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Rolling Contact Fatigue Measurement Using EMATs

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Summary

Transportation Technology Center, Inc. (TTCI) is working to encourage development of advanced non-destructive evaluation (NDE) technologies capable of measuring and characterizing rolling contact fatigue (RCF) in railroad rail. As part of this initiative, TTCI contracted Rosen, San Luis Obispo, California, to conduct a feasibility study for applying Electromagnetic Acoustic Transducer (EMAT) technology and its ability to measure different levels of RCF damage in rails. Results from this initial evaluation suggest that EMAT NDE method is capable of making precise sound wave velocity measurements (±0.2 percent) on the railhead running surface that could be correlated to the condition of rail material at the surface.

Velocity change was attributed to effective modulus changes of the fatigued material. An EMAT capable of detecting minute variations in surface quality due to ductility exhaustion in RCF conditions preceding the development of visible cracks. The system, however, is not capable of measuring crack length or depth. Visible surface damage attenuates the signal to the point that no measurement is possible if the material has already formed large cracks or spalls.

Four 136 RE rail samples were investigated — each approximately 4 feet long, from the same parent material, and with different levels of RCF damage. One was unused rail with no RCF damages, and the other three represented varying degrees of RCF damage as subjectively determined by TTCI experts (RCF Visual Rating 0.5 ~ 3, with 0 being no RCF and 3 being severe RCF). EMAT sensors with different wavelengths were used to measure sound velocity at different depths and locations on all rail specimens. Variations at different depths were found for each of the samples suggesting that there is a measurable velocity gradient; thus, a material properties variation at and near the surface. Thin layers of rail material (approximately 0.5 mm increments) were removed and sound velocity was measured in the progressive layers. In all samples, the sound velocity had returned to nearly the level of the new material after removal of about 2.0 mm of material. Sound velocity variations were also measured across the profile of the rail from the field side to the gage face. The maximum surface damage appeared on the gage face of the rail, which corresponds to where the flange rides on the high rail in a curve.

RCF presents significant economic and safety challenge to the railroads. To optimize rail maintenance cycles, railroads seek a method of measuring the depth of the damaged rail layer and the crack depth. Rail life can be maximized by optimizing grinding practices to remove the least amount necessary to eliminate the damaged material and restore rail integrity.

This work is being performed in support of the Association of American Railroads' Strategic Research Initiatives (SRI) Program.

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INTRODUCTION

The running surface of rail is continuously damaged by the passage of train wheels over the surface. The damaged layer may be thought of as cold worked steel “cold welded” to the underlying, undamaged layer. Small cracks can be seen along the edges of the cold worked layer. This is known as rolling contact fatigue (RCF). The small cracks can ultimately grow and join up to form a flake that falls loose, leaving behind a cavity in the running surface of the rail. This is mainly due to the increased stresses on rails as a result of higher train speed, more frequent usage, and increased axle loads. RCF presents significant economic and safety challenge to the railroads. It is estimated that the total costs to the railroads associated with RCF is close to $700 million.[1]

Rosen performed an investigation to determine if Electromagnetic Acoustic Transducer (EMAT) technology was suitable for measuring rolling contact fatigue on railroad rail. Initial testing was performed on the samples as received. EMATs with different wavelengths measured velocity at different depths. Velocity gradient versus depth was also studied using a destructive method of machining off material and measuring velocity at each step. Rosen also studied the RCF distribution across the width to the rail and determined an optimal wavelength for surface inspection. Later stages of damage, those levels of RCF where cracks and pits are visible to the eye, are quantified by larger wavelengths measuring deeper into the railhead. Severe RCF attenuates the shallower penetrating waves. A severity inspection could be provided by proper selection of wavelength with the ultimate limit set by attenuated signal drop-out.

FUNDAMENTALS OF EMAT

EMAT is a non-contacting technique that induces ultrasonic waves in the base material with a high current coil close to the surface. Depending on the sensor design, wave type and wavelength can be varied. The same or similar sensor senses a return signal and provides a very precise measurement of the propagation velocity of those waves. Figure 1 shows typical EMAT sensors for transmitting and receiving electromagnetic waves.

