels. We have developed a system which measures arrival times with an electronic precision of ±1 ns, for pulse-echo operation.

The birefringence was measured on two railroad wheels with different microstructure. The cast steel wheel had a sawcut, which enabled us to measure \( B_0 \) and hence convert our birefringence measurements to stress. We found good agreement between piezoelectric and EMAT results (stresses agreed to within 10 MPa). We also found that the EMAT was somewhat insensitive to surface preparation.

On the heat-treated wheel, we characterized this sensitivity and found that the scatter in EMAT results due to surface preparation was equivalent to about 25 MPa. This indicates that for practical use (e.g. in a railroad yard) only minimum surface preparation may be necessary.

We measured the birefringence on this wheel as a function of both radial and circumferential position. A steep gradient of birefringence in the radial direction was found; if the texture is homogeneous, the gradient was about 6 MPa/mm. Values of birefringence measured with EMAT and piezoelectric transducers were in good agreement, showing that the EMAT could be used to resolve this steep gradient.

The birefringence in the rim was found to be nearly axisymmetric close to the tread (where the wheel sits on the rail) but more erratic as the inner edge is approached.

To determine the accuracy of the method, we plan to perform destructive tests to measure the residual stress. Blocks cut from the rim will be used to measure \( B_0 \). An average value will then be used in equation (5) for ultrasonic predictions of residual stress and comparison made with destructive results.

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REFERENCES


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