Development and Evaluation of High Performance Rail Steels for Heavy Haul Operations

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ABSTRACT
Rail testing and evaluation prior to revenue service implementation is valuable to the railway industry. The data acquired during these studies provides the industry the information needed in the decision making process for optimized rail utilization. Transportation Technology Center, Inc. (TTCI) located in Pueblo, Colorado, USA, has been involved for over 20 years in premium rail testing for heavy axle load applications. Due to increased axle loads in revenue service and the need to understand their impact on track components, a full-scale Facility for Accelerated Service Testing (FAST), located at TTCI has been utilized to evaluate rails from leading worldwide manufacturers in a controlled environment. The current test initiated in 2010 is evaluating wear and fatigue performance of both premium and intermediate hardness (IH) rails.

Seven manufacturers are participating in the premium rail test, with a total of 10 rail grades being tested. The test section of 320m in length, is located on a 349m radius curve, has 10cm of superelevation, and is operated without direct rail lubrication. The test rails have been installed on both the high and low rails of the curve. The average top of railhead hardness of these rails is 407 hardness Brinell (HB). Intermediate hardness (IH) rails are also being tested, in a separate curve. There are six manufacturers with a total of eight rail grades participating in the IH rail test. The IH test section is 244m in length and is also located in a 349m radius curve with 10cm of superelevation, however, there is gage-face lubrication of the rail in this curve. The average hardness of this rail test section is 335HB.

In addition to the premium and IH rails from leading manufacturers being tested at FAST, TTCI sponsored research has led to the development of a next-generation rail steel, which is a fully pearlitic premium grade rail steel aimed at extending the in-service rail life by reducing the development of rolling contact fatigue on the railhead, thereby minimizing the grinding cycles. This rail steel is part of the premium rail test in the High Tonnage Loop (HTL).

The work presented here describes the mechanical test results, the in-track test layout, as well as the preliminary wear results for each rail type. The mechanical property data will be related to the rail wear in order to establish a correlation between the mechanical test results and wear performance.

BACKGROUND AND INTRODUCTION
With the advent of increased heavy axle load (HAL) operations in North America, the railway industry is placing increased emphasis on rail performance testing. Rail suppliers have made product improvements with the goals of improved rail cleanliness, metallurgy, and thermomechanical processing, resulting in rails that wear and fracture less, thereby lasting longer. TTCI has been conducting rail performance research to enhance and accelerate the improvement of rails. That research has included rail testing in a HAL environment. Testing at FAST, and revenue service experience have shown that rail quality and performance has improved. Today’s rails are more resistant to wear and fatigue than rails produced decades ago were. However, the improvements tend to be incremental. Rolling contact fatigue (RCF) and wear still result in reduced rail life,

Premium rail tests are currently being conducted by TTCI in section 7 of the HTL at FAST, a 349m radius dry curve with 10cm of superelevation and 320m in length. The metric utilized to quantify rail wear performance is rail profile measurement taken with a Miniprof™. Also, a qualitative assessment of top
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of rail RCF performance is being carried out. In addition to the premium test curve in section 7, IH rails are being tested in HTL section 3, which has the same geometry as section 7, and is 244m in length.

The FAST train consists of 110-115 rail cars with a gross weight per car of 142,700kg. The train is operated on the HTL using three locomotives at a speed of 64km/h. The balance speed for both curved track sections 3 and 7 is 53km/h, which yields 4.3cm of superelevation deficiency. Traffic is bi-directional, operating at approximately 50% in each direction. During train operations in 2010, the average daily tonnage was approximately ~1.55MGTonne.

The current premium rail performance test has seven participating manufacturers and 10 different rail grades. The manufacturers, countries of origin and number and type of rail grades in test are as follows:

- ERMS Rail Mill (USA) – 1 grade: OCP
- Corus Rail Mill (France) – 1 grade: MHH HE (head hardened)
- Nippon Rail Mill (Japan) – 1 grade: NSC-HEX (control rail)
- JFE Rail Mill (Japan) – 2 grades: JFE-A (SP2), JFE-B (SP3)
- Mittal Rail Mill (USA) – 1 grade: HC
- Panzhihua Rail Mill (China) – 1 grade: PG4 (head hardened)
- Voestalpine Rail Mill (Austria) – 3 grades: VAS-1, VAS-2, 400NEXT

For the IH rail wear test, there are six participating manufacturers with the following 8 rail grades:

- Corus Rail Mill (France) – 1 grade: MHH HE (as rolled)
- ERMS Rail Mill (USA) – 3 grades: ERMS-1 (IH), ERMS-2 (IH HS), SS (control rail)
- Panzhihua Rail Mill (China) – 1 grade: PG4 (as rolled)
- Mittal Rail Mill (Spain) – 1 grade: ML
- TrinecZelezarny Rail Mill (Czech Republic) – 1 grade: TZ
- Lucchini RS Rail Mill (Italy) – 1 grade: IH

