STRESS MEASUREMENT IN RAILROAD RAIL USING ULTRASONIC AND MAGNETIC TECHNIQUES

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INTRODUCTION

The nondestructive measurement of stress is a continuing concern to the railroad industry. Severe web cracking tendencies in some rails have been linked to high residual stresses created during rail production. Rails are plastically deformed during the final stage of production, known as roller-straightening. While most rails have the same characteristic stress distribution afforded by this process, safety concerns warrant the detection of pronounced stress levels that would lead to exaggerated cracking behavior.

Two techniques were evaluated in this study for their ability to detect stress distributions along a particular rail. Previous efforts identified this rail as having a pronounced longitudinal stress gradient. The instruments used to inspect for these stress characteristics were: an ultrasonic-based device developed by the Polish Academy of Sciences and marketed commercially as the Debro-30 Ultrasonic Stress Meter, and a device developed by the Center for NDE at Iowa State University that performs magnetic hysteresis tests, known as the Magnescope.

TEST PRINCIPLES

This section provides a very brief overview of the test principles behind the two methodologies used in this study. Previous articles in this series provide better detail [1,2], and the reader is encouraged to review them.

Ultrasonic Testing with the Debro-30

The Debro-30 has been demonstrated to credibly provide analyses of residual stress

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 14
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1995

states in rails [3]. Test implementation is based on a linear dependence of ultrasonic velocity as a function of stress. In practice, a probehead containing several ultrasonic transducers transmit subsurface compressional waves over short and long distances along a test specimen. Signal times-of-flight are detected through cursor adjustment on an oscilloscope, and this data is stored in a microprocessor. Specimen temperature is monitored with a thermocouple, and times-of-flight are adjusted for offset from a calibration setpoint value.

The acoustoelastic constant of the material controls the rate of change of ultrasonic velocity (or time-of-flight over a fixed distance) with respect to stress in the material. This constant, along with the time-of-flight data mentioned previously, is used as input to the Debro's computations for stress determination. Additionally, a stress-free calibration sample must be provided to allow for time-of-flight calibration in the absence of stress.

Magnetic Hysteresis Testing with the Magnescope

The sensing probe of the Magnescope consists of an electromagnet, a flux-sensing coil winding, and a Hall probe for magnetic field strength indications combined into an integral unit. A power supply, fluxmeter and multimeter are included in the mainframe of the device, and a portable PC controls the test and data acquisition. During the course of a test, the probehead is clamped to the specimen surface. The instrumentation runs through a demagnetization step, followed by a magnetic hysteresis loop. The values of applied field and detected flux are thus plotted out to create an apparent hysteresis loop. The data that is recorded includes magnetic coercivity, remanence, maximum differential permeability and hysteresis loss.

These values are labelled "apparent" as they are taken with the electromagnet incorporated into the magnetic circuit. Absolute, or intrinsic properties, are arrived at by placing specimens inside of a solenoid and inducing a magnetic field in the sample. The apparent values, however, may be adjusted through the use of suitable transfer functions to provide insight into the intrinsic properties of the test material. Alternately, the analysis of apparent properties, while not providing absolute quantitative data, generate information regarding changes in magnetic response to varying microstructure and stress. Of course, use of the Magnescope to determine apparent magnetic properties is eminently more suited for industrial NDE.

PROCEDURE AND RESULTS

Sample Pedigree

The two methods described above were used to detect longitudinal stress distribution in a particular length of rail. As stated earlier, roller-straightened rail typically exhibits a characteristic distribution of longitudinal residual stress. Figure 1 shows the roughly parabolic distribution of stress (tension in the head and base, compression in the web) that has been shown to arise from the roller-straightening process. The rail in question was expected to also exhibit this pattern, but not over the entire length of the specimen.

