IDEA

Innovations Deserving Exploratory Analysis Programs

High-Speed Rail IDEA Program

Rail Surface Characterization

Final Report for High-Speed Rail IDEA Project 55

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TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD

This investigation was performed as part of the High-Speed Rail IDEA program supports innovative methods and technology in support of the Federal Railroad Administration's (FRA) next-generation high-speed rail technology development program.

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IDEA Program Final Report

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IDEA PROGRAM

ABSTRACT

As part of an infrastructure subject to increased magnitude and frequency of loads, railroad track systems require regular inspection to assure high reliability for the safety of the public and passengers and the safe and efficient movement of goods. A key high-performance element in the system is the rail. In high-speed rail and heavy haul operations, these issues of risk and attendant costs have become more critical. This report summarizes the efforts of Waves*In*Solids LLC under TRB contract HSR-55 to develop a rail inspection technology to detect and characterize the condition of the rail surface and subsurface. Unattended traffic-hardened layers on the surface of the rails are operational hazards due to the inevitability of rolling contact fatigue cracks and larger transverse defects. In this project, the higher order surface wave, or Sezawa wave, was evaluated as the detection and measurement mechanism for traffic-hardened layers in used rails. Hardness tests were conducted on rail specimens with known traffic volume (in terms of million gross tons (MGT)) to determine surface and subsurface hardness gradients, prior to ultrasonic testing using angled beam wedge transducers. Metallographic analyses were also undertaken on these rail specimens. The tests using the Sezawa wave technology demonstrated the ability to interrogate and resolve traffic-hardened layers in the depth ranges of 0-1 mm, 1-3 mm, and 4-7 mm. The minimum Brinell Hardness (HB) gradient, between the hardened layer and underlying rail, required to support Sezawa wave generation was also investigated and determined to be greater than 20 HB. The technology was also tested on lubricated rail showing Sezawa waves, unlike Rayleigh waves, can travel on such surfaces with excellent signal-to-noise ratio and, therefore, can be applied to inspection of dry as well as lubricated rails. Finally, work was carried out to determine the feasibility of using electromagnetic acoustic transducers (EMATs) to generate Sezawa waves in the rails. If successful, this technology would then be incorporated into a non-contact system that could be mounted on a rail inspection vehicle that could be operated at speeds up to 25 mph. This effort was unsuccessful due mainly to insufficient coupling of ultrasonic energy generated from the non-contact EMATs into the Sezawa wave mode. A commercial product based on the outcome of this project has been developed. It is a handheld device using contact transducers based on Sezawa wave technology that is capable of detecting and resolving traffic-hardened depths in the millimeter range.

KEYWORDS

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EXECUTIVE SUMMARY

The ultimate goal of this project was to develop a non-contact Electro-Magnetic Acoustic Transmitter (EMAT) ultrasonic inspection technology to identify and characterize traffic-hardened layers in rails. If successful, this technology would then be incorporated into a system that could be mounted on a rail inspection vehicle that could be operated at speeds up to 25 mph. This could not be accomplished. However, an interim objective was achieved that led to the development of a commercial prototype that utilizes handheld contact piezoelectric transducers capable of detecting and measuring the depths of traffic-hardened layers in rails.

Rolling contact fatigue (RCF) cracks in traffic-hardened (work-hardened) rails initiate and propagate to a critical size if left unmitigated by either frequent MGT (million gross tons)-driven *preventive grinding* or, less frequently, on a time-based schedule, by *corrective grinding practices*. However, MGT- or time-based maintenance procedures sometimes cause unnecessary downtime and lead to loss in productivity, increased labor and train delay costs and other associated costs. Therefore, there has always been a need for a non-destructive inspection methodology that could provide a condition-based maintenance solution. Rolling contact cracks grow to increasing lengths - and hence result in increased safety hazard potential- in increasing thicknesses of the traffic-hardened layers. Thus, one way to provide condition-based maintenance is to monitor the deterioration of the rail's surface condition. Various methods have been considered in the past for rail surface characterization ranging from eddy currents for fine surface flaw detection to ultrasonic guided waves for residual stress measurement. None of these has found the same level of application as the current direct-contact ultrasonic inspection for detection of bulk defects. Conventional ultrasonic testing transmits a finite bulk ultrasonic pulse through materials to test for material loss and mechanical integrity. Guided waves are another family of ultrasonic wave modes that may be used to inspect structures with well-defined boundaries including rail, pipe, rod, plates, and layered media. Guided waves include Lamb waves, Rayleigh waves, Sezawa waves and Love waves

The investigative approach for this project involved the following steps:

- Documentation of a traffic-hardened layer measurement specification in terms of depth and/or hardness

- Hardness testing on rails with known MGT to determine surface and subsurface hardness gradients

- Metallographic analysis as a secondary measurement for traffic-hardened layer depth

- Measuring the traffic hardened layer with the proposed ultrasonic measurement technology and compare the results with the actual measured layer and performance specification.

- A secondary objective was to determine if the proposed technology could be used on lubricated rail.

These objectives were addressed as follows. The performance specification was defined in terms of the three rolling contact fatigue crack growth stages that occur in the traffic-hardened layer. Stage I was characterized by micro-cracks 0.25 mm deep that grow slowly. Stage II was defined by RCF that grow from 1-3 mm at an accelerated rate. In Stage III, RCF branching may occur in the traffic-hardened layer with accelerated crack propagation in the vertical direction at depths between 4 – 7 mm. In this context, it is desirable to have a technology capable of detecting traffic-hardened layers 0-1 mm, 1-3 mm, and 4 - 7 mm thick. Traffic-hardened layers in standard and high-strength rail samples were characterized using hardness profiles (Brinell Hardness) and metallographic techniques specified in the AREMA Manual Chapter 4. Initial tests were conducted using Plexiglas wedge-mounted piezoelectric ultrasonic transducers to generate Sezawa and surface waves in the rails. In the standard rail sample, traffic-hardened layers from 1.25 to 5mm were detected. The hardness at 1.25 mm was 330 (HB) which was 15 HB above the nominal. This hardness gradient was insufficient to support Sezawa wave generation. In the head-hardened rail, a traffic-hardened layer of less than 0.65 mm was detected. The tests using the piezoelectric transducers confirmed that it is possible to resolve traffic-hardened layers of thickness < 1 mm, 1 – 3 mm, and 4 – 7 mm. The Sezawa wave technology was evaluated on lubricated rail as well. Data were acquired on dry and lubricated rail. The results show that a small 2-5 dB drop in signal-to-noise ratio can be expected over the desired test ranges. Experiments were also carried out to generate Sezawa waves in the traffic-hardened layers of the rail using EMATs to study the feasibility of integrating this measurement technology with WavesinSolids' Hy-Rail vehicle rail flaw detection technology. This effort was unsuccessful due mainly to insufficient coupling of ultrasonic energy generated from the non-contact EMATs into the Sezawa wave mode.

While this project did not result in the envisioned Hy-Rail-mounted measurement technology, sufficient progress has been achieved in terms of characterizing these layers using contact ultrasonic inspection. The Sezawa wave technology

has been proven to be a capable tool for the identification and characterization of traffic-hardened layers as a result of this project.

A commercial product based on the outcome of this project has been developed. It is a handheld device using contact transducers based on Sezawa wave technology that is capable of detecting and resolving traffic-hardened depths in the millimeter range. It may be used to assist track management by prioritizing sections of track for internal rail flaw inspection and/or grinding. This is based upon the logic that deeper traffic-hardened layers pose more risk to track safety and operation due to the probability that serious flaws may initiate and propagate faster in thicker layers.   The technology, however, does not provide a point-by-point traffic-hardened depth profile across the head laterally.   It was determined that the technology could not be integrated practically into our rail inspection vehicle due to the EMAT's inefficiency to generate Sezawa waves with significant signal strength. An alternative laser ultrasonic generation and air coupled ultrasound receiver sensor is recommended for future research. This would involve laser pulses impinging on the rail surface and generating higher-order surface waves. These waves could then potentially be detected by non-contact air-coupled ultrasonic transducers. Since current air-coupled transducers have been shown to work well up to frequencies of 5 MHz, they are a suitable candidate for detecting Sezawa waves generated in traffic-hardened layers using the laser pulses. However, the orientation of the transducers, laser pulse characteristics (power, periodicity etc), and the ease of assimilation of the technology will all have to be thoroughly explored.