Each manufacturer provided their rail sections in 12.2m lengths. These sections were then welded at the Holland welding facility in Pueblo, Colorado, and delivered to TTCI via a rail train. It is worth noting that the track in both sections 3 and 7 was renewed prior to rail installation. Ballast was screened and replenished, and new wood ties were installed in the test sections. The ties were plated with Pandrol heavy haul cast plates with ‘e’ clips. The renewal was intended to provide uniform conditions through the test zones. As with the previous rail wear tests conducted at FAST, each rail grade was placed adjacent to the NSC-HEX control rail to account for any remaining position-in-curve effects. Due to the large number of rail grades tested, an arrangement sequence was developed that allowed the placement of at least one 12.2m rail grade adjacent to a control rail in the string. Figure 1 shows excerpts of both layouts for sections 3 and 7.

![Figure 1(a,b). Excerpts of FAST section 7 (a) and section 3 (b) rail test setups.](image)

Figure 2 shows the test curve and a sample of the load environment for the curve. The mean high-rail lead-axle lateral load is 24.52kN, and the mean high-rail vertical load is 207.41kN.
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Figure 2. Test Curve and Load Environment in section 7 of FAST.

The previous premium rail wear test conducted at FAST concluded at ~410MG Tonne of traffic due to heavy gage-face wear. It took approximately four years of FAST traffic to achieve this. Since the current test load conditions, track geometry, and lack of lubrication are similar to the previous premium rail test, it is expected that the current test will accumulate at least the same amount of tonnage.

RESULTS

Rail Microstructure

Railhead microcleanliness analysis to determine the amount of inclusions was performed on each steel grade tested at FAST. Sample extraction was done according to the American Railway Engineering and Maintenance of Way Association (AREMA) manual recommendations. The mean and maximum volume percents of voids, oxides (inclusion matter other than sulphides), and sulphides were determined according to ASTM E1245-03(2008) specification. All microcleanliness testing was performed at an outside independent laboratory. Figure 3 indicates the results for all the steel grades tested. Based on these results, all steels can be deemed very clean. The amount of oxides and voids in the railhead is relatively small in all grades tested. Although some of the premium rails had elevated maximum sulphide readings, the mean readings were similar to the IH rails tested.

Assessment of the head microstructures of all the above mentioned rails, indicates that all rails are fully pearlitic, which meets AREMA recommendations for premium and IH rails. However, using Scanning Electron Microscopy (SEM) analysis, some proeutectoid cementite (Fe₃C) has been observed at the grain boundaries in some premium rails (Figure 4). Data from investigations of the condition of rail following HAL traffic has shown that presence of Fe₃C may be linked to the occurrence of RCF. The rail industry recognizes that a combination of rail chemistry and thermo-mechanical processing is the cause of the formation of Fe₃C at the grain boundaries. Previous investigation has shown that the presence of proeutectoid cementite combined with an elevated inclusion level is detrimental to RCF prevention, because RCF cracks that initiate at the intergranular cementite can branch out into secondary cracking with the assistance of the entrained inclusions. Thereby, inclusions tend to speed up the occurrence of RCF in the railhead. Influence of inclusions on RCF development continues to be an important area of investigation. Future reports will address this issue.

Presence of inclusions can be directly linked to the steel chemistry. However, the individual rail chemistries for the test rails are not provided here at the request of the rail manufacturers.
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Figure 3. Microcleanliness analysis test results for both IH and premium rail steels tested.

Figure 4. SEM image of one of the premium rail steels indicating Fe₃C observed at the grain boundaries of the pearlite grains in the head region.

Railhead Hardness
Brinell hardness measurements (HBW 10/3000) were taken on top of the railhead for all rail grades. For the IH rails, the average reading was 335±15HB, and all but two of the readings met the minimum AREMA recommendations for IH rails (Figure 5). For the premium rails, the average hardness was 407±11HB, which is similar to the hardness measurements of the 2005 premium rail wear test. All the premium rail readings exceeded the minimum AREMA hardness recommendation for premium rails.

Improvements in rail hardness are generally associated with improved wear resistance in service. As such, all premium rails are expected to have relatively good wear performance over time. Future reports will focus on a link between head hardness, work hardening of the head over time, and wear performance of each grade as a function of these factors. It should be noted that although the IH rail curve has a substantially lower average hardness, this curve is lubricated on the gage face of the high rail, with top of low rail friction control. As a result, the wear performance is expected to be better than in the premium rail curve, which is not lubricated.
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Figure 5. Top-of-railhead hardness measurements for the IH and premium rails. Minimum AREMA recommendations for each grade type is indicated.