Modern railroad rail is rolled in 80 foot lengths. One domestic manufacturer of rail crops off the irregular end of the hot-rolled product prior to roller-straightening. The roller straightening device consists of offset rollers that plastically deform the rail to straighten it. The alternate rollers are spaced about 30 inches off center from one another. This means that rails which come from the manufacturer cited will exhibit a stress gradient over the first 30 inches of material, as only beyond this point will the rail experience the reverse bending of the offset rollers. This behavior has been documented in industry experience [3], and the specimen in question was expected to demonstrate the same idiosyncrasy. Thus, a sample was selected wherein longitudinal stresses would be expected to vary in a predictable manner. Additionally, one side of the head, web and upper base regions were milled flat to remove surface scale. This was done to provide information about the influence of surface condition on test performance.

Finally, it should be mentioned that the Debro device was used as the referee test in this study. Because of favorable prior experiences in stress measurement, no destructive measurements were made to confirm the stress data provided by the Debro. The rationale behind testing alternate methods for nondestructive stress evaluation is a desire to minimize the need for calibration on stress free components. This requirement somewhat limits the applicability of the Debro in industry-wide applications.

Stress Mapping with the Debro-30

Ultrasonic-based stress readings were made with the Debro-30 along the length of the sample rail. The probehead of this device is about 10 inches long, and the stress indicated by the device is an average over this distance. Measured stress values were recorded with respect to the middle of the probe's position. Thus, an averaged stress value over the 10 inch distance was cited as a single value at the midpoint of the sound path. Stress readings were taken with the middle of the probe over a point 6 inches in from the end of the rail, and at subsequent 3 inch intervals along the rail. Stress measurements were made on the running surface of the rail, both sides of the head, web and upper base, and along the base underside.

Figure 2 shows the stress readings taken along the length of the rail. The longitudinal stress gradient is most pronounced along the base underside and running surface of the rail. Readings of compressive residual stress change to moderate tension at about the 30 inch mark. Also as expected, stress readings in the web change from longitudinal tension to compression. The side of the head and upper base regions show the most uniform stress distributions.

Figure 3 shows the contrast between readings taken on milled surfaces and as received (scaled) surfaces. It appears that the milling process imparted a slight tensile stress at the surface of these regions. Alternately, it may be that the data reflects the presence of a stress gradient normal to the surface. While some additional work was performed on these specimens after an annealing treatment, the exact nature of the consistent offset between the milled and scaled surfaces is not clear.

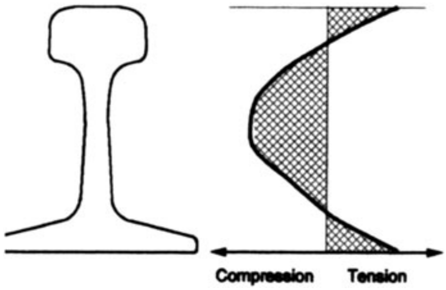

Figure 1. Typical longitudinal stress distribution in roller-straightened rail

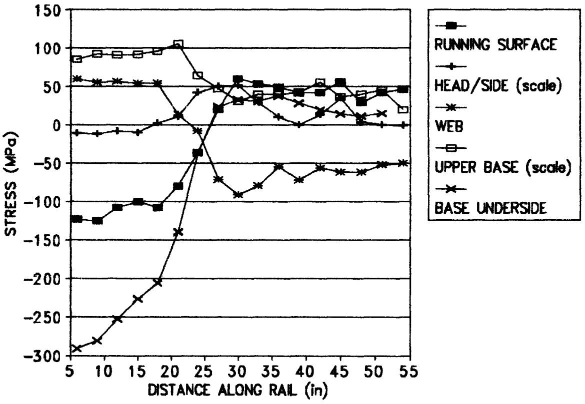

Figure 2. Longitudinal stress distribution in test rail, as measured using the Debro-30.

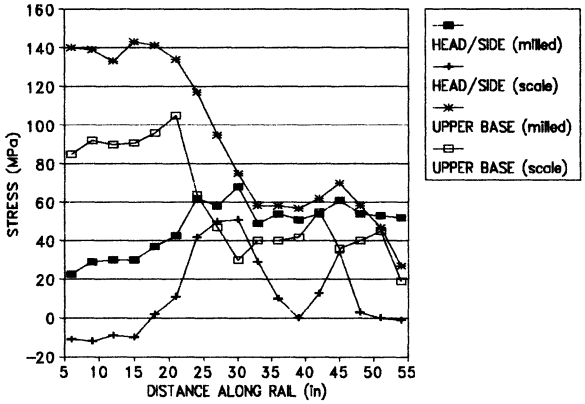

Figure 3. Longitudinal stresses measured on milled and scaled surfaces using the Debro-30.