1. BACKGROUND AND OBJECTIVES

Rolling contact fatigue (RCF) cracks in traffic-hardened (work-hardened) rails initiate and propagate to a critical size if left unmitigated by either frequent MGT (million gross tons)-driven *preventive grinding* or, less frequently, on a time-based schedule, by *corrective grinding practices*. However, MGT- or time-based maintenance procedures sometimes cause unnecessary downtime and lead to loss in productivity, increased labor and train delay costs and other associated costs. Therefore, there has always been a need for a non-destructive inspection methodology that could provide a condition-based maintenance solution. Rolling contact cracks grow to increasing lengths - and hence result in increased safety hazard potential- in increasing thicknesses of the traffic-hardened layers. Thus, one way to provide condition-based maintenance is to monitor the deterioration of the rail's surface condition. Various methods have been considered in the past for rail surface characterization ranging from eddy currents for fine surface flaw detection to ultrasonic guided waves for residual stress measurement. None of these has found the same level of application as the current direct contact ultrasonic inspection for detection of bulk defects. Conventional ultrasonic testing transmits a finite bulk ultrasonic pulse through materials to test for material loss and mechanical integrity. Guided waves are another family of ultrasonic wave modes that may be used to inspect structures with well-defined boundaries including rail, pipe, rod, plates, and layered media. Guided waves include Lamb waves, Rayleigh waves, Sezawa waves and Love waves.

The basic inspection premise is that surface wave modes travel at different velocities in new rail and used rail due to the development of a traffic-hardened layer.

❑ In new rail, one surface wave mode will be dominant and measurable. This is the Rayleigh surface wave or M_{11} mode.

❑ In older rail, two surface wave modes will be present and measurable. These are the M_{11} mode and the higher-order Rayleigh wave, called the Sezawa wave mode or M_{21} mode. The M_{21} mode is easy to discriminate from the M_{11} mode due to its faster wave speed.

The application of this technology to track inspection has two main areas of payoff:

❑ Early detection and classification of severity of potentially dangerous surface flaws to assist in ongoing maintenance planning and decision making, and

❑ Quantitative input to grinding operations to evaluate rail pre-grinding and post-grinding conditions.

The payoff is economic, both in terms of inspection cost and in the savings in maintenance costs derived from the input the system will provide to the railroad maintenance program.

The objectives of the efforts carried out by Waves*In*Solids were to:

1. Develop a quantitative performance specification for detection and measurement of traffic-hardened layers in terms of depth, rolling contact fatigue crack size, and hardness gradients.

2. Characterization of traffic-hardened layers in terms of depth and hardness in standard and head-hardened rail samples with known MGT via metallographic analysis and Brinell Hardness tests.

3. Detection and measurement of the same rail samples using the Sezawa wave ultrasonic measurement technique and benchmarking it against the performance specification and the measured hardened layers.

4. Evaluate the performance of the guided wave ultrasonic measurement technology on lubricated rail.

5. Evaluate the feasibility of using EMATs to generate Sezawa waves in the traffic-hardened layers of the rail.

2. DESCRIPTION OF IDEA PRODUCT

The ultimate goal of this IDEA project was to develop a non-contact Electro-Magnetic Acoustic Transmitter (EMAT) ultrasonic inspection technology to identify and characterize traffic-hardened layers in rails. If successful, this technology would then be incorporated into a system that could be mounted on a rail inspection vehicle that could be operated at speeds up to 25 mph. This could not be accomplished. However, an interim objective was achieved that led to the development of a commercial prototype that utilizes handheld contact piezoelectric transducers capable of detecting and measuring the depths of traffic-hardened layers in rails.

Based on the conducted research, we know that Sezawa waves have the dual capability of detecting and measuring the depths of traffic-hardened layers. In this context, a commercial service and/or product may be offered as the end result of this project. The IDEA product will consist of ultrasonic hardware designed to generate Sezawa waves in rail efficiently using piezoelectric transducers.   The PC-based ultrasonic hardware will be housed inside a portable lunchbox computer. The software will be designed to generate dispersion curves in rail, enable frequency sweeping of the ultrasonic hardware, detection and measurement of Sezawa wave data and hardened layered thickness measurement. The software flowchart and basic inspection procedure is described in Figure 1. The product shall be a mobile inspection service operated by moderately to highly skilled ultrasonic technicians.

Piezoelectric Transducers

Lunch Box PC

Software Flowchart

$13 \, ^7/_{16}$ "

Accommodates:
- One 300 volt pulser card
- 1 or 8 channel A/D
- 2 1x8 multiplexer cards

$9 \, ¼$ "

$17 \, ¼$ "

Generate dispersion curves for traffic-hardened layer to obtain cut-off frequencies

Generate high frequency Sezawa wave

Sezawa wave present?

No → Approximate thickness

Yes

Decrease frequency
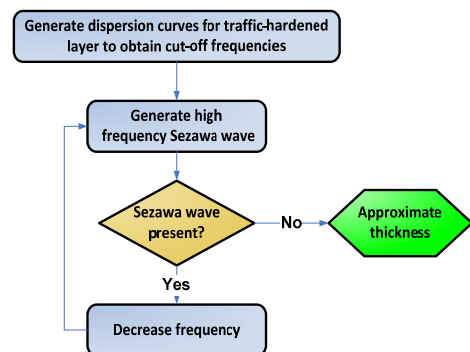
FIGURE 1 Description of IDEA Product

3. CONCEPT AND INNOVATION

Traffic-hardened layers of increasing depths develop in rail heads as they are subjected to increasing MGT. The difference in material properties between the traffic-hardened rail and the underlying rail create a set of unique boundary conditions that support the generation of a surface wave that can detect and measure traffic-hardened layers. The concept for traffic-hardened layer inspection in rails is based on ultrasonic Rayleigh and Sezawa waves that propagate on the surface of a solid with a penetration depth of the order of one wavelength. Therefore, these ultrasonic surface waves may be used to interrogate the rail surface and traffic-hardened layers. Surface inspection with Rayleigh waves can be carried out in pulse-echo with one transducer located on the surface of the test piece, acting as both transmitter and receiver. Using the reflection transit time from surface defects, the distance can be calculated from the Rayleigh velocity in the material. Rayleigh velocity is generally 0.93 times the shear velocity in the material. However, beyond this surface defect detection and measurement capability, this technology has the potential for detection and characterization of work hardening in the surface layer using advanced ultrasonic methods that take advantage of the phenomena of Rayleigh wave dispersion to estimate traffic-hardened depth is used.

A closer examination of the compatibility between generalized Lamb wave theory in layered media and the case for the used rail will give suggestions and ideas as to where adjustments would be made to the assumed values and definitions that would bring the predicted values in line with the experimental data and observations. The characteristics of generalized Lamb waves depend strongly on the ratio of the shear wave velocity in the substrate V_{sub} to the shear velocity in the layer V_{lay}. If the two velocities are appreciably different and $V_{lay} < V_{sub}$ there is only one generalized lamb wave solution.

When $V_{lay} < V_{sub}$, there are an infinite number of solutions which fall into two families of modes, often called the M_1 and M_2 series. These solutions reduce to the symmetric and anti-symmetric Lamb waves, respectively, when the density or stiffness of the substrate goes to zero, or equivalently, when only the layer remains and it behaves like a free thin plate. The fundamental modes of the two series M_{11} and M_{21} have interesting properties. For layer thicknesses approaching zero, the M_{11} mode approaches a Rayleigh type surface wave in the substrate, while the higher order M_1 modes (M_{12}, M_{13}, ..., M_{1n}) and all the M_2 modes (M_{21}, M_{22}, ..., M_{2n}) are leaky waves.

As the layer thickness is increased the first additional mode to become trapped in the layer is the M_{21} mode which is the Sezawa wave in this region. For very high frequencies or thick layers, the M_{11} mode approaches a Rayleigh type surface wave on the upper boundary of the layer. All the other higher modes (M_{1i}, M_{2i} for $i < 1$) such as (M_{12}, M_{22}), (M_{13}, M_{23}) etc., degenerate into essentially vertically polarized shear waves (SV) in the plate, that is, they behave like Lamb waves in a free thick plate. The behavior of the M_{11} (Sezawa wave) depends critically on the relative material parameters of the layer and the substrate. If the velocity of the shear wave in the substrate and the velocity of the shear wave in the layer are appreciably different the mode M_{21} also approaches a shear wave in layer when the layer behaves like a free thick plate. This unique surface wave is referred to as a Sezawa wave or higher order surface wave. The same rail will also support the generation of lower order surface wave – the Rayleigh wave (Figure 2).