Rail Mechanical Properties

Tensile and fracture toughness samples were taken from both the railhead and base, as indicated in Figure 6, for each rail grade. Tensile testing was carried out at room temperature according to ASTM E8-09 specification. Fracture toughness testing was carried out at room temperature according to ASTM E399-09 specification.

The mechanical properties obtained from the tensile testing were the Yield Strength (YS), the Ultimate Tensile Strength (UTS), and the Elongation to failure (El.). During the first round of testing, the mechanical properties of some rail grades failed to meet the minimum AREMA recommendations for premium grades of steel. Thus, for verification purposes the tests were repeated, with the second round of testing yielding similar results. Both rounds of blind study testing were conducted at two different independent laboratories. Figure 7 shows tensile test results for the railheads and bases for both IH and premium rail grades, as well as the minimum AREMA recommendations for the head of the rail.

Figure 6. Tensile and fracture toughness sample extraction locations in the head and the base of the rail. Measurements: inches [mm].
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Figure 7. Tensile test results for the IH rail and premium rail grades utilized in section 3 and section 7 rail wear test, respectively. Minimum AREMA recommendation for the head region of the rail for each property in each grade of rail is as indicated.

As indicated in Figure 7, the tensile results for the railhead in all IH rails meet the minimum AREMA recommendations, with the best properties displayed by the Lucchini IH rail. However, for the premium rails, UTS in the head region of the rail was the only tensile property that met the minimum AREMA recommendations for all premium rails. Numbers for both YS and El resulted in values that were below the minimum AREA recommendations for the railhead region in a number of rails tested. The best YS and UTS occurred in the Corus rail, whereas the best elongation was recorded in the 400NEXT rail. Fracture toughness testing was performed on both the railhead and the base, and was carried out in a similar way as in the previous rail wear test(Figure 6).
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As indicated on the graphs in Figure 8, the average $K_{IC}$ values for both the premium and IH rails in the head and base regions ranged from $38.2 - 40.5 \text{MPa} \sqrt{\text{m}}$, with some of the individual values ranging as far as $49.0 \text{MPa} \sqrt{\text{m}}$. Fracture toughness measurements are aimed at correlating the material’s resistance to brittle crack propagation, which may be used as a means to assess the propensity for in-service base cracks. These high values indicate that all rails being tested should be resistant to base breaks.

There is a perception that fracture toughness values are strongly affected by the carbon content in the rail steel. As a result, the attained $K_{IC}$ values for the railhead and base regions in both premium and IH rail grades were linearly correlated to the carbon content in each steel grade tested. There is a poor correlation between C[wt.%] and $K_{IC}$ for both the head and base of premium rails, and for the head of the IH rails; however, there was a relatively good correlation in the base of the IH rails ($R^2=0.67$). These correlations may be an indication that carbon content alone is not a good predictor of the $K_{IC}$ value, and thereby, not a good predictor of the resistance for base fractures in revenue service environment. Furthermore, current AREMA recommendations do not offer any guidelines concerning fracture toughness and its relation to different rail grades, making it difficult to gauge rail performance based on the $K_{IC}$ numbers. In order to properly understand the $K_{IC}$/base-breaks relationship, a more detailed study would be required. This study would require longer rail lengths and a longer test section than what is currently available at FAST. During the previous rail wear test, conducted between 2005 and 2009, the base breaks began occurring after 182MGTonnes, and to date the current test has accumulated 100MGTonnes with no base breaks reported in the premium rails.

**Figure 8.** Fracture toughness ($K_{IC}$) test results for the head and base locations in the rail.

**Preliminary Rail Wear Results**

Rail wear measurements were taken at 29.2, 54.7, and 81.1MGTonnes of accumulated traffic at FAST utilizing the Miniprof profilometer. Five rail profile measurements were taken at each rail test segment (Figure 9) with the outer measurements taken at 1.83m from the welds. Since each rail grade has two 12.2m track sections in the curve, this setup allowed for 10 rail profile measurements on the high and 10 on the low rail for each rail grade being tested in this curve (a total of 250 profile measurements for length of track). To date, no measurements have been eliminated from this setup (rail or weld breaks sometimes cause measurement sites to be removed).

