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Microstructure and Wear Performance of Premium Rail Steels

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Summary

Implementation of new rail materials can only be made possible if the economic life of these materials is superior to that of existing ones. The railroad industry in the United States has spent approximately $10 billion in the last 5 years on rail replacement. To support industry decisions, Transportation Technology Center, Inc. (TTCI) continuously conducts rail performance tests, which represent a multimillion dollar investment and take many years to complete.

The University of Illinois at Urbana-Champaign (UIUC) developed a laboratory test under joint funding by the Association of American Railroads and the Federal Railroad Administration that aims to predict rail performance, which in turn is expected to reduce the time and cost of rail wear testing. The UIUC laboratory test consist of a simple ball-on-disk, pure sliding wear experiment. This paper describes in detail the ball-on-disk wear test conducted on new and used rail samples; key results are further discussed. The ball-on-disk wear test was performed at different numbers of cycles (50, 100, 300, 600, and 1,000) followed by profilometric measurements to quantify rail wear.

The results of the ball-on-disk test indicate that rail wear performance can be predicted for new rail. Therefore, this test could be used as a screening method reducing the required number of expensive and time consuming full-scale wheel/rail track experiments. However, the ball-on-disk wear experiment showed no clear trends when applied to test worn rails (extracted by TTCI from the Facility for Accelerated Service Testing, Pueblo, Colorado, after 478 million gross tons of traffic). This can be attributed to the work-hardened layer formed on the head of the rail during testing and other complex phenomena. Micro-Vickers hardness measurements are in accordance with the wear data for the new rail samples.

- The ball-on-disk wear experiments showed that the improved wear performance of pearlitic rail is attributed to the significant work hardening of the pearlitic microstructure.
- The ball-on-disk technique can be used to determine wear performance for rail steels with different microstructures.
- Due to the simplicity of the ball-on-disk technique, this technique may be proposed as a test method to screen candidate rail steels allowing testing on rails with the highest wear performance, minimizing the very expensive and time consuming full-scale, wheel/rail track experiments.

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INTRODUCTION AND BACKGROUND

A major goal in the development of new rail materials is improving their wear performance. Historically, the main method to accomplish this goal was to manufacture rail steels with higher hardness, which was achieved by adding alloying elements, particularly carbon. However, there is, in theory, a limit to the hardness that can be reached with pearlitic steels. It is believed that this hardness limit had almost been reached in modern rails. Therefore, there is a need for examining other steel microstructures, such as bainite, that are harder than pearlite, which could result in a higher wear life, thus better performance.

The present work was conducted by TTCI in collaboration of the UIUC with funding from the Association of American Railroads (AAR) and the Federal Railroad Administration. The main goal of this work was to develop a laboratory methodology capable of the determination of the wear life and rail performance in order to optimize future full scale rail performance tests

SUMMARY OF THE RESULTS

Over the years, it has been observed that wear and hardness have a relationship. Note, however, that this relationship is not necessarily in accordance with Archard's wear law, given by $V = KWL / H$, where V is wear volume, K wear coefficient, W normal load, L sliding distance or length, and H is hardness.[1] However, it is believed that the limit for pearlitic rail has almost been reached with current casting techniques; therefore, it may be difficult to push pearlitic rail steel wear performance much beyond its current stage. In an attempt to develop rail steels with higher wear resistance, alternative microstructures, such as bainite (that posses higher hardness), were investigated as substitutes for pearlitic steels.[1,2,3,4]

The AAR developed bainitic steel, J6, that was used for this investigation and was tested in Section 7 (wear testing) of the High Tonnage Loop at Facility for Accelerated Service Testing (FAST). Table 1 shows the chemical compositions for J6 bainitic and premium pearlitic steels.[1] The initial bulk hardness of bainitic steel averages 415 Brinell Hardness Number (BHN). In fully pearlitic premium rail, the carbon content is typically 0.79 percent, which corresponds with the previous generation of rail. Currently tested rails at FAST were manufactured with ~ 1 percent carbon; resulting in an increase from 395 BHN to 430 BHN.[6] The hardness of the new premium rail is similar to J6 bainitic steel. Note that the carbon content in J6 bainitic steel is significantly lower (0.26 percent) compared to pearlitic steel.