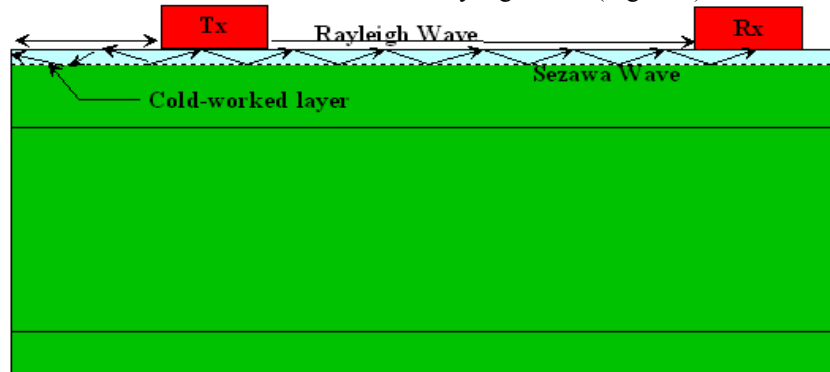**FIGURE 2 Transducer set up for detection of the traffic-hardened layer using the Sezawa M$_{21}$ mode**

To generate a Sezawa wave, the following conditions must be satisfied:
1. The shear wave velocity in the cold-worked layer c_{t1} must be less than that in the underling rail c_{t2}.
2. The longitudinal wave velocity in the cold worked layer c_{l1} must be greater than that in the in the underlying rail c_{l2}.

3.1 INSPECTION USING SEZAWA WAVE CUT-OFF FREQUENCY PHENOMENON

The wave velocity dispersion curves for the M_{11} and M_{21} modes were generated up to 7 MHz, using an ultrasonic wave propagation model. The model utilizes the characteristic equation for the higher-order surface waves that correlate the frequency of propagation to the wave's propagation velocity. This characteristic equation is iteratively solved using software programs like MATLAB to find the roots of the equation and plotted to provide the phase velocity and group velocity dispersion curves. Of direct significance to this work is the cut-off frequency for the M_{21} mode (1.25 MHz for 4 mm thick hardened layer). Below this cut-off frequency, it is impossible to generate the M_{21} mode. The cut-off frequency phenomenon, therefore, may be used to measure the depth of traffic-hardened layers. The concept is illustrated in Figure 4 using the M_{21} group velocity dispersion curves for hardened layers of increasing thicknesses (1, 2, 3 and 4mm). The cut-off frequencies of the M_{21} mode for decreasing layer thickness are approximately 1.25 MHz, 2 MHz, 3 MHz, and 5 MHz.

Since the cut-off frequency is a dynamic phenomenon that is influenced by traffic-hardened layer depth, it may be practically applied to measuring the depth of this layer. The dispersion curves in Figure 3 show that the M_{21} mode will be generated at lower frequencies as the layer progresses deeper into the head. It could be deduced from the curves, for instance, that if the M_{12} mode can not be generated at frequencies below 5 MHz, then the layer is less than 1 mm thick. Similarly, if the wave mode can not be generated at frequencies less than 3, 2, 1.25 MHz, then correspondingly, the layer is less than 2, 3, and 4 mm thick. A flow chart depicting the inspection procedure is shown in Figure 4. The first step would be to generate a high frequency surface wave. From the author's experience, 5 MHz is a good starting point because rail surface roughness complicates the generation of higher frequency surface waves. If the M_{21} mode is not observed it may be confirmed that a hardened layer may be approximated at less than 1 mm. If the wave mode is observed, frequency must be swept downward until the M_{21} mode disappears close to the cut-off frequency at which point the thickness may be approximated.
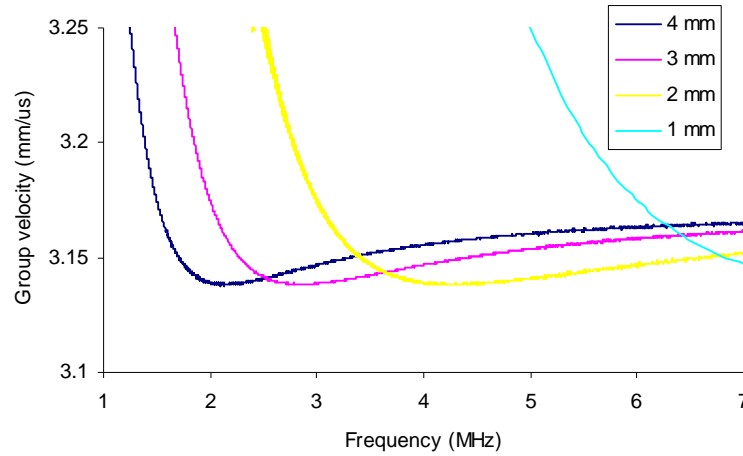

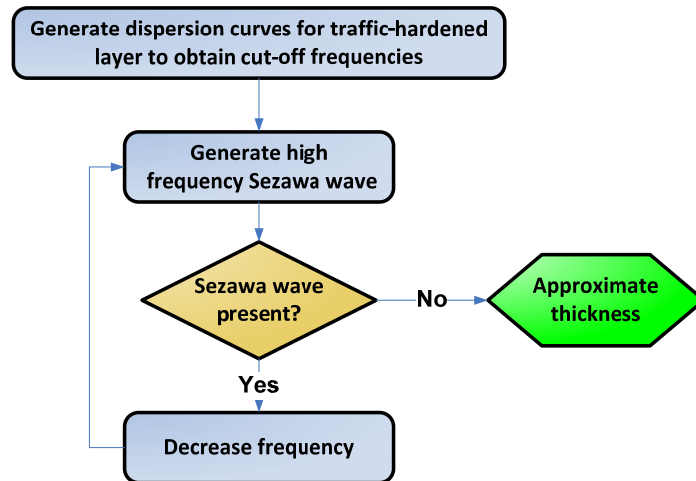**FIGURE 3 Sezawa wave dispersion curves for traffic-hardened layers of increasing depth**

FIGURE 4 Sezawa wave measurement procedure

4. INVESTIGATION

4.1 DEVELOPMENT OF PERFORMANCE SPECIFICATION REQUIREMENTS

To define the minimum detectable traffic-hardened depth, one must first understand the three stages of RCF growth in this layer. The first stage of RCF crack growth commonly occurs in the 5-7 MGT range during which micro-cracks are initiated and grow to a shallow depth gradually [1-3]. Published depths for the micro-cracks peak at 0.25 mm [1]. In this stage, the RCF cracks are typically in the millimeter range in length. In the second stage, the cracks grow at a small angle until they reach a critical depth at which they may begin to branch. In this stage, surface cracks propagate to depths up to 3 mm in dry rail and 7 mm in wet rail [1]. In the third branching phase, crack growth rate in the vertical direction is accelerated.

It is desirable to detect traffic-hardened layers depths that correlate to crack growth stages, as defined above. For instance, traffic-hardened layers less than 1 mm deep will propagate mainly as small Stage I micro-cracks that could be mitigated by preventive grinding. Micro-cracks that are not completely removed by the 0.25 mm preventive grinding pass will propagate faster in traffic-hardened layers in the 1-3mm depth range during Stage II. Finally in the last stage at depths beyond 3 mm, the RCF cracks may turn downward and propagate quickly.

The traffic-hardened layer thicknesses that need to be detected and resolved were then determined based on the ability of fatigue crack growth and propagation in these layers due to rolling contact. Based on the RCF crack propagation possibility in the different traffic-hardened layer thicknesses, it was identified that for layers of thickness more than 3 mm, it is a high risk situation due to the high probability of crack propagation. Therefore, it is absolutely essential that the proposed Sezawa wave be able to detect traffic-hardened layer of this thickness. Current rail inspection practices do not suggest any particular traffic-hardened layer depth specifications. Therefore, the specifications provided in Table 1 were arrived at using the input from the TRB advisory panel for this project as well as the RCF crack growth in different layer thicknesses.

TABLE 1 Traffic-hardened layer depth classification

Depth	Stage	Mitigation	Risk
< 1 mm	I	Preventive grinding	Low
1 – 3 mm	II	Corrective grinding	Moderate
> 3 mm	III	Multiple corrective grinding	High

4.2 DESCRIPTION OF STANDARD RAIL SPECIMEN

The standard rail used for testing was obtained after approximately 40 MGT of service life since the last grinding cycle. The length of rail tested was roughly 22 inches. Overall the head was flat over the 2-inch crown as can be seen in Figure 5. This rail was taken out of service because it was beginning to flake on the gage side. Fracture is also observed from the gage side towards the crown of the rail as shown in Figure 5. Superficial and bulk hardness tests were carried out in accordance with ASTM E18. According to this standard, hardness measurement must be at least 3 indentation diameters from the top surface. Accordingly, the first hardness data was acquired at 0.075" from the surface. Figure 5 shows the hardness indentations and Figure 6 shows a schematic of the indentation locations.

