

Mechanical properties and wear performance of premium rail steels

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Abstract

The railroad industry in the United States of America spends approximately \$2 billion USD yearly on rail replacement and repairs. The Transportation Technology Center Incorporated (TTCI), a wholly owned subsidiary of the Association of American Railroads, Pueblo, Colorado, continuously conducts full scale rail performance tests, which represent a multi-million-dollar investment and take many years to complete.

This research paper addresses the development of a simple laboratory technique that can be used as a screening method for rail performance. This method is cost effective and rapid and is intended to be used prior to the full-scale test. The laboratory test consists on a ball-on-disk, pure-sliding experiment. In the present research were used only premium rails from various manufacturers for both, the ball-on-disk and full scale test and the results of both tests are provided in the present paper. The full-scale rail performance test is conducted by TTCI at the Facility for Accelerated Servicing Testing (FAST), which consists of a 4.4 km of railroad heavy haul tracks. The results of both, ball-on-disk and full-scale tests, presented in this paper correspond to the two latest generations of premium (pearlitic) rails and one bainitic rail. Such rails were produced by six rail manufacturers. Both, FAST and ball-on-disk tests showed that under high contact pressures (heavy haul conditions) the bainitic rail does not perform well as the pearlitic rails. Due to the significant differences, in particular dynamic forces, among the ball-on-disk and full-scale tests there is no direct relationship among both tests. Nonetheless, the ball-on-disk test can be used to distinguish wear performance among the two generations of rails tested for the present research; therefore, the ball-on-disk test can be used as a screening method prior to the full scale test.

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1. Introduction

A major goal in the development of new rail materials is improving wear performance and mechanical properties. Historically, the main method to accomplish this goal was to manufacture rail steels with higher initial bulk hardness, which was achieved by adding alloying elements, mainly carbon. There is, however, in theory a limit to the hardness that can be reached with pearlitic steels. Therefore, there is a need to examining other steel microstructures, such as bainite, that are harder than pearlite and could, in principle, improve rail wear performance [1–7]. Over the years, a relationship between hardness and wear of rail steels has been observed [8]. It is believed that the limit for

pearlitic rail has almost been reached with current casting techniques and chemistries; therefore, it may be difficult to push the wear performance of pearlitic rail steel much beyond its current state [1,3].

The University of Illinois at Urbana-Champaign (UIUC) developed a laboratory test under joint funding by the Federal Railroad Administration (FRA) and the Association of American Railroads (AAR) the test predicts rail performance, which in turn, reduces the time and price for rail wear testing, when compared to full scale test. However, such test has proven to be a good screening technique for rails but is still not possible to predict the overall rail performance at the laboratory level. This is mainly due to the complexity of the full-scale train dynamics such as revenue or FAST.

This research paper describes the full scale and ball-on-disk tests conducted on rail samples extracted from new and used rails. All rails tested were identical for both tests methods, in

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fact, the samples for the ball-on-disk test identified in this paper as “used” were extracted from rails that were subjected to heavy haul traffic at FAST for more than 4 years. In such time, the accumulated traffic was 435 million gross metric tonnes (MGMT) for the used pearlitic rail samples and 275 MGMT for the bainitic one. The test was conducted on premium rails that are fully pearlitic except for one bainitic rail (AAR developed and coded as J6). The bainitic rail was removed from FAST after 275 MGMT due to excessive wear. These used rail samples for the ball-on-disk test are referred to as high rail or “HR” as they were extracted from the outside (or high) rail of the FAST curve track; MGMT refers to the accumulated rail tonnage in metric megatonnes.

Premium rails are made of high carbon steels with pearlitic microstructure that are suitable for high rail performance applications (i.e., high loads, rolling contact fatigue, wear, etc.). The premium rails at FAST are subjected to a nominal load of 35.5 metric tonnes per axle such rails are ideally used in curves with more than 2° of curvature. The degree of curvature is customarily defined in the United States as the central angle subtended by a chord of 100 ft (30.48 m). It means one degree of curvature has a distance of 1 ft (30.48 cm) at the center between the curve and the chord.

