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Qualitative Prediction of Rail Wear and Sliding Contact Fatigue Performance using Laboratory Methods

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SUMMARY

According to the 2006 Class I Railroad Annual Report to the Surface Transportation Board, railroads in the United States spend approximately $2.5 billion a year on rail replacement and repairs, making rail the most valuable asset for the railroad industry in North America. Transportation Technology Center, Inc. (TTCI), a wholly owned subsidiary of the Association of American Railroads, Pueblo, Colorado, continues to conduct full-scale rail performance tests to determine rail performance characteristics and develop new ways to increase rail life.

Recent research by TTCI and the University of Illinois–Urbana Champaign focused on methods to streamline the development of prototype rail steels.[1] The results of laboratory tribological tests indicated that typical pure sliding ball-on-disk tests have the ability to predict better performing rails. Additionally, the ball-on-disk test method was demonstrated to be effective to predict sliding contact fatigue and tribological mechanisms. This is, in turn, translated to a qualitative determination of rail performance. In contrast, the full-scale test at the Facility for Accelerated Service Testing (FAST) at the Transportation Technology Center (TTC) provides quantitative data of rail's performance. The ball-on-disk test method is a cost effective method that is conducted in a relatively short time (in comparison to the full-scale test) and the method seems to have good potential to screen rails for full-scale testing.

The primary findings of this study indicate that by using the ball-on-disk test method, it is possible to qualitatively compare wear and sliding contact fatigue performance of rails. Such a method is accurate and will be proposed as a screening test method for premium rails. Unfortunately, the results at this point are only qualitative and further research is required to standardize this method.

The ball-on-disk test method has been demonstrated to be the most suitable rail screening method to predict rail performance.

- By using the ball-on-disk test, it is possible to distinguish the rail with the best wear performance for a group of rails.
- The ball-on-disk method is also a good predictor of sliding contact fatigue.
- The results from the ball-on-disk test method are in good agreement with the results from the rail wear test at FAST.
- By using the ball-on-disk test method, it is possible to identify the work hardening characteristics of premium rails that are the best predictors of rail performance.

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INTRODUCTION

The goals in the development of new rail materials are improving wear performance, rolling contact fatigue (RCF), and mechanical properties. TTCI, in conjunction with the University of Illinois–Urbana Champaign, conducted tests to correlate laboratory tribology data and full-scale rail wear data collected from FAST. It is known that other tribological methods (pin-on-disk, twin disk), using more alike materials (steel) than ruby, have effectively demonstrated wear performance and better represent the rail wheel interaction. Though, the ball-on-disk test was validated against these methods and demonstrated comparable or better results showing its potential and suitability for rail testing.

BACKGROUND

Premium rail is made of high carbon steels with pearlitic microstructures that are suitable for severe environments and are mainly used by Class I railroads under heavy haul (freight) service in curves of more than 2 degrees. The minimum head hardness for premium rail is 370 Hardness Brinell (HB). Increased hardness is relatively easy to achieve by adding alloying elements to steel, mainly carbon, and strategically designing heat treatments. There is, however, a theoretical limit to the hardness that can be reached with pearlitic steels. Bainite is an alternate microstructure that can be harder than pearlite, but studies thus far have shown that pearlite is more suitable for the highly demanding and aggressive nature of the railroad load environment, such as heavy haul service in North America.[2] Therefore, hardness is no longer a good predictor of wear.

Six premium rail samples were used for this study, one from the first generation (2001) and five from the second generation (2005). The first generation rail test concluded in 2005 after accumulating 478 million gross tons (MGT). The second generation, currently in-test at FAST, accumulated 400 MGT (May 2008). The 2001 rail was used as a reference to compare rail wear performance between both generations of rails tested at FAST.

The 2001 rail hardness was from 382 to 405 HB in the as-rolled condition. After work hardening, they showed an average increase in hardness of approximately 32 HB. The maximum value of hardness, which correlates to the best workhardening ability, was 461 HB. The average head hardness for the 2005 rails in the as-rolled conditions was 410 ± 23 HB. Since work hardening is independent of the initial hardness of the rail, this study was completed to determine if the unique property of workhardening could be determined by a laboratory ball-on-disk test method.

The current research focused on comparing results of full-scale rail experiments and a laboratory tribology experiment to predict rail performance, workhardening, and sliding contact fatigue (SCF). SCF is an effect similar to RCF that occurs under pure sliding in the absence of rolling. Rails tested in service are subjected to rolling and sliding; however, the determination of SCF is of great interest since this effect can be related to RCF.