An alternate way of presenting the stress measurement data is shown in Figures 4 and 5. In these figures, stress values obtained around the profile of the rail at given distances are shown. The stress profile at the 45 inch mark along the rail is seen in Figure 4. It exhibits the characteristics of a typical roller-straightened rail, as expected. Figure 5 shows the stress profile measured at the 6 inch mark on the rail. The stress distribution of the rail that did not see the effects of roller-straightening is markedly different. It is evident that the straightening process can effectively reverse the residual stress pattern of the hot-rolled material.

Such stress patterns have been documented on other rail samples. We therefore have confidence in the validity of this data. These trends in stress distribution then become the benchmark by which to judge the data obtained with the magnetic measurement method.

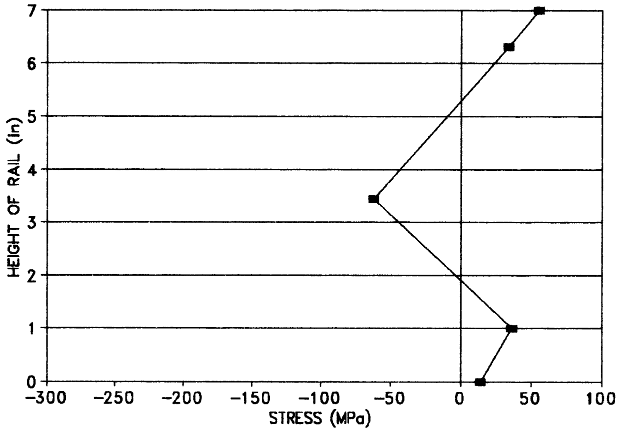

Figure 4. Residual stress profile at the 45 inch mark of the test rail, obtained with the Debro-30.

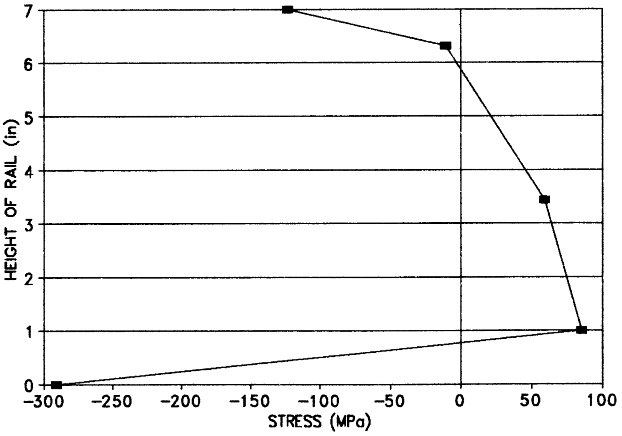

Figure 5. Stress profile at the 6 inch mark along the test rail, showing the change in distribution for material that has not been roller-straightened.

Data Acquisition with the Magnescope

The size of the inspection head used to get magnetic hysteresis data measures about 1 inch by 2 inches. Its small size allows for interrogation of a smaller region of material. Additionally, the alignment of the magnetic poles may be changed by simply rotating the assembly. In the present study, the probe was aligned parallel to the axis of the rail. This was done to focus on changes in magnetic properties caused by the longitudinal component of residual stress.

As mentioned earlier, use of the Magnescope provides information of several parameters of the magnetic hysteresis loop. Coercivity and remanence have been shown to be clearly affected by stress states. It was the behavior of these properties that was observed along the test rail. Hysteresis loops were performed on the same surfaces that were tested by the Debro-30, and the magnetic inspection head was moved along these surfaces in 3 inch increments. Extensive data was collected during the course of this research. Due to article size limitations, however, only selected data will be presented in this forum.