Table 1. Chemical Compositions for J6 Bainitic and Conventional Pearlitic Rail Steel

wt%	C	Mn	Si	Ni	Cr
J6 Bainitic	0.26	2.00	1.81	0.00	1.93
Pearlitic	0.79	0.91	0.66	-	0.47

Contrary to expectations, the J6 bainitic steel performed significantly worse, as far as wear resistance, when compared to premium pearlitic rail steels. Figure 1 shows the wear performance for the pearlitic and bainitic rails investigated at TTCI.[7] Notice the significant difference between the J6 bainitic steel in comparison to the rest of the pearlitic rails produced by different manufacturers. However, the J6 bainitic rail has a significantly better rolling contact fatigue resistance, which makes it a more suitable material for crossings.[8]

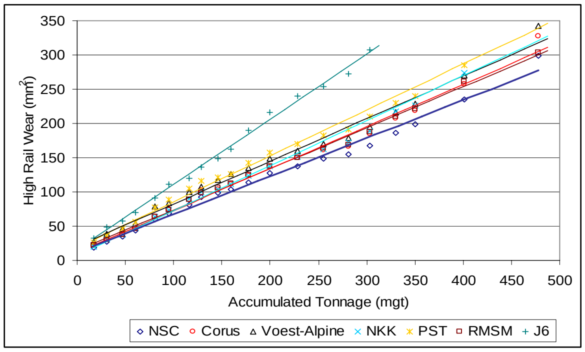
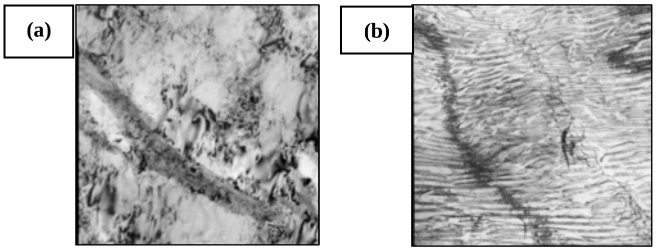


Figure 1. Field Wear Measurements [1,6,7]

The lower wear performance of the J6 bainitic steel is attributed to the absence of work hardening of this kind of microstructure. Figures 2a and 2b show the Transmission Electron Microscope images that illustrate that pearlite is more susceptible to deformation, thus work hardening, when compared to bainite. Pearlite is a phase composed of two constituents [ferrite (Fe_{α}) and cementite (Fe_3C)] that are alternatively arranged forming the long-range, pearlitic microstructure. Ferrite is a relatively ductile phase that can be easily laminated; such lamination results in an accumulation of cementite lamellas (cementite can be up to 5 times harder than bulk pearlite).[9] The accumulation of cementite lamellas (work hardened layers) form clusters or colonies at the top of the rail with a reduced amount of ferrite. In contrast, for bainitic steels, this mechanism is very limited.



Figures 2a and 2b. TEM Micrographs Showing the Effect of Deformation on: (2a) Bainitic (70,000x magnification) and (2b) Pearlitic Microstructures (14,000x magnification)

Ball-on-Disk Wear Experiments

A conventional tribometer was used to perform ball-on-disk wear experiments using pearlitic and J6 bainitic samples. Even though ball-on-disk wear experiments cannot fully account for real wheel/rail contact, which involves both rolling and sliding, this technique is useful in examining work hardening behavior of rail steels and can be used to screen materials after casting and rolling, resulting in considerable expense and time reduction when compared to a field tests.[8]

The equipment used provides the capability of recording detailed friction and wear data. The tribometer consists of a rotating (0 to 1,000 rpm) or oscillating (maximum arc 350°) spindle on which the disk specimen is mounted and a pin holder that applies the contact load (0.45 to 45 newton (N)) and measures the normal and friction forces.[9] Figure 3 shows a schematic of the tester interface, where for the specific rail tests, material A (pin) is a 1/16-inch (1.59 mm) diameter ruby sapphire sphere. The hardness of the sphere is at least 3.5 times higher (1,570 to 1,800 hardness Vickers number) than the bulk hardness of the rail (material B, disks). The sample disks were sectioned directly from new and used rails; used rail was extracted from FAST after 478 MGT. The main reason for choosing a very hard pin spherical surface is to act as a control surface without exhibiting significant wear itself; thus, to be able to clearly screen the rail materials without the concern of pin wear as well.