FULL-SCALE TESTING

Full-scale testing was conducted in Section 7 of the High Tonnage Loop (HTL) at FAST. Section 7 is a 5-degree curve that is over 1,000 feet long. It has a 4-inch superelevation with a 1.6-inch cant deficiency and an operating speed of 40 mph. This curve is non-lubricated to accelerate the rail wear and subject rails to a more aggressive environment and operating conditions.

Profile measurements at FAST were made with the Greenwood Engineering MiniProf to assess rail wear at 0 MGT (control measurement) followed by measurements every 15 MGT for the first 105 MGT, after that every 25 MGT. The full-scale testing is ongoing at FAST. Data will be collected on the rails until the end of the test, scheduled for late-2008, for an accumulated tonnage between 450 and 500 MGT.

BALL-ON-DISK TESTING

A conventional ball-on-disk tribometer was used to collect data on several rail samples over a range of cycles (50, 100, 300, 600, and 1,000). A constant normal force of 2.2 pounds, which corresponds to an initial Hertzian contact pressure of 580.2 ksi, was applied for all tests. The contact pressure is equivalent to the contact pressured observed on the high rail flanges for the full-scale tests. The tests were performed at 100 revolutions per minute, which correspond to a linear speed of approximately 2.36 inches per second on the sample geometry.

A small synthetic ruby ball used for testing has a 1/16-inch diameter and a hardness of 1,570 to 1,800 Hardness Vickers. The ruby ball is up to four times harder than the test rails, therefore no significant wear was incurred in the ruby ball; nonetheless, a new ruby ball was used for each test as a precaution against skewed results due to wear.

Cylindrical disk samples were removed from each premium rail sample for testing from an area approximately 0.32 inch below the surface of the railhead. The selected location eliminated the decarburized layer to assure all samples were from comparable locations. Each test sample was machined to a root-mean-square surface roughness of $3.14 * 10^{-5}$ inches. The ruby balls and rail samples were ultrasonically cleaned using acetone, rinsed with 2-propanol, and dried with warm air before testing to ensure they were not contaminated by outside sources.

The wear tracks were measured at four locations using a contact profilometer at the end of each selected cycle. Each sample was identified alphabetically (rail A through E) and grouped by rail type (old and new). Old refers to rail selected from a previous test (ended in 2005).[3] Both old and new rail types were studied for a direct comparison of wear performance between 2005 and 2001 rail generations.

INVESTIGATIVE TECHNIQUE

Several approaches are available to compare results from the ball-on-disk to those at FAST. In previous research, the wear analysis of the ball-on-disk measurement was conducted using the depth of the wear track or minimum, indicated as MIN_B in Figure 1. Figure 1 shows an illustration of profilometer data taken from the ball-on-disk testing. The approach provided valid information to distinguish between rail generations; however, it was not possible to distinguish the performance of independent rails and directly compare the results to those at FAST because when computing only MIN_B as equivalent to either gage loss (W2) or height loss (W3), results are usually reported as area loss. A new approach to interpret the ball-on-disk test method data was used in the current research that enabled the total area loss of the ball-on-disk test sample to be calculated. This technique is very similar to the profile overlay method used for full-scale testing, which better enables the wear performance prediction from the ball-on-disk laboratory testing.

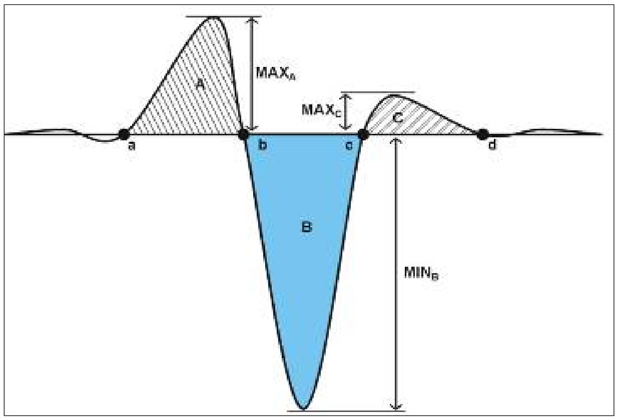

Figure 1. Profile Taken from Ball-on-Disk Test Samples

The ball-on-disk test data analysis used for this study considers the total area loss of the ball-on-disk test samples at various cycle counts. The solid shaded area in Figure 1 represents the wear track and the hatch marked areas represent the area of material flow on either side of the wear track (note: similar metal flow was observed in the rails tested at FAST, particularly on the low rail). The total area loss can be defined as the sum of the wear track area loss (B) and the gained area of the flow material (A and C) on either side of the wear track. The flow area (A and C) is directly related to the work hardening of the steel and the loss area (B) is related to wear of the sample. The sum of the areas A, B, and C is representative of the wear performance.