FIGURE 5 Standard rail specimen (top left), subsurface shelling on gage side (top right), head-hardened rail specimen (lower left), hardness indentations on standard rail specimen (lower right)
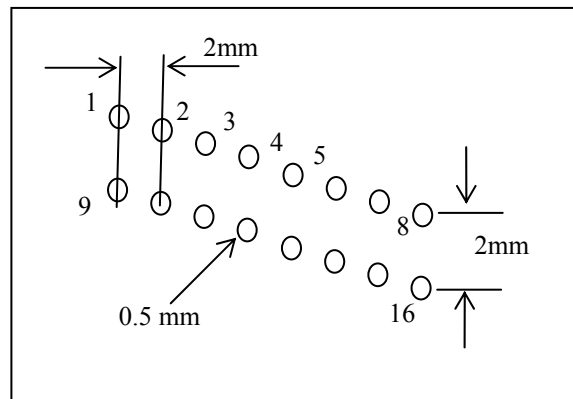
FIGURE 6 Location of hardness indentations

4.2.1 Hardness Tests in Standard Rail Specimen

A total of 16 Hardness measurements were made at increasing depths from 1.9 mm to 5.7 mm. Measurements 1 to 8 were taken along the first (upper) diagonal line in Figure 6. Measurements 9 to 16 were taken along the second (lower) diagonal line. Similar hardness measurements were performed on the head-hardened rail specimen as well. The measurements were undertaken with a Rockwell C superficial surface and standard Rockwell C hardness testing machines. The Rockwell C values were converted to Brinell Hardness values using the conversion table in AREMA's Manual for Railway Engineering – Chapter 4. The hardness values are listed in Table 2 and depicted in Figure 7. It can be seen from Figure 7 that the nominal hardness of a standard rail specimen is about 315 HB and the hardness measured on the surface of the rail after about 40 MGT of traffic since its previous grinding cycle is about 360 HB. Therefore, it can be seen that there is a gradient of 45 ΔHB through the traffic-hardened layer of approximately 5mm thickness.

TABLE 2 Hardness profile of standard rail after 40 MGT since the previous grinding cycle

Indentation Location Number	Distance from top rail surface (mm)	HRC	HB
Surface	0	37	359
1	1.9	35.1	344
2	2.15	35.5	344
3	2.4	35.6	344
4	2.65	34.4	336
5	2.9	34.4	336
6	3.15	34.4	336
7	3.4	33.3	328
8	3.65	34.3	336
9	3.9	33.3	328
10	4.15	33.3	328
11	4.4	33.0	328
12	4.65	32.0	321
13	4.9	31.7	314
14	5.15	31.5	314
15	5.4	31.4	314
16	5.65	31.2	314

Standard Rail Hardness Profile
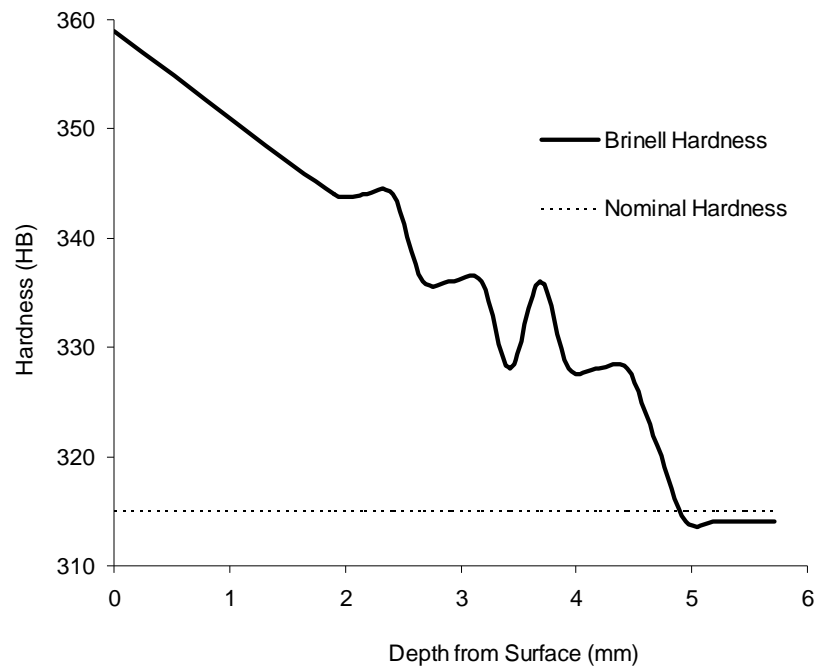
FIGURE 7 Hardness profile of standard rail showing 360 HB at the surface.

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4.2.2 Metallographic Analysis on Standard Rail Specimen

The rail specimens were also macro-etched and analyzed to further characterize the traffic-hardened layer depth. The specimen was polished to a 125 micro-inch finish and immersed in a hot (160 F to 180 F) one to one mixture, by volume, of concentrated hydrochloric acid (38 volume percent) and water as specified in the AREMA's Manual for Railway Engineering – Chapter 4. The result of the macro-etch is shown in Figure 8. A finer grain structure was observable up to 4.3 mm (0.17") which corresponds to the 5 mm layer detected with the hardness tests.

FIGURE 8 Macro etch of the standard rail specimen

4.3 DESCRIPTION OF HEAD-HARDENED RAIL

The head-hardened rail used for testing was obtained after approximately 20 MGT of service since the last grinding cycle. The length of rail tested was roughly 20 inches. Figure 9 shows a cross section of the head-hardened rail.

FIGURE 9 Head-hardened rail specimen

4.3.1 Hardness Tests on Head-Hardened Rail

The procedure outlined for the standard rail was used to profile the hardness in the head-hardened rail as well. Table 3 shows the superficial hardness at the surface is over 409 HB. Towards the interior, the hardness reverts back to the nominal value hardness of 360 HB at or before 1.9 mm. Note that it is not possible to acquire hardness data at depths less than 1.9 mm since data must be acquired at a minimum of 3 indentation diameters from the top surface. This could not be achieved due to the limitations of the hardness measurement system used. The indentation diameters generated by the technique used (Rockwell hardness testing machine) were not small enough to accommodate this requirement. The

hardness data shows us that there is a traffic-hardened layer and it is likely less than1.9 mm deep in the crown of the tested rail. Figure 10 shows how quickly the head-hardened sample returns to the nominal interior hardness.

TABLE 3 Head-hardened rail hardness profile

Indentation Location Number	Distance from Top Rail Surface (mm)	HRC	Brinell
Rail Surface	0	82.4	409
1	1.9	38.8	362
2	2.15	38.8	362
3	2.4	38.8	362
4	2.65	38.3	353
5	2.9	38.4	353
6	3.15	37.7	353
7	3.4	37.7	353
8	3.65	37.5	344
9	3.9	38.3	353
10	4.15	37.9	353
11	4.4	37.9	353
12	4.65	37.0	344
13	4.9	36.9	344
14	5.15	36.8	344
15	5.4	36.8	344
16	5.65	37.3	344

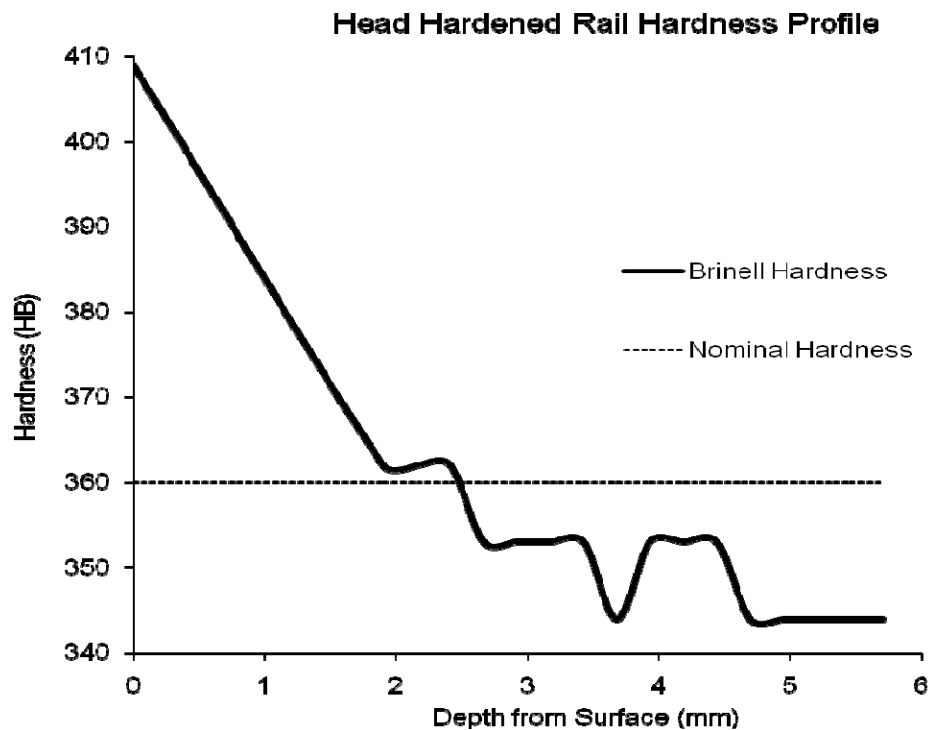FIGURE 10 Hardness profile of head-hardened rail showing 409 HB at the surface