Prior to the development of the “Premium Rail” the rail used was known as High Strength Rail with a head hardness of approximately 370 Hardness Brinell (HB). Premium rails are characterized for their higher hardness that results in better wear performance. Both, the ball-on-disk and full scale (FAST) tests were conducted on Premium Rails manufactured by the following companies: Corus, JFE Steel America Inc. (NKK), Mittal, Nippon Steel Corporation (NSC), Rocky Mountains Steel Mills (RMSM), and Voestalpine (VA).

2. Experimental procedure

The ball-on-disk and full scale tests were carried out using the same pearlitic and the J6 rails, in new (V) and used (HR) conditions. The new rails belong to the latest generation of premium rail, while the used rail is part of the previous generation of premium rails tested at FAST and removed after 435 MGMT of heavy haul traffic in June 2004. Together with the premium rails tested in the previous rail performance test at FAST the J6 rail was tested under similar conditions and for such test J6 was used as a control rail.

The Brinell hardness measurements were taken at the head of the rails at 0.8 ± 0.2 mm below the head surface of the rail as indicated by the AREMA specifications [14]. The surface of the rail heads were grinded prior the hardness measurement, removing an approximate depth of 0.8 mm (0.03 in.) from the surface as indicated by the AREMA standard [14].

Fig. 1 shows the layout of the rails along with the characteristics of Section 7 at FAST. Section 7 is fully dedicated to Rail Steel Evaluation and is a non-lubricated curve with the aim to increase wear, thus subjecting the rail to a more aggressive environment. The characteristics of Section 7 at FAST are as follows: approximate length of 305 m, a 5° curve with 10.2 cm of super elevation and 4.3 cm of cant deficiency. On a regular day the

accumulated traffic at FAST is approximately 90–95 MGMT. The layout shown in Fig. 1 represents the test concluded in 2004 and corresponds to the used rails. The layout of the current test (using the rail identified as new) is slightly different. The main differences among the previous and the current test are the size of the tested rail sections (24.4 and 12.2 m for the previous and current test, respectively) and the distribution of the rails along the curve. FAST consist of a loop track with a length of approximately 7.73 km. On a regular day TCI runs a heavy haul train at FAST that consist of approximately 80 cars, each car has a 130 metric ton capacity, and four locomotives such train runs in average 450 km or 100 laps.

A conventional ball-on-disk tribometer was used to perform pure sliding wear experiment for the new and used rail samples. Ball-on-disk experiments were performed at different numbers of cycles (50, 100, 300, 600, and 1000) followed by profilometric measurements after each test to quantify wear. The samples were named as follows: V1 through V5, where V denotes the new rail and HR1 through HR6, where HR denotes used rail (high rail subjected to 435 MGMT of FAST heavy haul traffic). The tribometer used provides the capability of applying controlled normal loading, motion, and recording in-situ friction. It consists of a rotating (0–1000 rpm) or oscillating (maximum arc 350°) spindle in which the disk specimen is mounted and a “pin” holder, which applies a contact load (0.45–45 N) and measures normal and friction forces [1]. Fig. 2 shows the general testing schematic of the ball-on-disk interface. The ball used for the ball-on-disk experiments was a small synthetic ruby ball with a diameter of 1.6 mm with a hardness of 1570–1800 HVN. Such ruby balls are at least 3.5 times harder than the tested rail. The significantly harder ruby ball was able to wear the rail steels without itself incurring significant wear.