The profile overlay method is conducted mainly using MiniProf software that allows comparing differences in overlaid profiles (e.g., new and worn rails). Figure 2 shows the MiniProf measurement analysis locations. The rail surface was prepared by removing impurities that could alter or affect the profile measurements. Four measurement locations were selected for each 40-foot rail section. Detailed test and layout information at FAST is given in References 1 and 3. The profile measurement locations were fixed to ensure that the proper area loss for each sample was determined. MiniProf analysis software was used to superimpose rail profiles at various tonnages and measure the area loss (wear).

MiniProf can determine wear based on the diagonals W1, W2, or W3, as the profile overlay method in Figure 2 shows. Diagonal W1 is commonly used to determine wear on the low rail where the forces are applied directly on the head resulting in the highest wear on the rail head. For the high rail, it is more common to analyze diagonal W3 and occasionally diagonal W2, because the wheel-rail loading conditions generate more wear on the gage face than on the head. Each diagonal can be analyzed individually, but it is best to analyze rail wear by total area loss because material loss is a clear indication of rail wear performance as per indicated by TTCI engineer's experience.

This data analysis approach is similar to the profile overlay method used in previous work, therefore it provides a technique to directly correlate results from full-scale and ball-on-disk testing.

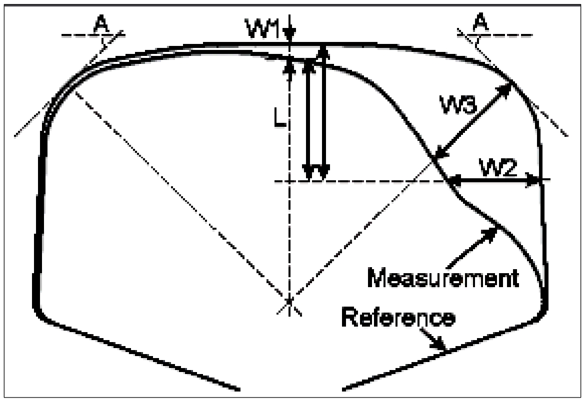

Figure 2. MiniProf Measurement Analysis Locations

DATA ANALYSIS

Work hardening has been identified as one of the most important properties for premium rail. Analysis of the flow material of the sample can be used to determine the work hardening properties of a sample. The total area of flow material was calculated for each sample at every cycle. Figure 3 shows the results for each sample. The x-axis is the total area under the curve for the flow on each side of the wear track, while the y-axis is the number of cycles.

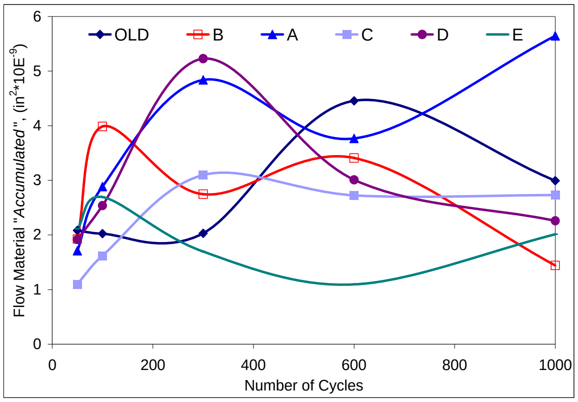

Figure 3. Ball-on-Disk Flow Material Analysis

Figure 3 shows that rails B and E have an initial rapid build-up of flow material, but end with a relatively low amount of flow material at the higher cycles. The old, A, and D rails show a slower initial response, but have higher amounts of flow at higher cycles. This indicates that rails with a fast initial hardening response usually show less work hardening ability over an extended number of cycles, while rails with a slower response have a better long-term work hardening response. These results were typical for the ball-on-disk testing and can be correlated to the data collected during the full-scale testing at FAST (Figure 4). Figure 4 depicts the normalized wear and workhardening behavior of the samples tested at FAST from 15 to 252 MGT. Rail B was used as the control rail (ratio = 1), because it was distributed seven times throughout Section 7. Normalizing the data based on the control rail eliminated the effects of location on the curve to show the direct effects of work hardening for each sample.