By using EMATs, it is possible to excite and detect ultrasonic surface waves using transducers that, unlike conventional piezoelectric transducers, do not need a coupling medium. With EMAT, the time-of-travel of a surface acoustic wave (SAW) over an accurately known distance can be measured and the velocity of propagation determined with a precision that is greater than 0.1 percent.

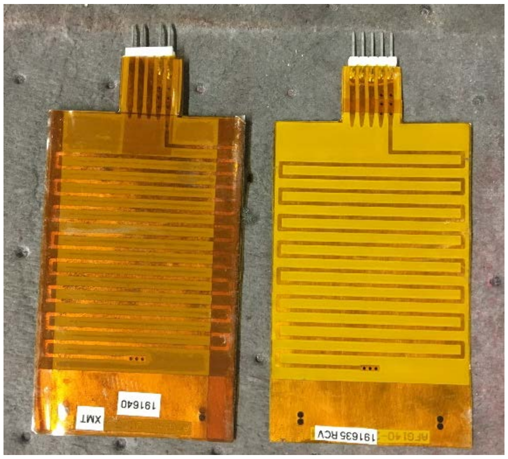

Figure 1. EMAT Sensor Elements

One source of error in this technique when applied to the head of a railroad rail is the effect of diffraction caused by the sound velocity variations across the width of the head. This causes different parts of the wave front to have different arrival times at the receiver and causes destructive interference. Further, it is well known that plastic deformation increases the attenuation of acoustic waves so that the wave reaching the receiver may be too small to detect reliably with large deformations and short wave lengths. This attenuation effect was observed to be serious even in the least damaged rail at wave lengths below about 4 mm (frequencies above 1 MHz).

SURFACE ACOUSTIC WAVES

Surface acoustic waves, or Rayleigh waves, are elastic waves that propagate along the surface of a solid and extend into the depth to a distance comparable to the wavelength of the wave. Their propagation velocity is slightly less (10 percent) than the velocity of a shear wave in the bulk of the solid. Because they are confined to the surface, their propagation velocity and attenuation depend on the properties (thickness, density and elastic modulus) of the surface layer. By measuring the velocity of surface waves with different wave lengths, it is possible to infer the physical properties of a layer on the surface. In particular, the thickness of the layer can be estimated from an observed dependence of the SAW velocity as a function of frequency; i.e., the wave length.[2] EMAT sensors provide the ability to make this measurement.

The damaged layer may be viewed as a layer of cold worked metal “cold welded” to the underlying material. There are two competing phenomena that may influence velocity of the surface wave. The “cold welding” process attaches a stretched layer to the un-stretched base steel. Thus, there may be a residual tensile stress left in the outer layer and a compressive residual stress in the base metal. The combination of these two competing stresses would appear as an average sound velocity gradient over the layer thickness. The cold worked layer can also have a reduced sound velocity caused by the presence of additional dislocation networks. This will appear as a delay or slowing down of the total wave front. The various wavelengths used in this study should detect this effect. Indeed, the experimental results indicate that the sound retardation due to material damage is dominant.

TEST RAIL

Partially worn rail surface shows a smooth, cold worked layer with many small cracks. In badly worn rails, the cracks may coalesce and flake off, leaving a row of irregularly shaped holes with depths on the order of 1 millimeter. Figure 2 shows the four rail samples that were used in this study. They are from the same parent stock and represent a range of RCF— qualitatively from new rail with no RCF to severely damaged rail.