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4.3.2 Metallographic Analysis on Head-Hardened Rail

The head-hardened specimen was micro-etched and analyzed. The result of the micro etching is shown in Figure 11. A small amount of "flow" can be seen in the top portion of the micrograph. This information seems to correlate to the hardness tests in that flow can not be seen below 1 mm from the surface. We expect this because nominal hardness had been achieved before the first hardness test location (1.9 mm).
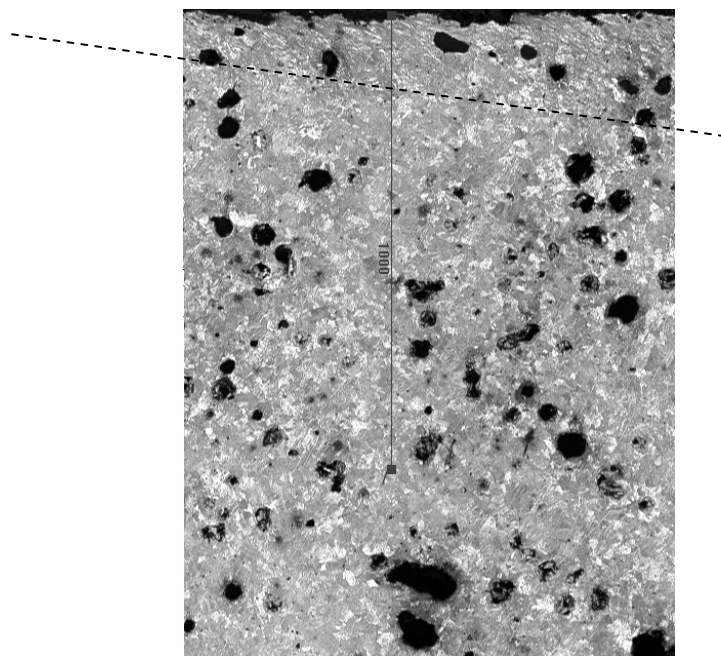
FIGURE 11 Micro-etch of head-hardened rail showing plastic flow at increasing depths towards the crown of the rail. Plastic flow is observed at up to 0.25 mm from the top surface. The 1000 label in the vertical direction refers to 1000 μm or 1mm.

4.4 EXPERIMENTAL PROCEDURE AND RESULTS

4.4.1 Tests using Angle Beam Piezoelectric Transducers

Three different frequency angle-wedge piezoelectric ultrasonic transducers were used to generate Sezawa waves in the rail. These were contact ultrasonic transducers and were coupled to the test rail using common ultrasonic couplant gel (Echogel from SONOTECH INC). These tests were carried out in the laboratory and on dry rails. The frequencies used were 1 MHz, 2.25 MHz, and 5 MHz. Each transducer had a footprint of less than 13 mm and was attached to Plexiglas wedges as shown in Figure 12. A RITEC pulser was used to send the electric pulse to the piezoelectric transducers and data was obtained using generic data acquisition hardware and software.

FIGURE 12 Typical transducers and wedges used in the Sezawa wave experiment

The Sezawa and surface waves were acquired at each frequency on the standard and head-hardened rails. The rail was tested over the same rail section that was selected for hardness and metallographic tests. Data were acquired at transmitter/receiver distances of 8 and 11". Data was first acquired over the original rail section. Rail surface was then removed in 0.625 mm and 1 mm increments and data reacquired until the Sezawa wave was not present. The top surface of the standard rail specimen was ground out at 0.625 mm, 1 mm, 1 mm and 1 mm increments. The top surface of the head-hardened rail was ground out at increments of 0.625 mm. After each grinding cycle, data were acquired at 1, 2.25, and 5 MHz. Rail samples after grinding are shown in Figure 13.

The Sezawa/surface wave amplitude ratio was calculated for each frequency after each grinding pass. By normalizing the Sezawa wave amplitude by that of the surface wave, the amplitude variations due to couplant, transducer orientation, etc. are minimized. A typical waveform obtained is shown in Figure 14. While variations in transducer couplant and orientation do affect Sezawa and surface wave amplitudes, their effect may be normalized out due to the fact that these parameters will not affect the amplitude ratio of the two modes. The normalization process enables comparison of inspection results at different frequencies and between different rails.

FIGURE 13 Standard rail (left) after 0.145" top surface removal and head-hardened rail (right) after 0.05" surface removal.
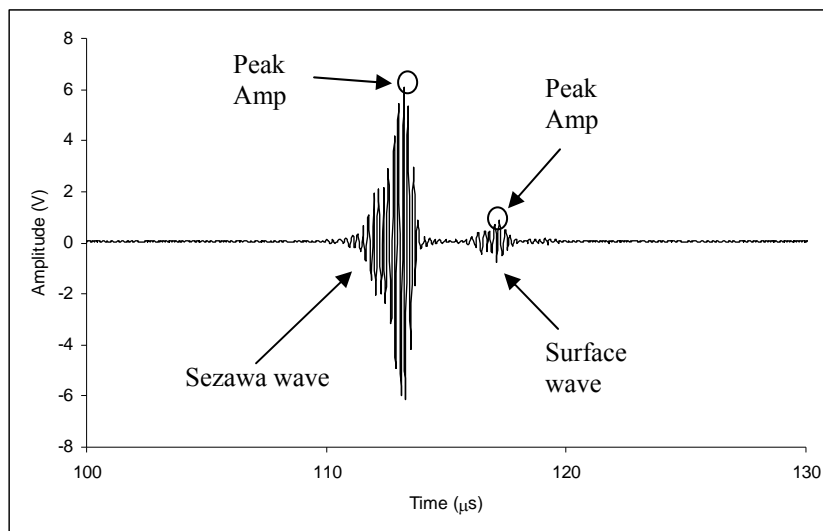
FIGURE 14 Experimental Setup showing angled beam transducers (left) and Waveform typically observed during the tests (right). This was generated at 2.25 MHz. Sezawa wave is faster than the surface wave and arrives first. Here, the Sezawa wave is the dominant mode (in terms of amplitude)

4.4.1.1 Results from Laboratory tests on Rails using Contact Piezoelectric Transducers

Analysis of the results first focused on two qualitative checkpoints:

➢ After each grinding cycle, the Sezawa wave amplitude decreased while the surface wave amplitude increased.
➢ As the thickness of the traffic-hardened layer decreased due to grinding, Sezawa waves at lower frequency disappeared.

The typical ultrasonic waveform obtained during these tests is shown in Figure 14. For both the standard and head-hardened rail, the Sezawa wave is the dominant mode in the original rail sample. In both cases, a decrease in Sezawa wave amplitude is observed as the traffic-hardened layer is ground out. As the layer decreases, the surface wave becomes dominant until the Sezawa wave completely disappears from the rail (Figure 15).

Similarly, in the standard rail that had a traffic-hardened layer in the 4-5 mm range, 1 MHz, 2.25 MHz, and 5 MHz Sezawa waves were observed in the original rail specimen. As the layer was removed, first the 1 MHz, then 2.25 MHz, and finally the 5 MHz Sezawa wave disappeared. Summarized in Table 4 and 5 are the detection results at each frequency and the corresponding Brinell Hardnesses of the measured rail and hardness gradients.

TABLE 4 Results from standard rail tests showing that the Sezawa wave method can detect layers > 3 mm thick and in the 1 – 3 mm range.

Grinding Depth (mm)	Layer Depth (mm)	DETECTION			Hardness (HB)	Hardness Gradient (ΔHB)
		1 MHz	2.25 MHz	5 MHz		
0.00	5	Yes	Yes	Yes	359	44
0.76	4	No	Yes	Yes	355	40
1.78	3	No	Yes	Yes	348	33
2.79	2	No	No	Yes	337	22
3.68	1	No	No	No	330	15

TABLE 5 Results from head-hardened rail showing that the Sezawa wave method can detect layers < 1 mm thick.

Grinding Depth (mm)	Layer Depth (mm)	DETECTION			Hardness (HB)	Hardness Gradient (ΔHB)
		1 MHz	2.25 MHz	5 MHz		
0.00	0.9	No	No	Yes	409	49
0.64	0.3	No	No	Yes	398	38
1.27	-	No	No	No	375	15

Detection of Layers Greater Than 3 mm Thick

The standard rail was used for this test as it had an initial traffic-hardened layer of thickness of 4.9 mm. At this thickness, the layer was detected by the 1 MHz, 2.25 MHz and 5 MHz Sezawa waves as shown in Table 4. After removal of the first 0.76 mm, the 1 MHz Sezawa wave disappeared while the 2.25 MHz and 5 MHz waves detected the layer. The hardness gradient for both layer thicknesses was above 40 HB. The gradient refers to the difference between the measured hardness at the layer depth and the nominal hardness of 315 HB.

