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FAST Rail Evaluation Test – Fracture Performance and Discussion

By Joseph Kristan

Summary

Transportation Technology Center, Inc. (TTCI), Pueblo, Colorado, is currently evaluating the mechanical properties, including fracture toughness, of the rail at the Facility for Accelerated Testing (FAST), at the Transportation Technology Center. The tests are being performed to quantify differences between the current rails and previous rail evaluation tests to explain an increase in rail fractures.

The rail in the current rail evaluation test that began in October 2001 at FAST has an average hardness of 395 HB. During the current test, this rail has sustained seven rail fractures (all in the base of the rails) after only 460 MGT of traffic. This is significant because in the previous test of average 365 HB rail there were no rail fractures subsequent to 517 MGT. Obvious differences in the two tests include the strength and hardness of the rail along with the differences in section from 136 RE to current 141 RE, which accounts for a difference of 2.4 percent bending stress at the base of the rail.

The fractures in the current evaluation all occurred in the high rail due to fatigue at the base of the rail initiated by mechanical damage. The extent of mechanical damage leading to fatigue initiation and amount of fatigue crack propagation prior to final brittle fracture appeared to be qualitatively smaller than typically found at FAST. Thus, an attempt was made to determine the cause of the increase in rail fractures in the current FAST test. The operating conditions, rail installation practices, rail maintenance practices, and personnel performing the maintenance each are identical to those of the previous rail evaluation test. This does not preclude the influence of operating conditions at FAST or maintenance practices as having contributed to the increase in rail fractures. However, due to the relatively light mechanical damage that led to each of the fractures, it is not unreasonable to consider differences in rail performance between the two tests along with the 2.4 percent increase in bending stress in the 141 RE rail as contributing to the increase in rail fractures under the 39-ton axle load environment at FAST.

Each of the premium rails in both tests was head hardened and thus, hardness of the web and base of the rails is substantially lower than that of the head. Additional alloying included in the current rail steel to allow the production of the higher hardness head is obviously present throughout the cross-section of the rail. Thus, the hardness of the respective rail segments (web and base in addition to the previously evaluated head hardness) is currently being evaluated to quantify the differences between the previous, current, and future rail generations. It is important to note that there was not a single rail type, alloying, or track location consistent with the rail fractures. The increased fractures are more likely due to or influenced by the resulting mechanical properties and not a specific alloying addition or heat treatment.

The metallurgical generalities that fracture toughness (resistance to cracking) decreases with increasing material strength and notch sensitivity (reduced ability to resist fatigue initiation) increases with increasing material strength may assist in explaining the fracture increase.

It is possible that the increase in rail fractures in the current FAST rail evaluation test could simply be an anomaly. Additional laboratory testing and results from the next rail evaluation test, to begin this year will likely provide the data required to establish conclusions based on quantitative analysis. However, in respect to fracture mechanics and mechanical properties of steel, there is not a limitless strength or hardness suitable for rail application and thus it is prudent to investigate the current rail fractures to determine the available factor of safety.

Introduction

Rail steel technology has continued to evolve in the attempt to improve rail wear and thus longevity of the rail. Premium rail steels have an increased strength and hardness to resist wear in curves in comparison to standard rail, which would otherwise require frequent and costly rail replacement. Premium rail steels are typically utilized for curvatures greater than 2 degrees.

AREMA defines premium rail as having head hardness above 341 HB. Rail manufactures have eclipsed this rail hardness and strength with a fully pearlitic microstructure found in the rail currently in the test in Section 7 at FAST, in which six rail steel types have an average hardness of 395 HB.

Several manufacturers have indicated that the newest state-of-the-art rail steel to be installed for the next rail evaluation will possess hardness in excess of 415 HB. This increased hardness should provide further improved wear performance based on previous test results. Additionally, other metallurgical advances have allowed improvement in rolling contact fatigue performance. This important advance allows reduced maintenance requirements for the rail by reducing the need for grinding, which in turn reduces the life cycle cost of the rail. However, fracture toughness of a steel generally decreases and notch sensitivity generally increases as the strength and hardness increase. These are important points to consider as several fractures have occurred in the current rail steel test at FAST, while in the previous test, no fractures occurred throughout the test.