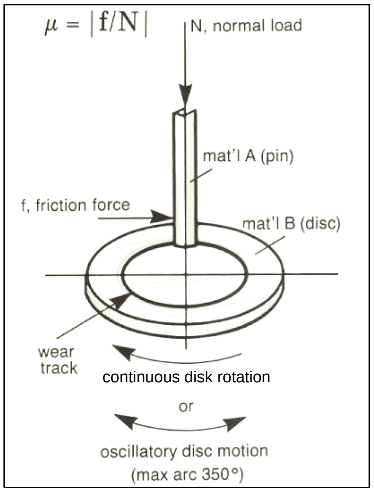


Figure 3. Ball-on-Disk Wear Testing Configuration

The initial Hertzian contact pressure was set to 4.0 giga-pascal (GPa), which is equivalent to the actual wheel/rail contact pressure (at the head of the rail). The new rail samples of both J6 bainitic and pearlitic microstructures were sectioned in disk shapes, 12 mm diameter by 5 mm thick. Note that for the new rails, the disk samples were taken approximately 5 mm away from the rail surface to avoid the softer decarburized layer, whereas the high rail samples (used rails) were cut directly from the surface. Also, the top surface to be tested is perpendicular to the wheel/rail contact direction. The disks were sectioned perpendicular to the contact direction, so that the ball is loaded in the same direction as wheel/rail contact.

The tests were performed at 100 rpm (~0.053 m/s) with 10 N constant normal load. Figure 4a shows the scratch wear testing configuration, and Figure 4b shows a typical disk sample after a test, illustrating clear evidence of wear.

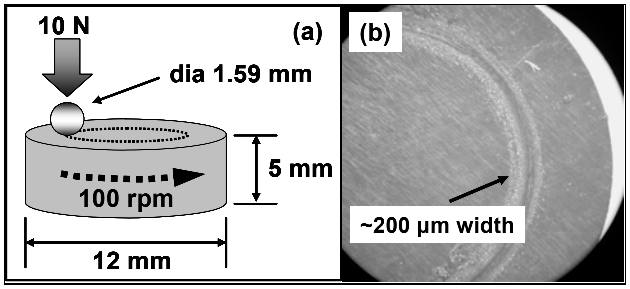
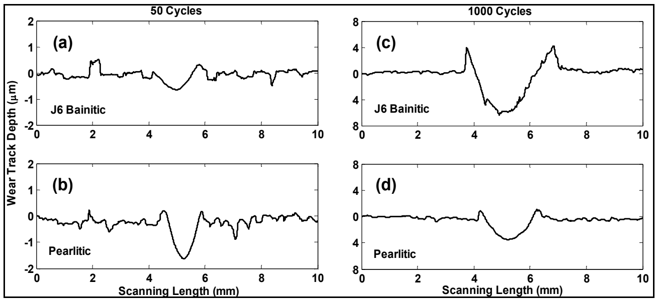


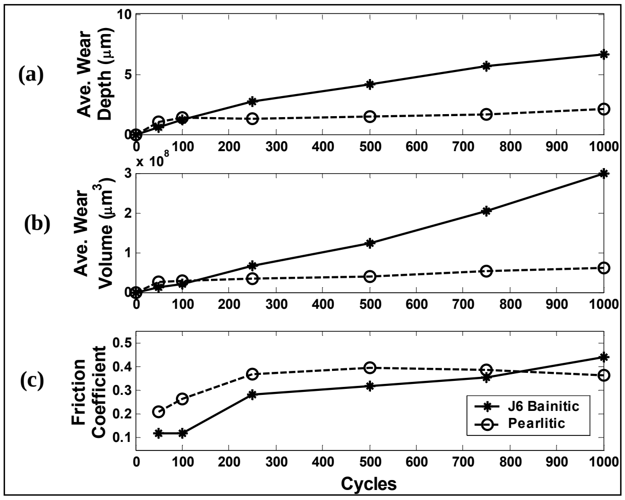
Figure 4a. Close up Schematic of Ball-on-Disk Testing Configuration. Figure 4b. Typical Disk after Ball-on-Disk Wear Testing

Disk wear measurements were performed after 50, 100, 250, 500, 750, and 1,000 cycles using a precise contact profilometer, as typical wear depths were only few microns. Note that the tribometer has an in-line wear measurement system (linear variable displacement transducer); however, as the wear depths in these experiments were only a couple of microns, more accurate results could be obtained off-line with a contact profilometer. Four different locations (line scans) on each disk were measured and the average wear values in terms of depths were reported. Representative examples of wear track scans are depicted in Figures 5a, 5b, 5c, and 5d for J6 bainitic and pearlitic steels after 50 and 1,000 cycles. J6 bainitic rail shows less wear after the initial 50 cycles, but significantly more wear at higher cycles, compared to pearlitic rail.