**Figure 9.** Miniprof head profile measurement locations in each rail grade tested.
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Profile measurements yielded W1 (vertical), W2 (horizontal), and W3 (auxiliary) location measurements, as well as the ‘area loss’ measurements. Since the current accumulated MGT level is relatively low at this point in the test, the only measurement comparison presented here will be the area loss on the high rail (Figure 10). For the IH rails, the lowest loss to date is in the ERMS-1 rail, whereas the highest loss is in the Mittal rail grade. For the premium rails, the lowest loss is in the Corus rail, whereas the highest loss is in VAS-2 rail. Having said that, at this point the wear trends are preliminary, and they may change with accumulated tonnage due to work hardening effects. The 400NEXT rail was installed at a later date than the other premium rails and has only accumulated 20.1MGTonne to date. The wear data for this tonnage has been included in the premium rail wear curve; however, accumulated tonnage performance comparison to other premium rails cannot be made at this point in time. Measurements in the 400NEXT rail will be taken at the same tonnage as the other premium rails for future comparison.

The noticeable difference between the wear rate of the IH rails and the premium rails is most likely due to the non-lubricated environment in the premium rail test curve. The IH rails (which are fully lubricated in high rail) have on average ~50% less wear than the premium rails, even though the average top of the rail hardness is ~72HB points lower. This confirms previous test results, and supports the argument for lubrication in curves as a way of rail-life-extension.

<table>
<thead>
<tr>
<th>Rail Type</th>
<th>Average High Rail Wear Area (mm²)</th>
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<tbody>
<tr>
<td>ERMS-1</td>
<td>29.2 MGTonne</td>
</tr>
<tr>
<td>ERMS-2</td>
<td>54.7 MGTonne</td>
</tr>
<tr>
<td>ERMS-SS</td>
<td>81.1 MGTonne</td>
</tr>
<tr>
<td>Corus</td>
<td>29.2 MGTonne</td>
</tr>
<tr>
<td>Mittal</td>
<td>54.7 MGTonne</td>
</tr>
<tr>
<td>VAS-2</td>
<td>81.1 MGTonne</td>
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Figure 10. Preliminary average high rail wear area for section 3 IH and section 7 premium rail test (n=10 railhead profile measurements for each bar reading on the graph).

To date, the RCF development in each rail grade tested is relatively minor. Premium rails have more head checks in the gage corner of the high rail and on top of the low rail than IH rails do. Figure 11 shows examples of RCF conditions in two premium high rails. At this point in time, the head checks are very shallow and have not led to any spalling. Lubrication in the IH rail curve appears to reducing the development of head checks. Monitoring of head surface conditions continues.

<table>
<thead>
<tr>
<th>Rail Type</th>
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<tbody>
<tr>
<td>ERMS-1</td>
<td>20.1 MGTonne</td>
</tr>
<tr>
<td>ERMS-2</td>
<td>29.2 MGTonne</td>
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<tr>
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<td>54.7 MGTonne</td>
</tr>
<tr>
<td>VAS-3</td>
<td>81.1 MGTonne</td>
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Figure 11. Comparison between the high rail gage corner RCF (bottom of each rail) in two different rail grades of rail tested at FAST.
CONCLUSIONS

To date, there have been no rail breaks in the premium test curve. There was one base break in the IH test curve, determined to have initiated at base nicks caused during rail installation. There was one flash but weld break that initiated at the shear marks in the web.

Based on the microcleanliness investigation, all steels are considered to be very clean with a relatively low level of sulphides, and very low levels of oxides and/or voids. Although all rails are fully pearlitic, some of the head microstructures have limited amounts of intergranular pro-eutectoid cementite (Fe₃C), which has been linked to increased occurrence of RCF in previous studies. All hardness measurements for the premium rails meet the AREMA minimum recommendations; however, two of the IH rails have head hardnesses just below the AREMA recommendations.

Uniaxial tensile testing revealed that all IH rails meet the AREMA minimum recommendations for YS, UTS, and EI; however, some of the premium rail values for YS and Elw are below the AREMA minimum recommendations. TTCI acknowledges that in the past an argument has been made by some rail manufacturers that sampling close to the rail end may not reflect the true rail properties due to lack of constraint at the rail ends during the rail straightening process, which has an influence on the residual stress level in the final rail product.

Fracture toughness measurements for both the IH and premium rails are in the $38.2 - 40.5 MPa\sqrt{m}$ range, with some of the individual values ranging as high as $40.0 MPa\sqrt{m}$. These are relatively high results and are expected to yield a lower occurrence of base breaks in revenue service conditions.

Preliminary rail wear on high rail indicates that despite the lower hardness level, IH rails are wearing on average ~50% less than the premium rails. This is attributed to lack of lubrication in the premium rail curve.

To date, RCF development is minimal in the IH curve. The premium rail curve has substantially more head checks on the gage side of the high rail; however, they are shallow and have not led to any spalling so far. Lubrication in the IH rail curve appears to be reducing the development of head checks in these rails.

The FAST rail wear test is expected to continue for 3-4 years; further reports detailing performance evaluation will follow as additional tonnage is accumulated.

Acknowledgements

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REFERENCES


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