The current rail evaluation test at FAST, which began in October 2001, has a total tonnage accumulation of 460 MGT. Through the course of the test, typical wear performance of the different rail steels has been statistically quantified. However, there have been an atypical number of fractures in the test rail. Seven fractures have occurred in three different rail types within 450 MGT of accumulated tonnage. In the previous rail evaluation test, there were no fractures of the test rail after 517 MGT of traffic.

Each of the seven fractures was analyzed to determine the cause with similarities found among the group. All of the fractures occurred in the high rail of the test curve and were located at the bottom of the rail base and initiated at mechanical damage in the rail. Three fractures initiated beneath the bottom of the rail base at the center of the rail due to interaction between the rail base and the edge of the adjoining tie plate. Figure 1 shows one of the three fractures.

The other four fractures occurred at the bottom edge of the rail base.

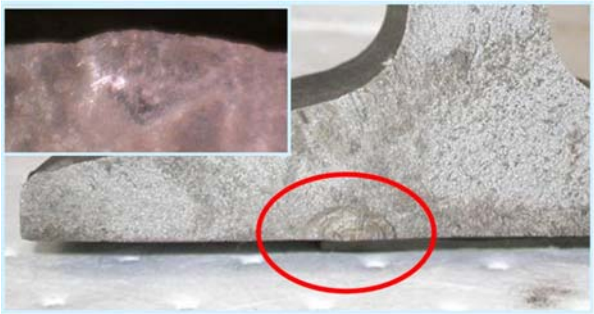

Figure 1. (Circled in red) One of Three Base Fractures. (Upper Left) Plastic Deformation at the Bottom of the Base due to Interaction with the Edge of the Tie Plate.

It is not unusual for rail fractures of these types to occur at FAST, as the operating conditions are more severe than typical service (39-ton axle load and 1.7-inch cant deficiency). However, the installation procedures and operating conditions for both the current and previous rail evaluation tests are identical and thus other variations between the two tests are being investigated to assist in explaining the difference in the number of fractures. For comparison purposes, other similar premium test rail (approximately 400 HB) is being monitored for fracture performance at FAST (grinding test in Section 25).

There have been no fractures to date in the grinding test after 230 MGT. The grinding test is being conducted in Section 25 of fast concurrently with the rail evaluation test and contains some of the same rail types also in 141 RE Section. It remains unclear if the seven rail- base fractures in Section 7 are an anomaly and not characteristic of rail steel performance. Additional investigation is thus ongoing to determine the cause or causes of the rail fractures. Regardless, at some point in the future, unless new technological break-troughs occur, the continued balance of rail strength and hardness verses the resulting mechanical properties will not be conducive for rail steel. However, quantification of the current factor of safety in regard to the rail fracture performance will assist in development, handling, and maintenance for future rail steels.

Fracture Toughness and Notch Sensitivity – Importance and Explanation

Fracture toughness of steel is a generic term for the measures of resistance to the extension of a crack, which is a material property as are yield and tensile strength[3]. The lower the fracture toughness the easier a crack will propagate through the steel. The term fracture toughness is usually associated with the fracture mechanics methods that deal with the effect of defects on the load bearing capacity of structural components[4].

The yield strength of a material is inversely proportional to fracture toughness, with few exceptions, within a specific microstructure (rail steel is fully pearlitic) as is shown in Figure 2[4]. For a given metallurgical structure, toughness increases with increasing temperature and decreases with increasing strain rate or rate of loading[2]. This is explained by the ability of the steel's matrix to tear in a ductile manner during crack propagation, which consequently absorbs energy. As steels' strength is increased, less energy can be dissipated on a microscopic level by ductile tearing and thus the fracture toughness is reduced.