Detection of Layers in 1 – 3 mm Range

Summary of the data for the 1-3 mm range is also shown in Table 4. After 2 mm of rail was removed, leaving a layer 3 mm thick, detection was observed with both the 2.25 and 5 MHz Sezawa waves. Once the traffic-hardened layer was reduced to 2 mm the 2.25 MHz Sezawa wave disappeared and detection was observed only with the 5 MHz wave. The hardness gradients for the 3 and 2 mm thick layers were 33 and 22, respectively.

Detection of Layers Less Than 1 mm Thick

When the hardened layer in the standard rail was machined down to 1 mm, Sezawa waves were not detected at any frequency. This is most likely due to the small Hardness gradient between the hardened 1 mm layer and the nominal

rail hardness.   The gradient is only 15 HB. This layer is over 3 mm under the original surface of the rail.   The gradient suggests that a minimum of 15 HB difference in hardness is required to generate Sezawa waves in rail. In contrast, the head-hardened rail had a comparably thin traffic-hardened layer with a very high hardness gradient.   In this case, the layer was less than 1 mm thick and had an initial hardness gradient of 49 HB.   Prior to machining, the thin layer was detected only with the 5 MHz Sezawa wave. The layer was reduced to approximately 0.3 mm and detection was again observed by the 5 MHz Sezawa wave. The hardness gradient was 38 HB.
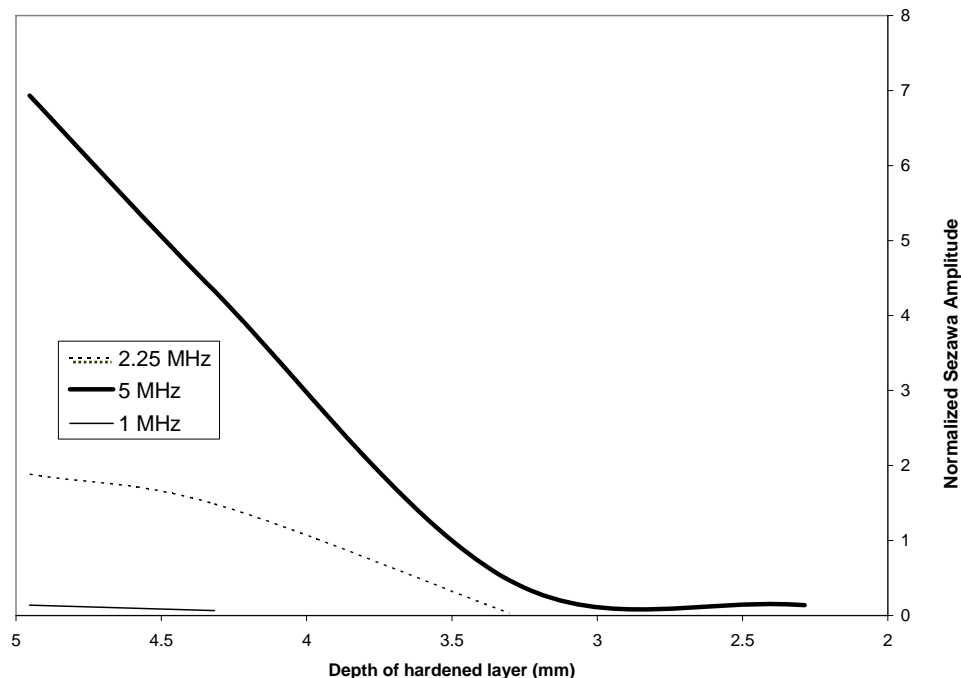
FIGURE 15 Plot depicting decrease in normalized Sezawa amplitude with increased grinding

4.4.2 Inspection of traffic-hardened layers using EMATs

EMATs (Electro-Magnetic Acoustic Transducers) are ultrasonic transmitters that do not need to have contact with the material to create strong acoustic waves. Since EMATs do not require physical contact with the inspected specimen, they are more advantageous than regular contact ultrasonic inspection methods in that they are very amenable to rapid inspection, do not require any couplant medium (such as ultrasonic gel), and could work very well in unclean and high-temperature environments. Figure 16 shows a conceptual diagram of the generation of ultrasound using an EMAT. A permanent magnet is placed near the surface of the sample, creating a magnetic field within the sample. A coil (Figure 17) with an AC current is then placed near the surface of the sample, creating an alternating field within the sample, which creates eddy currents. These eddy currents interact with the permanent magnetic field and create deformations in the material due to Lorentz force. These deformations propagate as ultrasonic waves through the material.
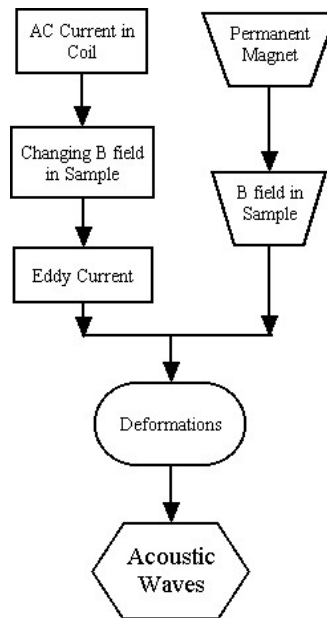
FIGURE 16 Conceptual Diagram – Ultrasound Generation using EMAT

FIGURE 17 Coil used in the EMAT

Experiments were conducted to generate higher-order surface waves in the rails using EMATs. The coil shown above was placed along with permanent magnets on the rail surface. The coil was excited using toneburst signals from a RITEC pulser at frequencies of 1 MHz, 2.25 MHz and 5 MHz. A pair of EMATs were used, one as a transmitter and the other as a receiver. The received signal was displayed using generic data acquisition software on a computer. However, it was observed that Sezawa waves of any significant signal strength could not be generated in the rails using the EMATs. Figure 18 shows the waveform obtained while trying to generate the Sezawa wave in a standard rail at 1 MHz. Similar results were obtained using the 2.5 MHz and 5 MHz EMATs designed for this project. It is quite possible that the EMATs used could not generate ultrasonic waves with displacement components sufficient enough to support the Sezawa waves to be observed. The input ultrasonic waves could not couple enough energy to sustain the Sezawa wave generation in the traffic-hardened layer of the rail.
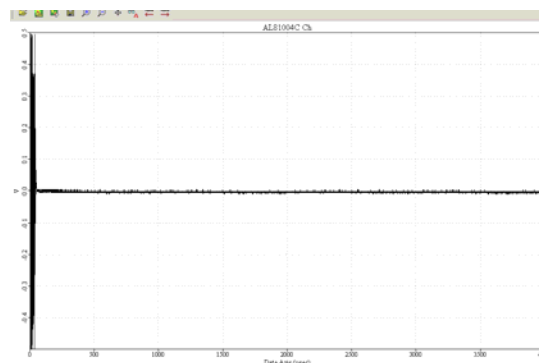
FIGURE 18 Observed waveform during an attempt to generate Sezawa wave using EMATs in the laboratory

4.4.3 Performance on Lubricated Rail

Experiments were conducted on lubricated rail to determine whether Sezawa waves could be practically applied to lubricated rail. The attenuation of the wave measured in lubricated and dry rail were compared. Attenuation of the Sezawa wave amplitude was measured as a function of distance between the transmitting and receiving transducers (8" (203 mm), 16" (406 mm), 24" (609 mm) and 32" (812 mm)). A layer of Whitmore's Railmaster® #1W lubricant (Table 6) was applied to the entire top surface of the test area. The lubricant was applied to the head of the rail at thicknesses ranging from 1/8" to ½" (Figure 19). Even though such lubricant thicknesses would not be found under normal real-life situations, these were applied to create extreme situations. The Sezawa wave methodology using contact angle-beam transducers worked well in resolving and characterizing the traffic-hardened layers with no significant reduction of performance. The experimental set up was similar to that of the tests conducted on dry rail. Standard ultrasonic gel couplant was used to couple the transducers to the rail.