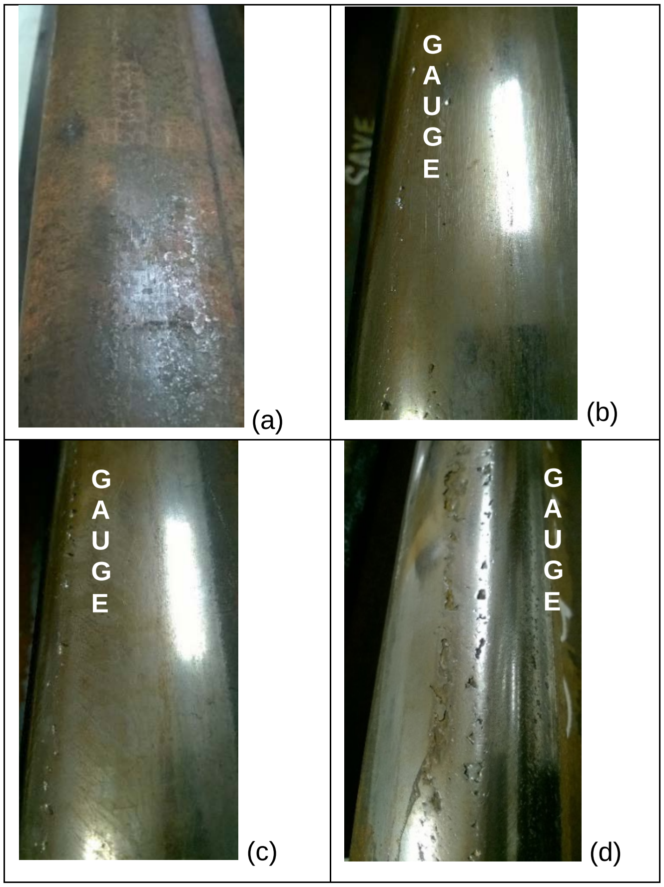

Figure 2. (a) Rail No. 0, Virgin; (b) Rail No.1 Light RCF; (c) Rail No. 2 Medium RCF; and (d) Rail No. 3 Severe RCF

RESULTS

The surface acoustic wave was measured on all four rail samples as received. Depth was varied by varying the wavelength. Figure 3 shows the SAW velocity variations on the as-received rail samples. The surface roughness of Rail Number 3 completely attenuated the signal. No measurement was possible on the heavily damaged rail.

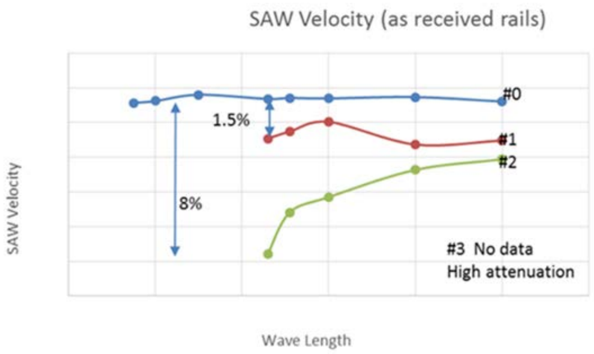

Figure 3. Surface Acoustic Wave Velocity at Various Wavelengths

The result of the as-received test shows that there is a measurable and significantly different wave velocity varying with depth on each of the rail samples. The velocity becomes slower near the surface as the amount of RCF increases.

The next step was a destructive test. Rosen machined off the surface by 0.5 mm increments and took measurements at each depth. Figure 4 shows these results for Rail Number 2.

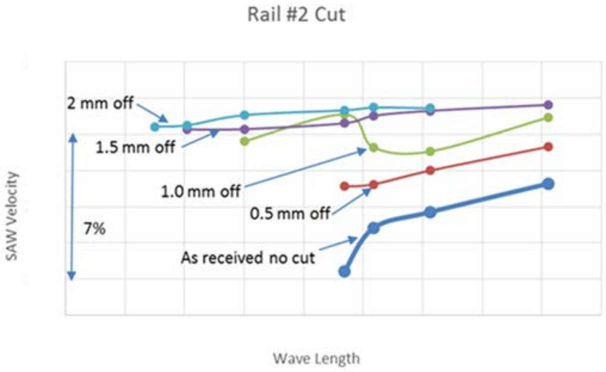

Figure 4. Dispersion of the SAW Velocity as Material is Removed

In general, the removal of damaged material caused the dispersion (the dependence of the velocity on wave length) to decrease, as would be expected from the removal of a layer with properties differing from the substrate. In all cases, it appears that removal of 2 mm was sufficient to minimize the dispersion caused by the damage. However, some residual dispersion did remain in all cases.

The value of the surface wave velocity could be correlated to the degree of surface damage. Figure 5 shows this correlation.