Figure 6 shows the distributions of coercivity and remanence along the test rail. Data from the running surface, web sides and base underside only are shown. The data is presented after a 3-point averaging was applied to the raw data. Two characteristics are immediately apparent. First, the anticipated longitudinal stress gradient is not reflected in the measured properties. Secondly, the absolute values of both coercivity and remanence vary dramatically on the web side that received milling versus the original mill-scaled side. This could be due to the curvature of the or scaled surface acting as a lift-off variable on the inspection head. Alternately, the magnetic technique could be seeing localized stresses due to the milling operation. At the current time, it seems possible that the data reflects a complex combination of these effects.

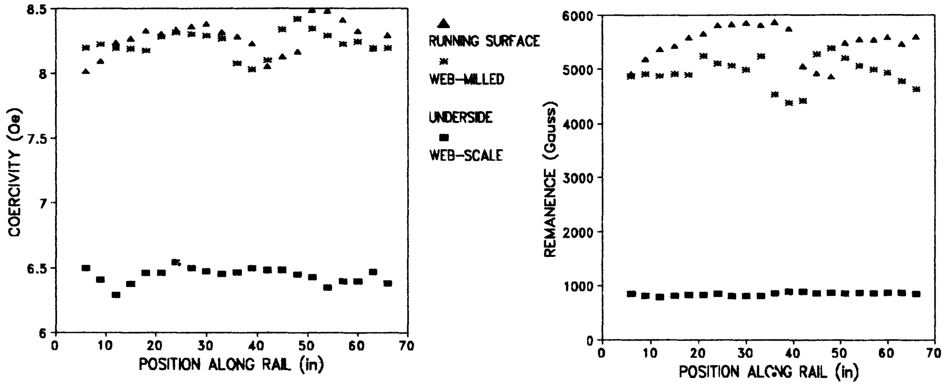

Figure 6. Coercivity (left) and remanence (right) measured along test rail, using the Magnescope.

The effect of testing on different surfaces can be seen in Figure 7. In this figure coercivity and remanence are plotted as a function of position on the rail profile, similar to the Debro data in Figure 4. The magnetic data was taken with the inspection head at the 45 inch mark on the test rail. The running surface (milled) and the base underside (scaled) are the only points that match on the various plots. If the surface scale were only to impart a lift-off effect, one might expect that the trends from point to point on the rail would correspond, but that was not the case. Again, whether this complex reaction was a response to the removal of the surface in conjunction with induced machining stresses is not well defined.

Although not presented here, additional comparisons were made between the ultrasonic and magnetic test data at other points along the rail. No immediately obvious correlations were noted when viewing magnetic property data alongside Debro stress profiles.