TABLE 6 Specification sheet for Railmaster® lubricants

ASTM #		TYPICAL CHARACTERISTICS			
	NLGI Grade	0	1W: Winter	1S: Summer	2
D-217	Cone Penetration (Worked)	380	340	320	290
D-2265	Dropping Point, °F (°C)	475 (246)	470 (243)	470 (243)	>500 (>260)
D-445	Kinematic Viscosity (Base Oil with Polymer)				
	cSt @ 40°C	30	84	84	179
	cSt @ 100°C	4.4	8.5	8.5	12.9
Gardner	Density, lb/gl @ 60°F (15.5°C)	7.73	7.60	7.61	7.89
Method	Specific Gravity, g/cc @ 60°F (15.5°C)	0.928	0.912	0.914	0.947
D-2596	Four Ball EP, Weld Point, kg	315	315	315	315
D-4049	Water Spray-Off, % Loss	N/A	15	10.8	9.5
(Modified)	12 psi @ 77°F (25°C) @ 30 min.				
D-1743	Rust Test	Pass	Pass	Pass	Pass
D-4048	Copper Strip Corrosion for Greases	1B	1B	1B	1B
(Modified)	212°F (100°C) @ 3 hrs				
	Thickener Type	Aluminum Complex	Aluminum Complex	Aluminum Complex	Aluminum Complex
OEM	Low Temperature Pumpability				
Standard	Lincoln Ventmeter @ 400 psi, °F (°C)	-45 (-43)	-18 (-28)	-12 (-24)	25 (-4)
	Farval @ 2,000 psi, °F (°C)	-60 (-51)	-42 (-41)	-27 (-33)	15 (-9)
	Solid Lubricants	Yes	Yes	Yes	Yes

For each test location on the dry rail, there were two distinct peaks in the waveform as shown in Figure 14. The first peak at each location was the faster traveling Sezawa. The second peak is the slower traveling surface wave. Given the nature of surface waves it was possible to physically damp out the wave by pressing down with a finger the rail's top surface along which the surface wave propagates. This method was used to verify that the wave was, in fact, a surface wave. Both modes, however, were observed at excellent signal-to-noise ratios.
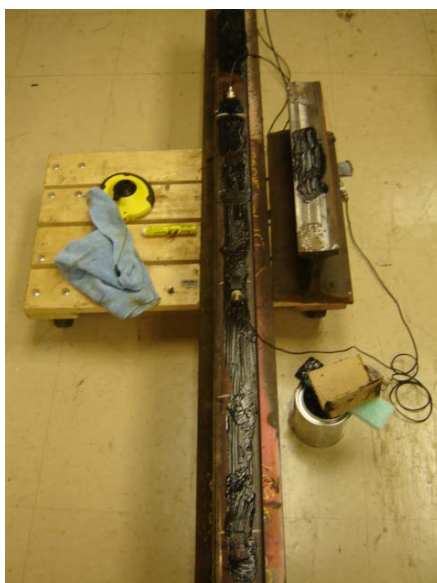

FIGURE 19 Lubricated rail test set up

During the lubricated rail tests, the surface wave was completely attenuated at each test location. The Sezawa wave, however, was still generated with a good signal-to-noise ratio. Data was acquired at 1 MHz, 2.25 MHz and 5 MHz, but only data from 2.25 MHz is presented here in detail, noting that comparable results were obtained for 1 MHz and 5 MHz. Table 7 summarizes the observed Sezawa wave amplitudes in dry and lubricated rails. The signal-to-noise ratio of Sezawa waves in dry and lubricated rail deteriorated beyond a transmitter-receiver distance of 16" (400 mm). Figure 20 shows the respective amplitudes of the Sezawa wave on dry and lubricated rail, as well as the surface wave on dry rail, as a function of distance between transmitter and the receiver. While the Sezawa waves in the lubricated rail start off at lower amplitudes, the rate at which they attenuate is comparable to that in the dry rail.

TABLE 7 dB loss between dry and lubricated rail at 2.25 MHz

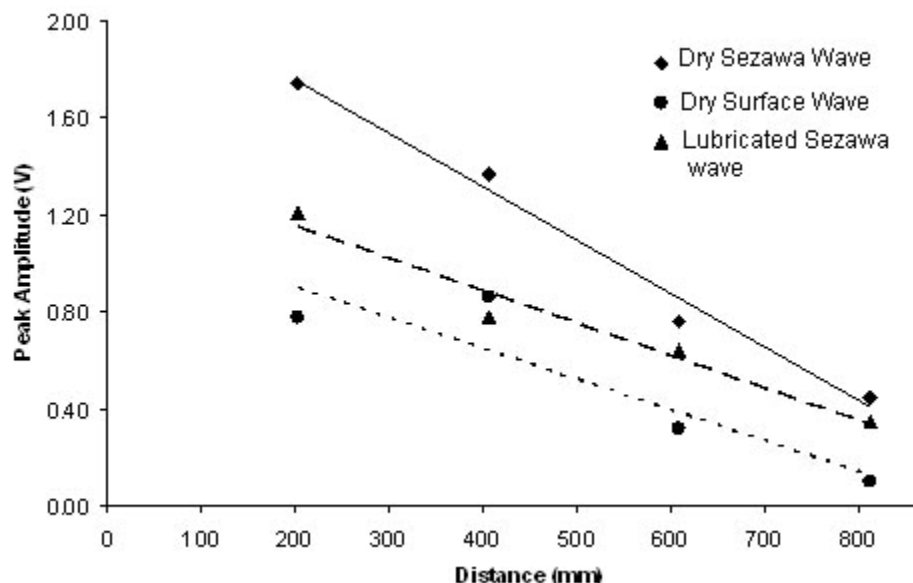| Distance (mm)	Dry Rail Sezawa Amplitude	Lubricated Rail Sezawa Amplitude	dB Loss
203	1.74	1.21	-3.16
406	1.37	0.78	-4.89
610	0.76	0.64	-1.49
813	0.45	0.35	-2.18

FIGURE 20 Sezawa wave amplitude on dry and lubricated rail showing comparable signal loss over increasing distance between transmitting and receiving transducers.

4.4.4 Identification of Minimum Hardness Gradient

The wave propagation models generally used for defect identification in traffic-hardened layers do not address the material property gradients through the cross-section of the rail. It is known that the shear and longitudinal bulk wave velocity, and hence the moduli, across the hardened layer are not constant. The deviation from the matrix rail is the greatest towards the top surface of the rail. These same properties shall gradually approach those of the matrix rail at greater depths based on the metallurgical makeup of the rail and tonnage to which it has been subjected. The previous work on rails have not investigated the minimum hardness and/or material property gradients required to support Sezawa wave mode excitation. This is an important limitation of the measuring technique since it should be able to detect a minimum hardness gradient that is comparable to those observed over the lifetime of a rail. In standard rail, for example, the nominal surface hardness is 310 HB (AREMA Chap 4). Since it is desirable to control the surface hardness at or below 360 HB, the measurement technology should be able to detect hardness gradients of at least Δ50 HB but sensitivity to smaller gradients is desirable. In head-hardened rail, the nominal surface head hardness is 370 HB with an upper limit of 410 HB. Sensitivity to Δ40 HB and less is required for head-hardened rail.

A secondary objective of this work was to determine the minimum detectable hardness gradient in rail using the Sezawa wave mode. The general procedure used is shown in Figure 21. Data is acquired on rail using the angle beam

piezoelectric transducer set up, with a known depth hardness profile (HB). If the Sezawa wave mode is observed, then there is sufficient hardness gradient to support the mode. From Table 2 and 3, it can be seen that there was reduction in hardness with removal of material from the rail surface by grinding. By removing up to 1 mm of material from the rail surface the hardness gradient should decrease as well. If Sezawa wave is still observed more material is removed until the mode is no longer present. At this point, it may be concluded that the hardness gradient is insufficient to support the Sezawa wave mode. The difference between the hardness at this depth and that of the nominal hardness is the minimum detectable hardness gradient.
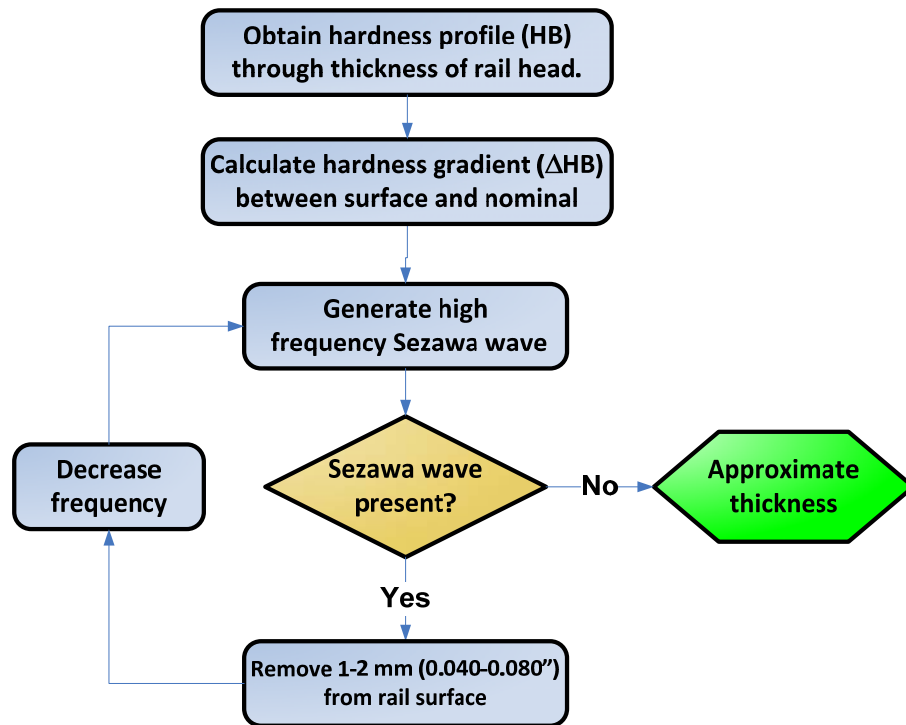

FIGURE 21 ΔHB measurement procedure

5. PROJECT PANEL

The kick-off meeting for the "*Rail Surface Characterization*" Project, Contract Number: HSR-55 was held on 23 August 2006.   The panel members in Table 8 participated in the conference call. A presentation summarizing the core project technology and project objectives was sent to panel members before the meeting. Panel members were lead through the presentation by W*in*S.

