

The work described in this document was performed by Transportation Technology Center, Inc.,
a wholly owned subsidiary of the Association of American Railroads.

Linking Fatigue, Microcleanliness Tensile, and Fracture Toughness Tests

F. C. Robles Hernández and Joseph LoPresti

Summary

Research conducted under the Association of American Railroads' Strategic Research Initiatives Program has led to the development of a methodology to enhance the understanding of the development of rolling contact fatigue (RCF).

The methodology is based on the results of conventional rail testing (e.g., tensile strength, fracture toughness, and cleanliness). It is well known in the rail industry that fracture toughness is almost independent of fatigue. However, the first portion of the fracture toughness test, which involves the development of a microcrack induced under dynamic loading, might lead us to a better understanding of RCF.

This work is preliminary, and further validation is needed. But, if this initial work is confirmed, this method could be used as a standard method to predict fatigue related damage. Early results from this work include:

- An analysis of crack growth rates during fracture toughness tests shows a correlation with the severity of RCF on the rails currently being tested at the Facility for Accelerated Service Testing.¹
 - Variations in steel cleanliness also affect RCF and may have reduced the correlation between crack growth rates and RCF for some rails.
 - This method of predicting RCF would have to be refined and standardized before general implementation.
 - An automated, scientific method for assessing RCF damage is needed.
- It is virtually impossible to produce steel free of defects (pores and inclusions). However, the number, size, shape, and type of inclusions can be modified using standard practices. Improving the cleanliness of steel (particularly reducing defect size) would improve fatigue life, and extend rail life.
 - When defects are above a "critical size (d_c)," they can be considered as microcracks that reduce fatigue life considerably.
- Steel cleanliness tests, as prescribed in ASTM standards E45 and E1245, are not comprehensive measures of cleanliness. A more detailed analysis of cleanliness demonstrates that inclusion characteristics, such as defect size, are important factors that affect the endurance limit and other performance aspects of the rail steel.
 - Other defect related parameters that should be examined in future research include:

Distribution	Nature (e.g., oxide, void, sulfide)
Morphology	Number



INTRODUCTION

Fatigue-related failures, such as RCF, base breaks, and detail fractures are serious impediments to rail life extension for North American railroads. There are currently no practical methods for assessing the severity of RCF, although the technology is being developed. Those that exist are too complex, labor intensive, costly, or time consuming to be widely used. Although there have been significant improvements in rail performance, the latest generation of premium rail appears to be more sensitive to RCF and notch damage than premium rail from 10 years ago.

The quantification and understanding of RCF on rail represents a difficult challenge. Research conducted under the Association of American Railroads Strategic Research Initiatives Program has led to the development of a methodology (still under investigation) to understand the correlation between crack growth and RCF. This methodology is based on the results of conventional fracture toughness (K_{IC}) tests. The tests were conducted on commercially available premium rail currently being tested at the Facility for Accelerated Service Testing, Pueblo, Colorado (FAST). Fracture toughness testing for rail is not required by AREMA, but as premium rail has become harder, fracture toughness has been affected. Preliminary research has indicated that detailed analysis of the results of fracture toughness tests can be valuable in furthering the understanding of rail fatigue related phenomena.

Fatigue Related Phenomena

When surface contact between components (e.g., wheels and rails) results in excessive normal or surface (usually shear or sliding fatigue) stresses, accelerated surface failure results. Microstructural defects, such as voids and inclusions, act as stress concentrators and promote crack formation and propagation. Stresses at the rail surface reach levels close to, or above the endurance and shakedown limits of rail. In addition, the notch sensitivity of rail is such that a small defect (stress concentrator) can facilitate crack initiation. This results in premature rail failure, potentially reducing rail life by a substantial amount. Previous work shows that crack initiation and sliding contact fatigue can be predicted in the laboratory using pure-sliding methods.² This research has examined a new method of assessing crack growth and understanding RCF phenomena by using a common mechanical test (i.e., fracture toughness, K_{IC}).

Fracture Toughness

Fracture toughness is the property that describes the ability of a material to sustain a crack of a certain length when subjected to a static uniaxial tension. Fracture toughness can be more of an issue in the winter, when rail is constantly subjected to tension. This is also the season when rail breaks occur. Fracture toughness testing is conducted in two stages. In Stage 1, a crack is induced orthogonally to the direction of the cyclic (fatigue) loading. In Stage 2, the sample is ruptured under uniaxial tension. The analysis presented here is based only on Stage 1 testing.

There are two potential arguments against the approach described above: (1) RCF is mainly driven by shear (mode II) or tear (mode III), not tension, and (2) fracture toughness is a property related to static loading conditions that have little, if anything, to do with fatigue. However, the approach of this work is to analyze the crack growth (Stage 1) values that are obtained prior to the actual K_{IC} test and to relate those values to the crack growth that occurs under dynamic cyclic loading. This crack growth rate is related to modes I, II, and III. For this analysis, fracture toughness results are ignored and the focus is purely on crack growth.