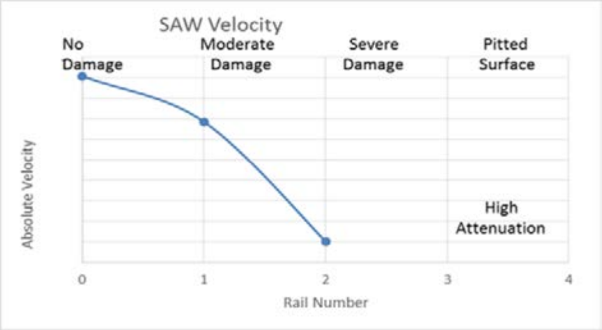

Figure 5. Correlation between Measured SAW Velocity and Surface Damage

LOCATION OF MAXIMAL RCF

RCF varies along on the running surface and across the width of the rail. Because the EMAT sensor has a finite size, the velocity measurement represents an average value under the area of the sensor. For the material removal test, Rosen presumed that maximal RCF occurred along the center of the worn patch at about 4.5 degrees offset from vertical. Figure 6 shows the machined groove. Arrows show the area evaluated by EMAT.

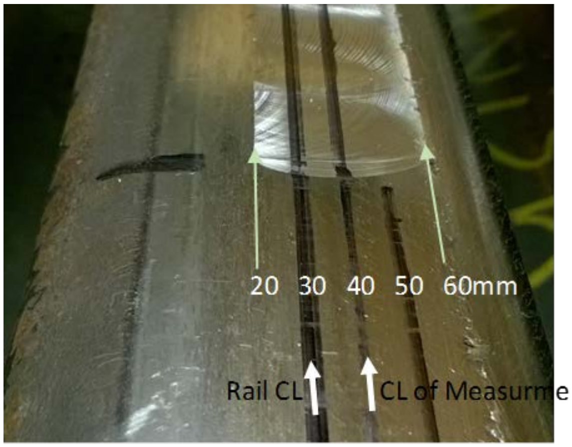

Figure 6. Location of Milled Groove and Area Measured by EMAT Sensor

Because the RCF varies across the width of the railhead, Rosen ran the EMAT sensor across the width of the head from the field side to the gage side. Figure 7 shows the setup and identifies the coordinate system to reference when viewing the results in Figure 8.

Figure 7. Setup for Scanning Across the Railhead Width. Rail Centerline at 30 mm. Field side is near zero mm

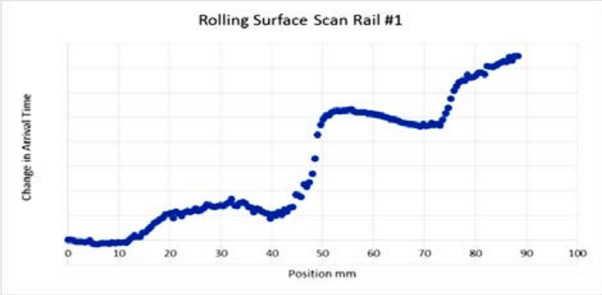

Figure 8. Scan across the Rolling Surface of Rail Width using 12-mm Wide EMAT. Rail Centerline at 30 mm

CONCLUSION

EMATs can measure the velocity of surface waves on rail heads within an accuracy sufficient to resolve moderate levels of RCF in the rail. As the RCF damage level increases, the attenuation of the high frequency waves increases to the point that complete attenuation occurs where cracks are visible. Thus, high frequency EMAT is not suitable for measuring crack depth, but it can accurately detect ductility exhaustion in the rail material just prior to crack formation. A rail condition evaluation regiment based on EMAT could lead to a condition based maintenance cycle to optimize rail life.

NEXT STEPS

TTCI will continue this research and the vendor will create a custom EMAT sensor to be tested at Transportation Technology Center to measure rail surface condition in service at the facility.

References

1. Tournay, H. November 2010. “Overview of Rolling Contact Fatigue Prediction Models,” *Technology Digest TD-10-040*, Association of American Railroads, Transportation Technology Center, Inc., Pueblo, CO.
2. Szabo, T.L., 1975, "Obtaining subsurface profiles from surface−acoustic−wave velocity dispersion," Journal of Applied Physics, Vol. 46 (4), pp. 1448-1458.