Profile measurements were taken from FAST tracks at Section 7 at 0 MGMT followed by measurements every 15,000 MGT (14,640 MGMT) through 105,000 MGT (95,500 MGMT), then every 25,000 MGT (22,730 MGMT) until the end of the test. Note MGT stands for million gross tonnes, megatonnes, in English system and MGMT is in metric system. Profile measurements are taken using the Miniprof apparatus and analyzed with its respective software. Prior to the measurements the rail surface is prepared by removing the grease and any other impurity that can alter the Miniprof measurements, this process is manually conducted. The Miniprof software is used to superimpose the profiles at the various tonnages and compare them to the reference profile to determine losses in area as shown in Fig. 3. Four measurement per rail section, shown in Fig. 1, are taken the locations are fixed and every time the profile is taken from same location.

The disk samples for the ball-on-disk test were directly obtained from actual rail heads and were prepared in all cases similarly. Fig. 4 depicts the procedure to extract the disk samples from the rail’s heads, also all disk samples were extracted 8 mm from the surface eliminating the decarburized layer and assuring that all samples were extracted from comparable locations. All steel disk samples were machined to a surface roughness (R_q) of $0.8 \mu\text{m}$. Both the ruby balls and the disks were cleaned ultrasonically using acetone, followed by a rinse with alcohol

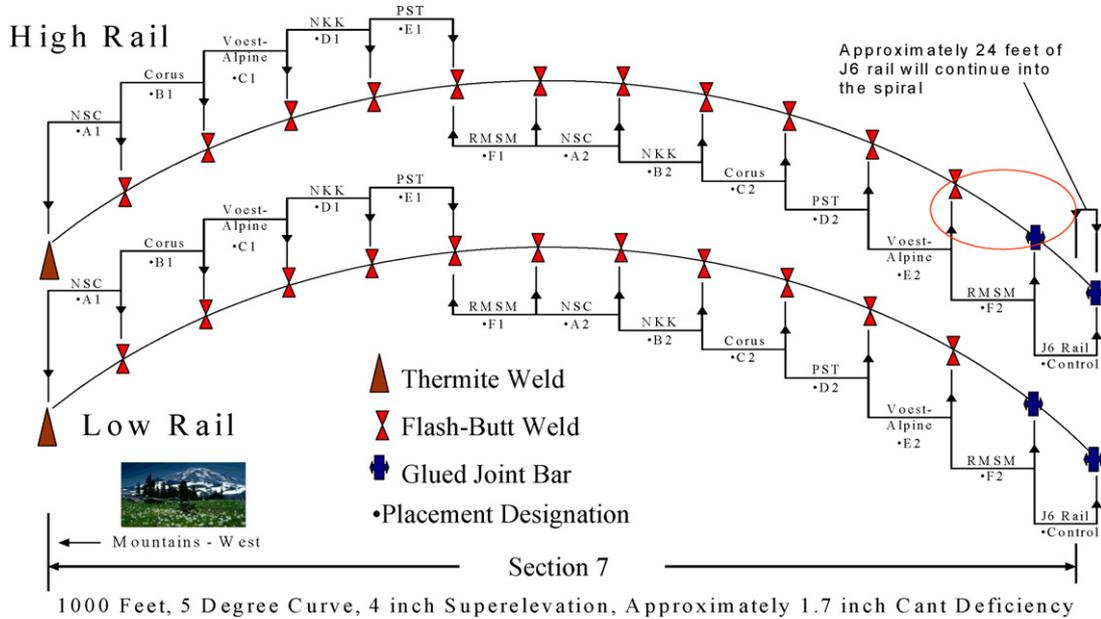


Fig. 1. Layout of FAST Section 7 Rail Steel Evaluation. The approximate length of the rail steel evaluation (Section 7) at FAST is 305 m and each section of rail measure is approximately 24.3 m, 5° curve with 10.2 cm of super elevation and 4.3 cm of cant deficiency.

and drying with warm air. Ruby balls were used intentionally to better control the contact pressure and wear on the rail steels. Note that UIUC also performed experiments using carbon steel balls (to better simulate the wheel/rail contact) and the results are in accordance to the results of the present research [5]. A new ruby ball and a new disk sample were used for each test at the different cycles. The normal load applied was kept constant at 10 N through each test and the same load was applied for each test. Such load is equivalent to a yielding a Hertzian contact pressure of 2.5 GPa, which is comparable to the contact pressure in actual wheel/rail conditions. The rotational speed of

the disk was 100 revolutions per minute (RPM), equivalent to approximately 0.085 km/s (linear speed). The friction and normal forces (and resulting friction coefficient) during test were recorded via a data acquisition system (Labview) linked to a personal computer.