Microcleanliness

Currently, the section of the AREMA manual that describes the analysis of rail microcleanliness using the ASTM E45 standard only specifies average and maximum cleanliness ratings.³ Particle characteristics are not mentioned. For the work described here, the analysis was conducted by using the ASTM E1245 standard. It is possible to determine the number of particles and their characteristics, such as surface area, type of defect (void, oxide or sulfur), size distribution, and shape factor using the E1245 standard. With that information, the potential effects of inclusions on the fatigue performance of premium rail can be explored. One method of doing this is by determining the effect of inclusions on endurance limit by means of the Murikami equation.⁴

Analysis of Results

The major factors that determine the mechanical properties of steels are chemical composition, thermomechanical processing, and cleanliness. Microstructure is determined by these factors and can be manipulated by modifying them.

Poor cleanliness is associated with poor fatigue performance. Murikami developed a semi-empirical model that has been widely used to determine the reduction in endurance limit (and thus fatigue performance) caused by inclusions in steels.⁴ Previous reports indicate that the endurance limit on railroad wheels can be reduced by up to 20 percent by the presence of inclusions typical of those found in broken wheels.⁵ The Murikami equation (Eq. 1) is used to determine the endurance limit of steel subjected to cyclic loading, as a function of hardness and the size of microstructural defects.

$$\sigma_{el} = \frac{1.41(H_v + 120)}{\sqrt{(Area_{Max})^{1/6}}} \tag{1}$$

where: σ_{el} = fatigue endurance limit (MPa)

H_v is the Vickers hardness and $H_v = HB * 1.056$

$Area_{Max}$ = area of the largest inclusion/void

The critical particle size was assessed using a mathematical model that involves the endurance limit and the hardness of the rail. The equation follows:

$$d_c \sqrt{\frac{2}{\pi}} \times \left[\frac{1.56(H_v + 120)}{\sigma_{el}} \right]^6 \tag{2}$$

where d_c is the calculated critical diameter of a defect. A defect at least as large as d_c is considered to be a crack (it

performs similarly). Smaller defects also affect the endurance limit, but they will require longer incubation (crack initiation) time in order to develop a crack. It is known that 80 to 90 percent of the time needed to fatigue a component is comprised of crack nucleation; the rest is crack propagation.⁶ This is a major reason that cleaner steels are more resistant to fatigue related problems. The validation of this work will require a significant effort involving nonconventional testing (e.g., multiaxial fatigue and/or cold rolling). Once d_c is validated experimentally, it will be used in setting a new microcleanliness standard for premium rail. Table 1 is a summary of the microcleanliness analysis and some metallurgical parameters of rail currently under investigation at FAST. High strength rails 2 and 6 were manufactured by the same provider.

Table 1. Endurance Limit, Critical Defect Size and Largest Defect Detected during Microcleanliness Analysis

Rail ID	1	HS [†] , 2 & 6	3	4	5
Endurance limit, (ksi)	117.4	99.5	87.4	96.9	91.9
Yield strength, (ksi)	146	114	112	121	120
Head Hardness, (HB)	430	415	375	429	401
Fract Tough, ksi√in	40.6	37.9	35.9	43.2	34.6
Summary of Microcleanliness Results and Analysis					
Max. Area, (in ² E ⁻⁴)	2.1	11.5	8.9	4.1	8.1
Critical size, (in E ⁻³) "dc"	1.2	1.1	1.8	1.3	1.7
Particles above "dc"	31	39	17	66	62
RCF rank at 270 MGT [‡]	2	5	3	1	4

[†] HS stands for high strength rail.
[‡] 1 indicates best and 5 worst.

Crack Growth Rates from Fracture Toughness Testing

The fracture toughness samples were extracted from the railhead, as Figure 1 shows. The location and orientation of the fracture toughness samples were determined based on the orientation of detail fracture growth in the railhead. In the first stage of the fracture toughness test, a microcrack is induced orthogonally to the loading direction. The objective of this portion of the test is to induce and grow a microcrack that serves as a stress concentrator during the second stage of testing. A load from 1,450 pounds to 2,400 pounds at 60 Hz is applied to induce the crack.