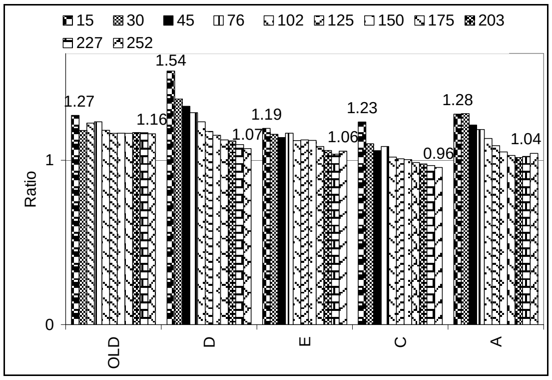

Figure 4. FAST Rail Wear Data for Test Rails at Multiple MGT

Figure 4 shows that all test rails have higher wear rates at the beginning than the control rail (rail B); however, wear rate decreased as the accumulated tonnage increased. Rail D showed the highest initial wear rate (54 percent more than rail B) at the beginning of the test; however, after 300 MGT the wear rate dropped to 7 percent more than rail B. Rail C had a 23 percent higher wear rate than the control rail, and, after 300 MGT, it dropped to 4 percent lower than rail B. This agrees with Figure 3. Also, the ball-on-disk results show that at the beginning of the test rail B had better wear performance, but at higher cycles rail C had better wear performance. Figure 4 also shows that the old rail had limited to no work hardening ability similar to rail E. This conclusion was verified during the ball-on-disk testing, which showed that the selected rail from the 2001 test (old) rail was performing worse than the 2005 rails. This suggests that the 2005 rails have better wear performance than the rails manufactured in 2001.

Another difference observed during the ball-on-disk testing was the type of wear debris generated. The characterization of the debris helped to understand a mechanism for SCF. At the completion of the ball-on-disk tests, samples could be distinguished by the debris adjacent to the wear track. Figure 5 shows the ball-on-disk test samples with and without debris.

Figure 5. Micrographs of Wear Tracks with and without Debris

The analysis of the debris and the surface track using the scanning electron microscope (SEM) allows use of the ball-on-disk tests to study SCF. Analysis of SEM micrographs and the respective energy dispersive X-ray for the debris showed that the presence of inclusions, particularly alumina, usually fail under brittle conditions leaving behind microcracks with potential to propagate when subjected to dynamic loading conditions that result in RCF. By extrapolating the ball-on-disk test results to the full-scale experiments at FAST, it was found that the rails produced significant amounts of debris corresponding to those showing RCF at FAST.

Figure 6 compares SEM micrograph samples of different wear mechanisms on rails used in the ball-on-disk test and at FAST. Figures 6c and 6d show the railhead at FAST and correspond to rails currently under test. Figures 6a (rail A) shows a significantly smooth surface dominated by plastic deformation. Figure 6b (rail C) shows a surface with plastic deformation, but with a significant amount of cracking, which is represented by the surfaces of the full-scale tests at FAST in Figure 6c (rail A) and 6d (rail C). Figures 6a to 6d show that RCF could be predicted by fully analyzing ball-on-disk test samples.

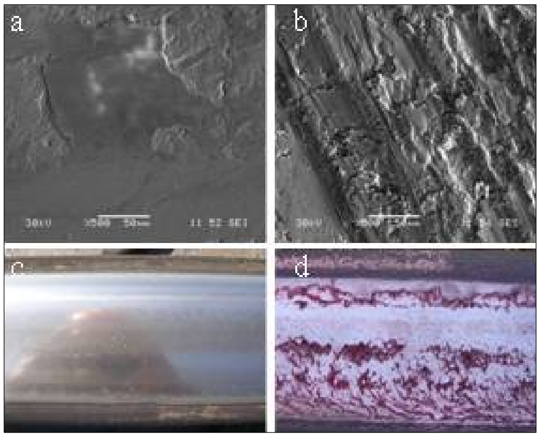

Figure 6. SCF and RCF Comparison of Two Premium Rails

CONCLUSIONS

The laboratory tribology tests completed during this study indicate that typical pure sliding ball-on-disk tests are capable of determining qualitatively wear performance and work hardening ability of rails. This allows the use of the ball-on-disk test as a prescreening method for rail selection ensuring a more accurate rail assortment for future FAST or revenue service tests. The cost effective ball-on-disk test method can be conducted quickly, and results can correlate with the full-scale results from FAST and potentially from revenue service. There is a correlation between the high density of cracks observed with the SEM on the tribo-tested surface with the RCF on rails at FAST. This means the rails showing more cracks under the SEM are the ones that developed faster RCF at FAST. However, other test methods (e.g., twin disk) can better simulate the wheel rail interactions and can be more adequate to predict RCF.

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