3. Results and discussion

The carbon content of the J6 rail is 0.26 wt% and its overall chemical composition is given in Table 1. All premium rails were fully pearlitic with a carbon contents between 0.74 and 0.85 wt%

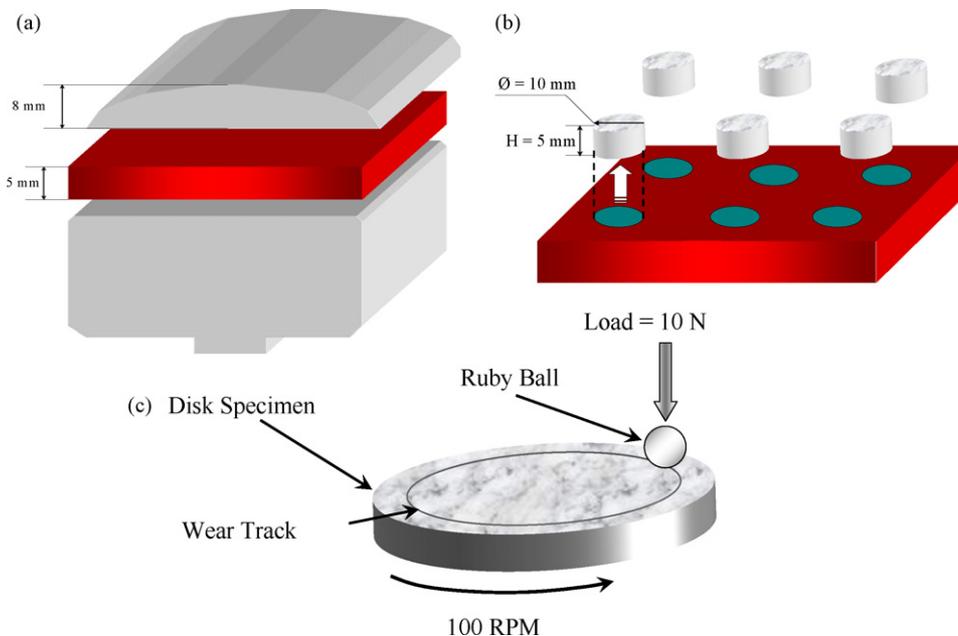


Fig. 2. Schematic of scratch wear testing configuration. (a) Rail's head and scattering to extract the ball-on-disk samples below the decarburized layers, (b) samples extracted for the ball-on-disk test and (c) schematic of scratch wear testing configuration.

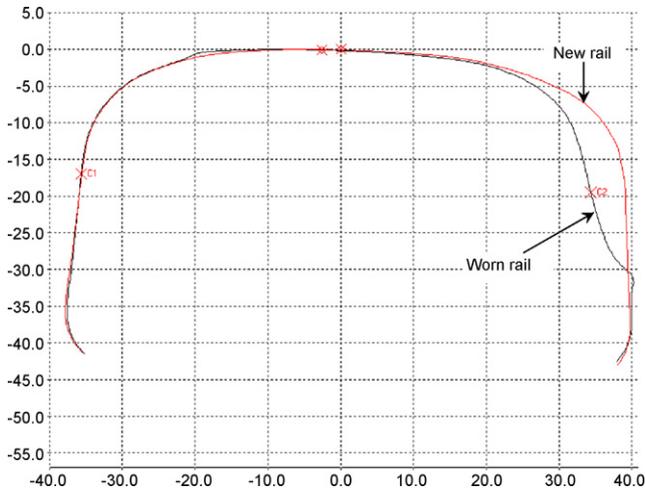


Fig. 3. Profile measurement taken using Miniprof for the current FAST test at 0 MGMT (new rail) and 140 MGMT (worn rail) of accumulated tonnage. The rail wear is measured in mm² of lost area. The scales are in mm.