Figure 2 shows crack growth rates for different rail as a function of load. For loads below 2,000 pounds, Rail 6 has the highest crack growth rate, followed by rails 4, 3, and 2. Note that while most of the rails show a relatively steady increase in crack growth rate as loads are increased, Rail 3 shows a dramatic increase in growth rate for loads over 2,000 pounds. The rail with the highest crack growth rates also tended to develop more RCF at FAST. On the other hand, rails 1 and 5 exhibit the lowest crack growth rates, and Rail 1 shows the second lowest amount of RCF at FAST after 270 MGT (see Table 1). However, there are rails that did not show a good correlation between crack growth rate and development of RCF at FAST. Rails 4 and 5 had more defects above the critical size. The largest defects, which probably contributed to the development of RCF, are identified in rails 2, 6, 3 and 5. Although Rail 4 on the low rail had among the least RCF, it was the first to develop significant RCF on the high rail. The effects

of microcleanliness will be discussed in detail in the following sections.

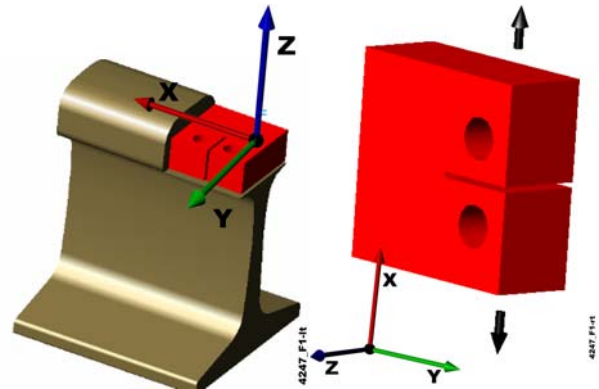


Figure 1. Sketch of a Section of a Rail showing the Location and Orientation where the Fracture Toughness Sample is Extracted and the Direction of the Dynamic Loading

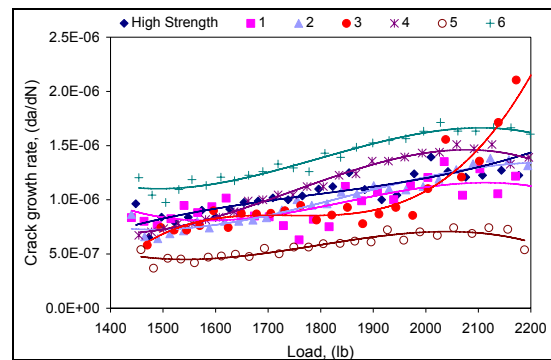


Figure 2. Crack Growth for Different Rails using a Compact Test Fracture Toughness Sample

The two primary mechanical/metallurgical properties that affect RCF development are hardness and cleanliness. Cleanliness is related to the propensity of the material to develop cracks. Defects in the microstructure act as stress concentrators, and the larger they are, the more detrimental they are. Based on the Murikami model, a defect at least as large as d_c is considered a microcrack that hypothetically eliminates the time required for crack initiation.⁴ This in turn reduces the fatigue life of components 80 to 90 percent. Table 1 shows that there are relatively few defects above d_c in the rails tested. But these defects were found in an area about the size of a quarter. Each of the larger defects can act as small cracks; the smaller defects are potential stress concentrators or weak points that facilitate crack initiation. It is clear that improving cleanliness is potentially one of the most effective methods for rail life extension. The values of d_c shown in Table 1 were determined for each rail based on its respective mechanical properties — d_c is different for each rail. But in order to simplify Figure 3, TTCI researchers decided to represent d_c for all rails with a single line as an approximation of the individual values.

Figure 3 shows the theoretical effects of hardness and defect size on the endurance limit of the rails, where values calculated using Equation 1 are plotted. Equation 1 predicts that the endurance limit increases with hardness, but decreases with poor cleanliness. This effect may be the reason for the previously

mentioned discrepancies in the prediction of RCF, for rails 4 and 5. More work is needed to confirm the hypothesis. Figure 3 also illustrates that Rail 1, the rail with the highest cleanliness, has the highest endurance limit. This is in agreement with the results shown in Figure 2 and findings at FAST (Table 1). Based on this preliminary work, it seems that the analysis of crack growth and microcleanliness constitute a viable approach to predicting RCF. However, further validation is required to demonstrate the accuracy of the findings presented here.

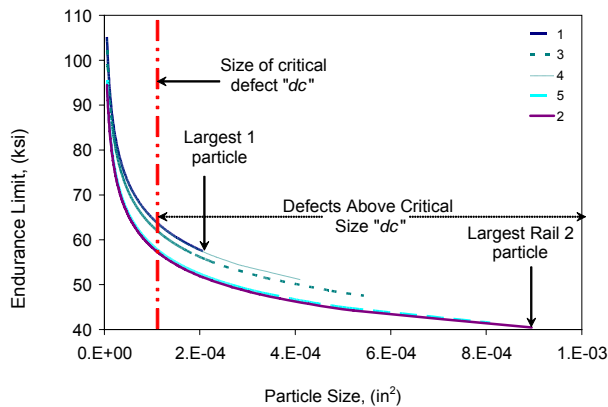


Figure 3. Determination of the Reduction in Endurance Limit by the Presence of Inclusions