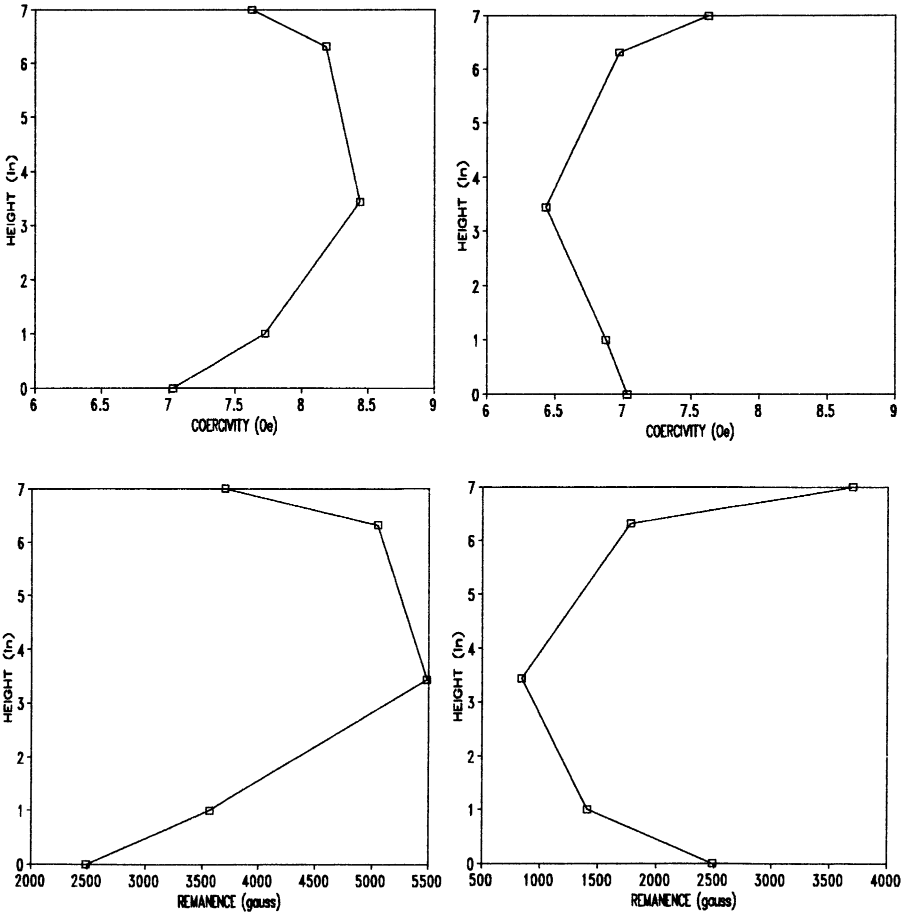

Figure 7. Coercivity (top) and remanence (bottom) measured on milled (left) and scaled (right) surfaces of the test rail at the 45 inch mark.

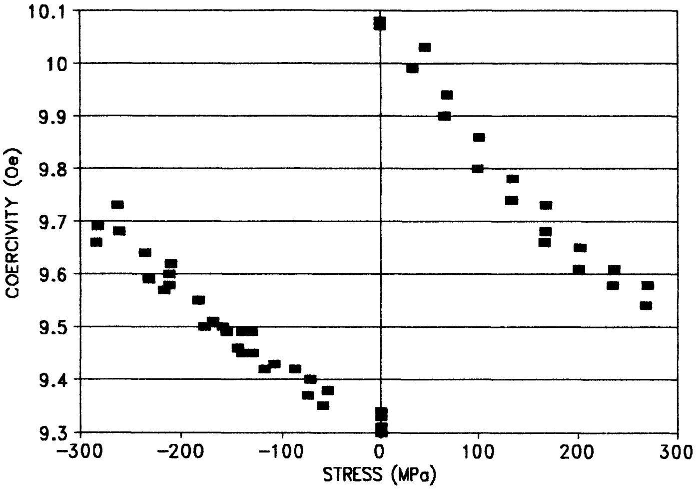

Figure 8. Coercivity measured in tension (steel sample) and compression (full rail).

Applied Load Tests

To allay concerns regarding the sensitivity of magnetic measurements to stress, a series of applied load tests were performed. Compressive loads were applied to a full-size rail section, while applied tension tests were performed on a sample machined from the same rail steel. Due to the large cross sectional area of a rail, applying tension is difficult in most labs. At the same time, it is not wise to apply high compressive force to a narrow specimen, due to buckling possibilities.

The test results are seen in Figure 8. A very similar trend occurs for coercivity over the same nominal range of applied stress, although absolute values are quite different.

DISCUSSION

The ultrasonic stress measurement technique embodied in the Debro-30 is viewed as a useful tool for determining residual stress patterns in railroad rail. The required calibration on a stress-free sample of the same material, however, is viewed as potentially cumbersome for the measurement of axial stress of in-track rails of unknown pedigree. The portable magnetic hysteresis technique for stress measurement has undergone much development through industrial and academic collaboration. New levels of test sensitivity and reproducibility have been achieved through this research. However, the real surfaces of railroad rails may not allow for widespread usage of this technique. Either a direct calibration on a given test piece will be a requirement for stress measurement, or additional data interpretation techniques must be developed.

REFERENCES

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2. M. Negley and D. C. Jiles, in *Review of Progress in QNDE*, this volume, *op cit.*
3. D. Utrata, AAR Research Report R-799, Chicago, IL, 1993.