TABLE 8 Project panel members

Panel Members	Affiliation	Contact info
Chuck Taylor	**TRB**	ctaylor@nas.edu 202-334-2065
Bob and Tom Hay	*WinS* WavesInSolids LLC	bobhay@wavesinsolids.com thomhay@wavesinsolids.com 814-571-6530
Nick Nielsen	CN	nick.nielsen@cn.ca
Bob McCown		Bob McCown, 9333 Franklin Place Seabrook, MD 20706, 301 908-0283, bob.mccown@gmail.com
Don Plotkin	FRA	202-493-6334
Jeff Gordon	the VOLPE center	617-494-2303

The panel identified some of the major issues to be considered in the approach for rail surface characterization which included the effect of rail profile, the problem of micro-cracking in the traffic-hardened layers, and the influence of rail metallurgy. The project context and requirements were discussed in detail by the project panel members and agreed upon. The benefits of in-service rail maintenance, and the associated rail profile and surface maintenance operations were discussed. The lubrication and grinding practices generally adopted during maintenance operations were discussed. The requirement of the project was identified as follows: Metal surface that is fatigued to the point of concern can often be seen, but there is no technology yet to measure this, or its thickness, while traveling over the track. Grinding this layer, and assessing the results, is done mainly by observation at the site and visual observation after a grinding pass. Hence, an approach is needed to measure the relative fatigue crack density and depth of cracking (or layer thickness). The significance of rail profile variations were discussed as well.

6. SUMMARY OF RESULTS

The goal of this IDEA project was to develop a non-contact Electro-Magnetic Acoustic Transmitter (EMAT) ultrasonic inspection technology to identify and characterize traffic-hardened layers in rails. If successful, this technology would then be incorporated into a system that could be mounted on a rail inspection vehicle that could be operated at speeds up to 25 mph. This could not be accomplished, however, due mainly to insufficient coupling of ultrasonic energy generated from the non-contact EMATs into the Sezawa wave mode. An interim objective was achieved that led to the development of a commercial prototype that utilizes handheld contact piezoelectric transducers capable of detecting and measuring the depths of traffic-hardened layers in rails.

Project tasks included documentation of a traffic-hardened layer measurement specification in terms of depth and/or hardness, hardness testing on rail with known MGT to determine surface and subsurface hardness gradients, metallographic analysis as a secondary measurement for traffic-hardened layer depth, measurements of traffic-hardened layers with the Sezawa wave ultrasonic measurement technology, and comparison of the results with the actual layer measurements and performance specification. A secondary objective was to determine if the proposed technology could be used in lubricated rail.

The performance specification was defined in terms of the three rolling contact fatigue crack growth stages that occur in the traffic-hardened layer. Stage I was characterized by micro-cracks 0.25 mm (0.001") deep that grow slowly. Stage II was defined by RCFs that grow from 1-3 mm at an accelerated rate. In Stage III, RCF branching may occur in the traffic-hardened layer with accelerated crack propagation in the vertical direction at depths between 4 – 7 mm. Based on this information, traffic-hardened layer thickness specifications were developed. It is desirable to have a technology capable of detecting traffic-hardened layers 0-1 mm, 1-3 mm, and 4 - 7 mm thick. Traffic-hardened layers in standard and head-hardened rail samples were characterized using hardness profiles and metallographic techniques. In standard rail, traffic-hardened layers from 4.9 mm to 1.27 mm range were detected corresponding to the hardness and metallographic analysis. The hardness at 1.27 mm was 330 (HB) which was 15 HB above nominal value. This hardness gradient was insufficient to support Sezawa wave generation. In the head-hardened rail, traffic-hardened layers of less than 0.65 mm were detected corresponding to the hardness and metallographic analysis. The tests confirmed that it is possible to resolve traffic-hardened layers < 1 mm, 1 – 3 mm, and 4 – 7 mm thick. The technology was also evaluated on lubricated rail. Data were acquired on dry and Railmaster® lubricated rail. The results show that a small 2-5 dB drop in signal-to-noise ratio can be expected over the desired test ranges.

The Sezawa wave was generated in the traffic-hardened layers of the rail using Plexiglas wedge-mounted angled beam ultrasonic transducers. They were, able to resolve hardened layers of different thicknesses using the cut-off frequency inspection procedure. Efforts were carried out to generate the Sezawa waves in the rail surface using non-contact EMATs. These efforts were not successful. Even though the ultimate goal of the project could not be accomplished, an interim objective was achieved which has led to the production of a commercial handheld prototype for characterizing traffic-hardened layers that uses contact angle beam piezoelectric transducers.

The significant achievements of this project are listed as follows:

- Development of a quantitative performance specification for detection and measurement of traffic-hardened layers in terms of depth, rolling contact fatigue crack size, and hardness gradients
- Identification of the minimum hardness gradient requirement in traffic-hardened layers to facilitate Sezawa wave generation
- Development of a minimum hardness gradient detection procedure using cut-off frequency inspection methods
- Measurement of traffic-hardened layer thicknesses using Sezawa waves
- Demonstration of the Sezawa wave technology's ability to work on both dry and lubricated rail surfaces
- Development of a commercial handheld prototype that uses contact piezoelectric transducers for traffic-hardened layer identification and characterization.

The technology, at this point, is capable of detecting and resolving traffic-hardened depths in the millimeter range. In this context, it may be used to assist track management by prioritizing sections of track for internal rail flaw inspection and/or grinding. This is based upon the logic that deeper traffic-hardened layers pose more risk to continued track safety and operation due to the probability that serious flaws may initiate and propagate faster in thicker layers.

The efforts to generate Sezawa waves in the traffic-hardened layer using EMAT were unsuccessful. The EMATs did not generate higher order surface waves of any significant strength. This is probably due to an inefficient coupling of the input ultrasonic mode to the Sezawa wave.

An alternative laser ultrasonic generation and air coupled ultrasound receiver sensor is recommended for future research. This would involve laser pulses impinging on the rail surface and generating higher order surface waves. These waves could then potentially be detected by non-contact air-coupled ultrasonic transducers. Since current air-coupled transducers have been shown to work well up to frequencies of 5 MHz, they are a suitable candidate for detecting Sezawa waves generated in traffic-hardened layers using laser pulses.

7. IMPLEMENTATION

The handheld contact piezoelectric transducer-based commercial system will be marketed to the rail track maintenance community. At this point, it is not envisioned that the system would be sold independently as a product to be used by the railroads. Obviously, if there is a market for the inspection hardware the total system would be packaged professionally and offered to prospective clients. At the current technology readiness level, a moderately to highly skilled ultrasonic technician would be required to acquire and interpret the data. The inspection service, therefore, will be offered by WavesinSolids to prospective rail clients and delivered using our portable ultrasonic data acquisition system by a trained ultrasonic technician.

GLOSSARY

MGT – Million Gross Tons (of traffic)

RCF – Rolling Contact Fatigue

Head-hardened rail – Rails whose heads alone are heat treated during their fabrication process

Traffic-hardened layer – Rail surface that has been hardened due to traffic (usually in terms of MGT), sometimes referred as work-hardened layer

Guided waves – Ultrasonic waves whose propagation in a medium is guided by the finite dimensions of medium.

Surface wave - A mechanical wave that propagates along the interface between differing media

Rayleigh Wave – It is a type of Surface wave. As it passes through the surface, a surface particle moves in a circle or ellipse in the direction of propagation. The amplitude of the Rayleigh wave decreases rapidly with depth in the material.

Sezawa Wave – Higher order Surface wave

EMAT – Electro-Magnetic Acoustic Transducer

Angle Beam Transducer – An ultrasonic transducer mounted on a Plexiglas wedge to send ultrasonic energy into a medium at a desired angle of incidence.

Dispersion curves – Graphs that indicate the change in the ultrasonic wave velocities with respect to the frequency

Group Velocity – The velocity with which the variations in the shape of the wave's amplitude (known as the modulation or envelope of the wave) propagate through a medium. The group velocity is often thought of as the velocity at which energy is propagated along a wave.

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