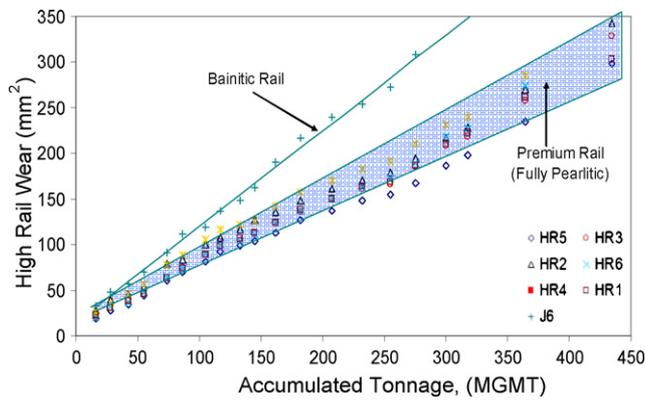


Fig. 4. Field wear measurements for bainitic and pearlitic rails. Notice the difference in wear among bainitic and pearlitic rails.

for the rails identified as used or HR (previous generation) and between 0.85 and 1 wt% for the rails identified as new or V (latest generation). The average head hardness for the respective used and new rails in as-rolled conditions (it means before work-hardening, thus, installed and tested at FAST) are 410 ± 23 HB and 395 ± 9 HB. Note that the carbon content in J6 bainitic steel is significantly lower than the one of the pearlitic rails. The initial bulk hardness, in as-rolled conditions, of the J6 rail averaged 415 HBN.

Table 2 summarizes the results of the rail head Brinell hardness. The grinding is conducted to partially remove the

Table 1
Chemical compositions for J6 bainitic and conventional pearlitic rail steel

wt%	J6 bainitic
C	0.26
Mn	2.00
Si	1.81
Ni	0.00
Cr	1.93

Note: pearlitic rails' composition is confidential and these rights belong to the rail manufacturers.

Table 2

Results of head hardness analysis conducted on the head of the rails used for present research

Used rail	Brinell hardness (HB)		New rail	Brinell hardness (HB)
	As rolled ^a	Used ^a		
HR1	399	461	V1	401
HR2	402	415	V2	430
HR3	393	429	V3	375
HR4	390	415	V4	429
HR5	405	429	V5	415
HR6	382	415		

^a The “as rolled” condition indicates that these hardness measurements were made before the rail was installed on tracks. The “used” condition represents the hardness of the rail after 435 MGMT of heavy haul traffic at FAST.

decarburized layer (soft material) from the head of the rail. It is important to notice from Table 2 that the initial hardness of the HR rails (in as rolled conditions) varied from 382 HB to 405 HB, a 23 HB difference; however, after work-hardening the rails HR2, HR4, and HR6 showed similar increment to 415 HB, while the hardness of HR3 and HR5 increased to 429 HB. The only rail showing significantly higher hardness, thus, work-hardening ability, is HR1, which increased to 461 HB. In contrast, the J6 rail showed after work-hardening an increase on head hardness of no more than 8 HBN.

Despite the initial higher bulk hardness of the J6 bainitic steel and the expectation that it should have better wear performance compared to the lower hardness pearlitic steels; the wear rate performance of the J6 rails was significantly worse when compared to premium pearlitic rails. Fig. 4 shows the wear performance for the bainitic and pearlitic rails investigated by TTCI at FAST [4,13]. Fig. 4 illustrates that the bainitic rail shows considerably higher wear than the pearlitic rails tested. In addition to the lower than expected rail wear performance of the J6 rail after 275 MGMT of heavy haul FAST traffic the J6 rail fractured letting behind a reduced tests section that could potentially affect the adjacent rails forcing the removal of the J6 rail from FAST tracks.