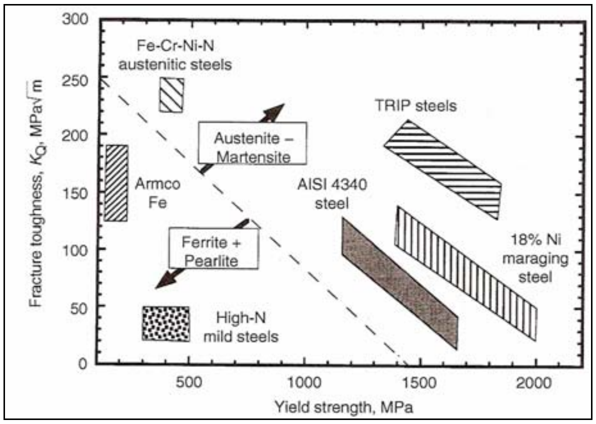

Figure 2. Fracture Toughness as a Function of Yield Strength for Various Steels[4]. Below the Dotted Line is the Pearlitic Region (note: Rail Steel is Fully Pearlitic)

As rail is a structural component, the application of fracture toughness is considered appropriate. Results from fracture toughness tests are often useful in fracture control, based on either service experience or empirical correlations[3]. The fracture toughness of a material is not to be confused with impact toughness (Charpy testing) as impact toughness is used to determine the tendency of a material to behave in a brittle manner at high strain rates and is most meaningful when conducted over a range of temperatures to allow determination of the ductile-to-brittle transition temperature[4].

The influence of fracture toughness, as predicted by fracture mechanics, is shown in Figure 3. A material with lower fracture toughness is not able to sustain stress levels of a higher fracture toughness material at the same crack length. This is consistent with the qualitative observations made about the size of the fatigue crack observed in the six fractures of the rail in the current evaluation test in comparison to other fractures typically observed at FAST.

The fracture toughness was tested at the base of the rail for each of the six current rail types along with a single conventional premium rail steel (370 HB head hardness premium rail) and is shown in Figure 4. The single conventional rail type possesses statistically superior fracture toughness in comparison to the 395 HB average rail steel based on the limited test data available.

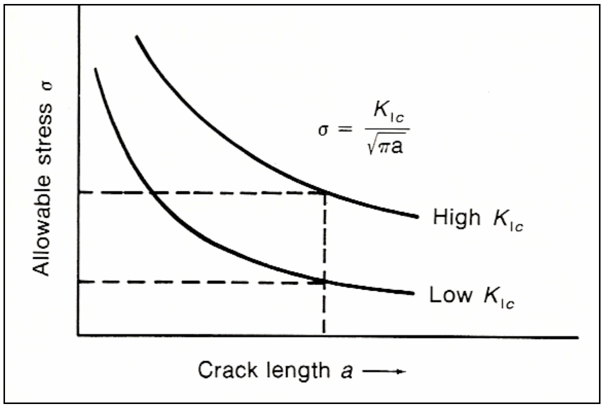

Figure 3. The Allowable Stress for a Given Crack Size is Decreased as the Fracture Toughness (K_{IC}) is Decreased. A Smaller Crack will Produce the Final Brittle Fracture in the Lower Fracture Toughness Material

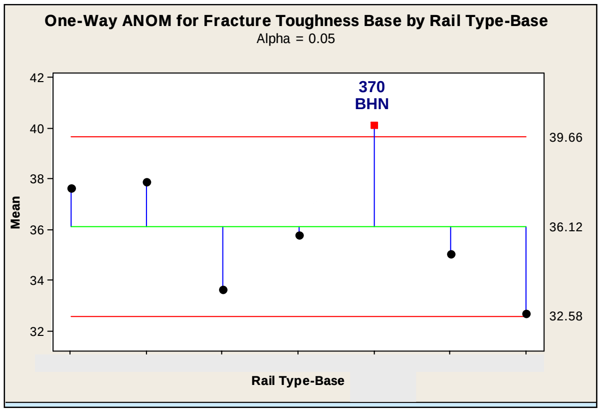

Figure 4. Premium Rail Fracture Toughness Data of the Rail Base for the Currently in Test and one Conventional 370 HB Premium Rail as Obtained from Two-Test Specimen per Rail Type Taken from the Base of the Rail Data Presented in ksi√in

Notch sensitivity is a reduction in a material's ability to resist fatigue due to a stress raiser in comparison to a pristine surface. The notch sensitivity of steel is of equal or greater importance than fracture toughness in regard to service performance. In general, the fatigue performance of steel improves as the strength of the material is increased. However, as Figure 5 shows, notch sensitivity increases with tensile strength, meaning the material is more susceptible to fatigue initiation with increasing notch sensitivity[2]. Thus, it is possible to actually decrease fatigue performance by increasing the hardness or tensile strength of a material[2]. Typically, lower strength steel will be less susceptible to fatigue initiation from a stress raiser (notch or scratch) in comparison to the higher strength and hardness material.