An alternative method of evaluating steel’s propensity to develop RCF is the determination of the shear strength (K_e). Shear strength is the resistance of the material to yield in shear (Mode II), which is one of the modes that drive RCF. Figure 4 shows the results of calculations of shear strength as a function of hardness for the rails currently under test at FAST. The shear strength was determined using Equation 3:

$$K_e = \frac{\sigma_y}{\sqrt{3}} \quad (3)$$

where K_e is the shear strength and σ_y is the yield strength

Rails 1 and 4 have higher tensile strengths, which result in higher endurance limits, and more resistance to fatigue-related failures. In contrast, due to their lower shear strengths, rails 3, 5, 2, and 6 would be expected to have a greater propensity to fail under fatigue. One of the major findings in the analysis presented here is that whether based on crack growth rates, cleanliness, or shear strength, rails 6 and 3 seem to be the rails with the highest propensity to fatigue failure. Rails 1 and 4, which have the highest shear-yield strength and microcleanliness, are least likely to fatigue. Poor cleanliness may explain the increased propensity of some rails to develop fatigue failures, even though their crack growth rates or shear strength may be acceptable.

Additional work will be needed to validate and develop the methods described here into commonly accepted practices for predicting RCF. If successfully validated, they will be proposed to AREMA and the railroads. The validation will include the

quantification of RCF on rails at FAST and revenue service, as well as a more detailed analysis of the effects of cleanliness, crack growth rates, and shear strength. Detailed analyses of the effects of defect types; e.g., voids, oxides, and sulfides, and their distribution, shape, and composition, will be required to fully understand the effects of cleanliness.

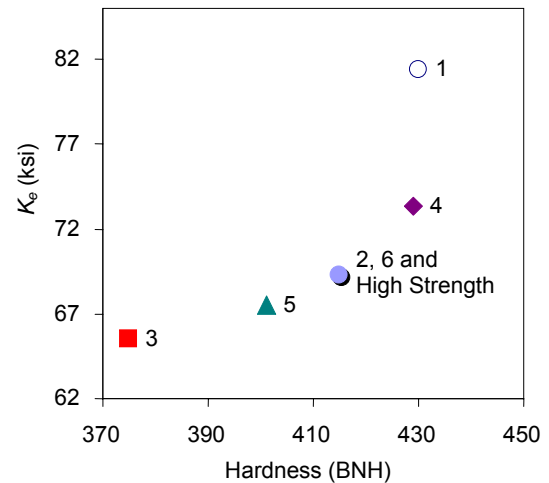


Figure 4. Determination of the Shear Strength of the Different Rails in Test at FAST

CONCLUSIONS

The precracking conducted as the first stage in the fracture toughness test can be used to determine crack growth rate. Crack growth rate seems to be a relatively good predictor of fatigue performance. Another parameter having a direct effect on fatigue is steel cleanliness. Microscopic defects can present a serious concern, as they are potential sites for crack propagation on or near the surface of rail.

REFERENCES

1. Robles Hernández, F.C. and Joseph LoPresti. June 2007. “Interim Evaluation of Premium Rail Steels at FAST,” *Technology Digest* TD-07-018, AAR, TTCI, Pueblo, CO.
2. F.C. Robles Hernández, et al. 2007, “Mechanical properties and wear performance of premium rail steels,” *Wear* 263 766–772.
3. American Railway Engineering and Maintenance-of-Way-Association Manual, Chapter 4, Section 2.1.9.6.3. 2006.
4. Murakami, T. and M. Endo. April 1994. “Effects of Defects, Inclusions and Inhomogeneities on Fatigue Strength,” *Fatigue* Vol. 16 pp. 163-182.
5. Stone, D. H., F.C. Robles Hernández, and G. Dahlman. August 2007. “Effect of Microvoids, Oxide Inclusions, and Sulphide Inclusions on the Fatigue Strength of Wheel Steels,” *Technology Digest* TD-07-022, AAR, TTCI, Pueblo, CO.
6. Lanciotti, A. and C. Polese. 2008. “Fatigue properties of monolithic and metal-laminated aluminum open-hole specimens,” *Fatigue & Fracture of Engineering Materials & Structures*, 31, 10 911-917.

Visit our website at <http://www.ttc1.aar.com>

Disclaimer: Preliminary results in this document are disseminated by the AAR/TTCI for information purposes only and are given to, and are accepted by, the recipient at the recipient’s sole risk. The AAR/TTCI makes no representations or warranties, either expressed or implied, with respect to this document or its contents. The AAR/TTCI assumes no liability to anyone for special, collateral, exemplary, indirect, incidental, consequential or any other kind of damage resulting from the use or application of this document or its content. Any attempt to apply the information contained in this document is done at the recipient’s own risk.