In Fig. 4, it can be observed that at the beginning of the test both, J6 and the pearlitic rails showed similar wear behavior, however, as the heavy haul traffic accumulated is clear that all pearlitic rails materials show significantly lower wear rate than J6. Moreover, the wear rates among all the pearlitic rails are comparable along the entire test. The reason for the worse wear performance of the J6 bainitic rails is that despite its initial higher bulk hardness than pearlitic rails, the pearlitic rail work-hardening ability is significantly higher than for bainitic steels. A previous research investigation shows that the work-hardening area is contained in the vicinity to the worn surface and can be well studied using micro-Vickers hardness [9,15].

To directly compare the FAST data (Fig. 4), with ball-on-disk experiments, samples HR1 through HR6 were extracted after the completion of the FAST trials and used to perform ball-on-disk experiments. Fig. 5 shows the wear performance results of the ball-on-disk test using pearlitic J6 samples in as-rolled (or brand new) and used conditions (subjected to heavy haul

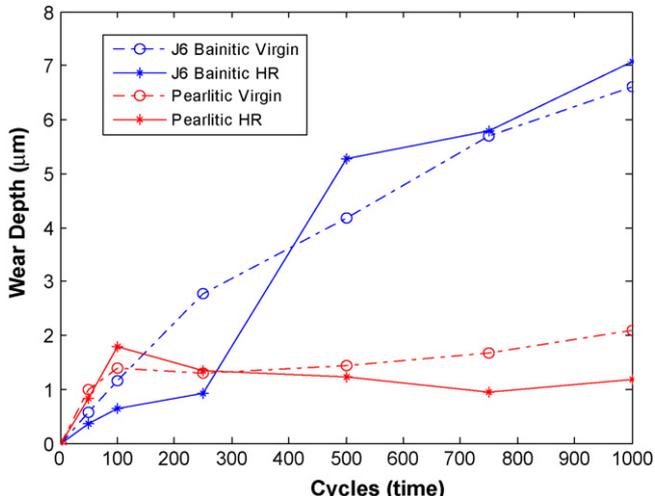


Fig. 5. Ball-on-disk sliding wear measurements for J6 bainitic and pearlitic rails.

traffic at FAST). Comparing Figs. 4 and 5 (FAST and ball-on-disk, respectively) can be observed that the wear performance of the pearlitic rail (HR) is significantly better than the wear performance of the J6 rail. Furthermore, in both tests at the initial stages (for the ball-on-disk test until 300 cycles) it is not so clear that pearlitic (HR) rails have better wear performance than J6; however, at the higher cycles, pearlitic rails show significantly better wear performance. This behavior is similar for both unused samples as well as the highly stressed used samples. It can therefore be concluded that the wear performance results of the pearlitic and J6 rails obtained from the ball-on-disk and FAST tests are in agreement.

Fig. 6 shows the results of the ball-on-disk test for all rails used for the concluded FAST test, it means for all the rail samples identified as “HR” and the J6 rails. In Fig. 6, it can be observed that there is no distinctive difference in wear among the six used pearlitic rails; however, the J6 bainitic rail clearly shows higher wear. Nevertheless, FAST results certainly show similar but and distinguishable trends among the various pearlitic rails