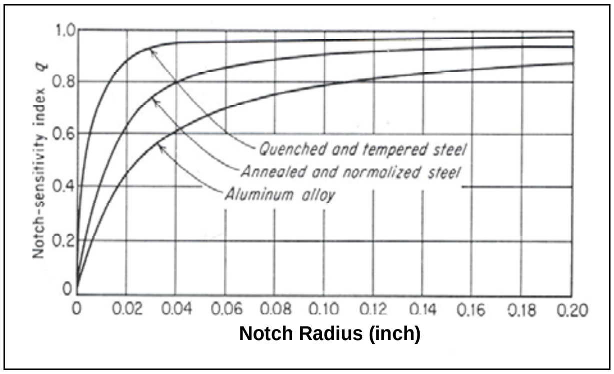

Figure 5. The Notch Sensitivity of a Material Increases with Increasing Strength and Hardness[2]

It is important to note that the seven rail fractures at FAST are not characteristic of a specific type, manufacturer, or grade of premium rail steel but appear to be related to the resultant mechanical properties. The indicated trends are related to metallurgical fundamentals and there is not a specific technique in alloying or processing used to increase hardness and strength that results in the steel being more or less susceptible to notch sensitivity or influenced by fracture toughness based on available test data. Thus, fracture of the test rails can not be correlated with a specific manufacturer or manufacturing practice used to obtain the high strength and hardness in the head of the 400 HB rail steel, but rather the general properties. It is also obvious that the 2.4 percent increase in the tensile stress at the bottom of the base of the 141 RE rail is due to the increase in profile height. This is likely a contributing factor in the observed fractures.

Discussion

Rail manufacturers use different metallurgical alloying and heat treatments to produce high hardness premium rail steels. From all data available, there does not appear to be a single reason that accounts for the increase in rail fractures in comparison to the previous rail evaluation test at FAST. The fractures occurred in three different rail steel types on the high rail at differing locations within the test curve. The rail was installed and maintained using the same personnel and techniques utilized for the previous rail test. This does not preclude handling prior, during, or subsequent to installation as accounting for, or at least contributing to, the fractures. However, the number of fractures that has occurred along with the size (smaller relative to typical rail fractures at FAST) of the mechanical damage (qualitatively evaluated) at the base from which the fractures initiated appear to vary from those typically observed at FAST.

It is possible that the fractures sustained in the rail evaluation test are simply an anomaly. However, another explanation is that the fractures that have occurred in section 7 are a foreshadowing of what can happen under high axle loads and tonnage in high strength and hardness rail steel. If the latter is true, the factor of safety in regard to fatigue and fracture resistance has diminished with the increased hardness in comparison to the previous rail evaluation test (30 HB hardness increase in the current test). The change in rail profile from 136 RE to the current 141 RE rail accounts for a 2.4 percent increase in tensile stress at the bottom of the rail base, which is due to the increased height of the 141 rail and is also a contributing factor in rail fractures.

The next rail evaluation test with an estimated 10 to 15 HB further hardness increase in the head of the rail in comparison to the current test will be closely monitored. Laboratory testing will also be performed comparing and contrasting the fracture toughness and full scale fatigue performance of conventional (370 HB), current (395 HB), and future (410 HB) premium rail steels to quantitatively establish performance and possible criteria to ensure minimum performance in track.

A positive result of current testing is that one of the rail manufacturers has made changes to its manufacturing processes to reduce the hardness of the rail base with the goal to increase fracture toughness and reduce notch sensitivity. Thus, regardless of the findings at FAST, this proactive measure will likely increase the factor of safety in regard to fracture resistance of the rail base, which may reduce the propensity for the type and frequency of rail base fractures observed at FAST.

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