Figures 5a, 5b, 5c, and 5d. Representative Wear Track Scans: (5a) J6 Bainitic at 50 Cycles, (5b) Pearlitic at 50 Cycles, (5c) J6 Bainitic at 1,000 Cycles, and (5d) Pearlitic at 1,000 Cycles

The average wear depths and wear volumes for all the tests are summarized in Figures 6a and 6b, respectively. For both wear depth and wear volume, pearlitic rail clearly shows better wear performance at higher cycles, while J6 bainitic exhibits less wear during the first 100 cycles only. These wear test results are in good agreement with the micro hardness measurements of the same samples reported in Reference 9. It is also observed from Figures 6a and 6b that pearlitic rail reaches steady-state conditions and measurable wear does not occur at higher cycles, which is not the case for J6 bainitic rails. Figure 6c shows the ball-on-disk friction coefficient values that are comparable to the values obtained at FAST.

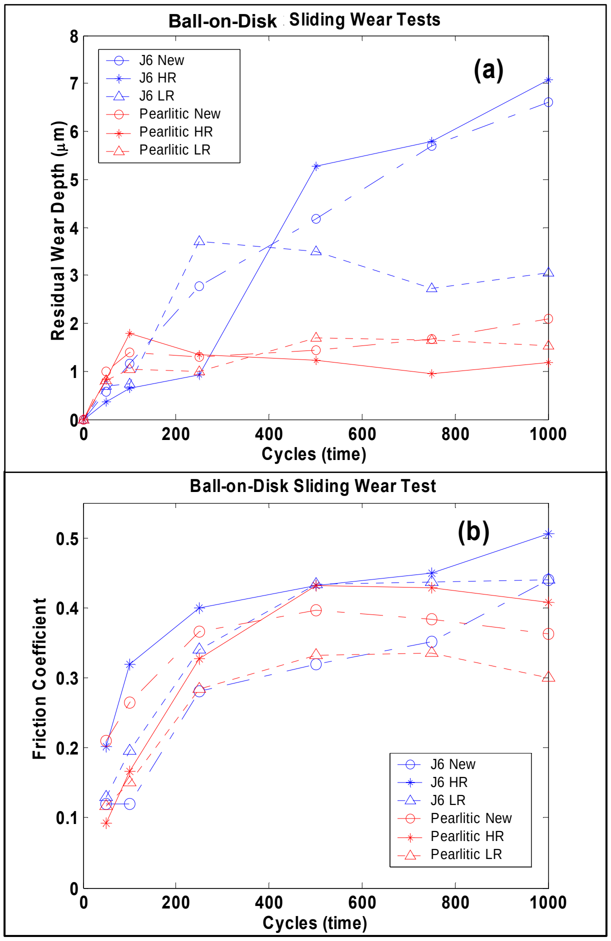


Figures 6a and 6b. Ball-on-Disk Wear Experiments: (6a) Wear Depth, (6b) Wear Volume, and (6c) Friction Coefficient Value

Micro-Vickers hardness measurements were performed both inside and outside of the wear track using light loads (25, 50, and 100 grams force were used for 15 seconds of indenting time). The results showed that the worn part of the disk is indeed harder than the unaffected new part, in agreement with Reference 9.

Thus, it is confirmed that the pearlitic rail steel was work hardened during the sliding wear tests, which resulted in better wear performance.

Figures 7a and 7b show the residual wear depth and friction coefficient for the bainitic and pearlitic steels, as obtained from the profilometer/ball-on-disk test/measurements. Observations show that bainitic steel has a continuously increasing wear depth for the entire test. Pearlitic rails have an increment of wear depth up to ~250 cycles, which tapers off for the rest of the test. This is in full agreement with the results from FAST. The friction coefficients of J6 bainitic increased gradually from 0.27 to 0.4 after an initial run-in period of 250 cycles, whereas for pearlitic steel, the friction coefficient remained constant between 0.36 and 0.37.



Figures 7a and b. Scratch Ball-on-Disk Wear Experiment Results using Ruby Sapphire Balls: (7a) Average Wear Depth and (7b) Average Friction Coefficient

CONCLUSION

In order to characterize wear behavior of rail steels and to propose a simple technique to screen new rail materials, ball-on-disk wear experiments were performed at a similar contact pressure than actual contact pressures found in wheel/rail contact. Moreover, rail samples were tested against a control hard spherical surface that wears the rail steels but not itself. Clearly, the simple scratch sliding wear experiments were able to show that the improved wear performance of pearlitic rail is attributed to significant work hardening. Despite the fact that pure sliding experiments are not able to fully explain actual wheel/rail contact since the wheel/rail interface generally involves both rolling and sliding, the ball-on-disk technique correctly predicts the wear performance that has been measured in both field tests and rolling and sliding experiments performed by Sheffield.[5] Due to the simplicity of the scratch experiments, this technique may be used as a test method for screening rail samples that will in turn allow the selection of rails that have significantly better wear performance for tests at FAST or in revenue service.

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