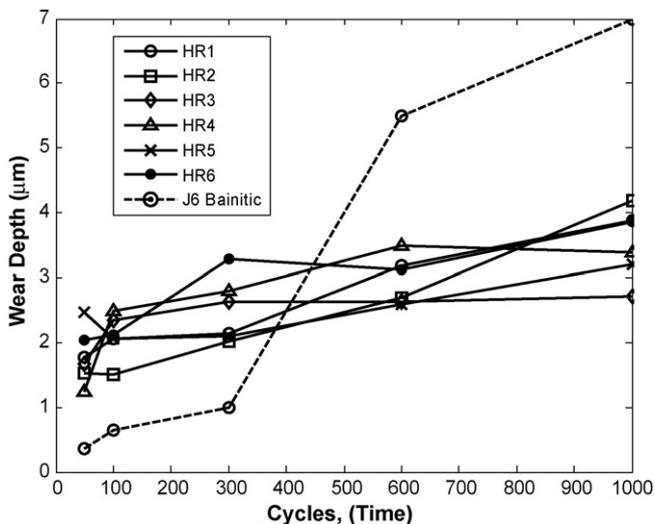


Fig. 6. Summary of ball-on-disk sliding wear experiments for high rail samples.

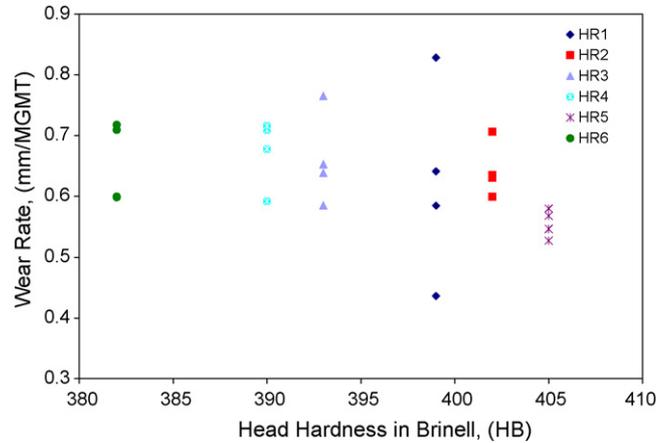


Fig. 7. Influence of initial rail hardness on rail wear (after 435 MGMT) [16].

(see Fig. 4), in contrast in the ball-on-disk test there is no clear distinction among the pearlitic rails.

It can be concluded that due differences between the ball-on-disk and the full-scale (FAST) tests, it is difficult to extrapolate one to one the results among ball-on-disk and full scale (FAST) tests. These differences could be attributed to the complexity (such as load dynamics) of the full scale test at which the rails are subjected at FAST that are hard to simulate in well controlled (laboratory) conditions. Some of these differences can be observed comparing Fig. 4 with Fig. 6. However, the wear differences among pearlitic and bainitic steels are evident in both tests and in good agreement demonstrating that the ball-on-disk tests is a laboratory method capable of selecting the most suitable microstructure, in this case pearlitic, for rail steel applications.

Previous reports show a good correlation among initial (as-rolled) head hardness versus wear rate [9,10,13]. This is valid when the wear hardness of the rails is averaged; however, for the independent rail wear measurements the correlation is not clear, as Fig. 7 shows. This can be translated in that the wear rates results diverge from the linearity as the accumulated traffic in the rails increases, which is attributed to the complex rail dynamics taking place in the full scale test. The above findings are in agreement for both, the ball-on-disk and FAST tests.

The new generation premium pearlitic (V1 through V5) rails is harder than the earlier generation rails (HR1 through HR6), as Table 2 shows. Direct comparisons between the full scale test and the ball-on-disk tests for the new rails cannot be done in the present research because as of October 2006, the accumulated tonnage at FAST is approximately 146 MGMT, which is an early stage for the current FAST test. The reason is that as the tonnage accumulates there is a divergence of the rail performance test at FAST as shown in the previous results, therefore, any conclusion made at this point for the current test can or cannot be valid for the final results. Therefore, it is too early to draw solid conclusions from such test [11].

Fig. 8 shows typical profilometric measurements of two of the disk samples. Fig. 8a shows the wear depth of a scan across the ball-on-disk wear track of the V2 sample after 50 cycles, while Fig. 8b shows the wear track of the V5 sample, also after 50 cycles. Fig. 8c and d shows the same samples after 600 cycles.

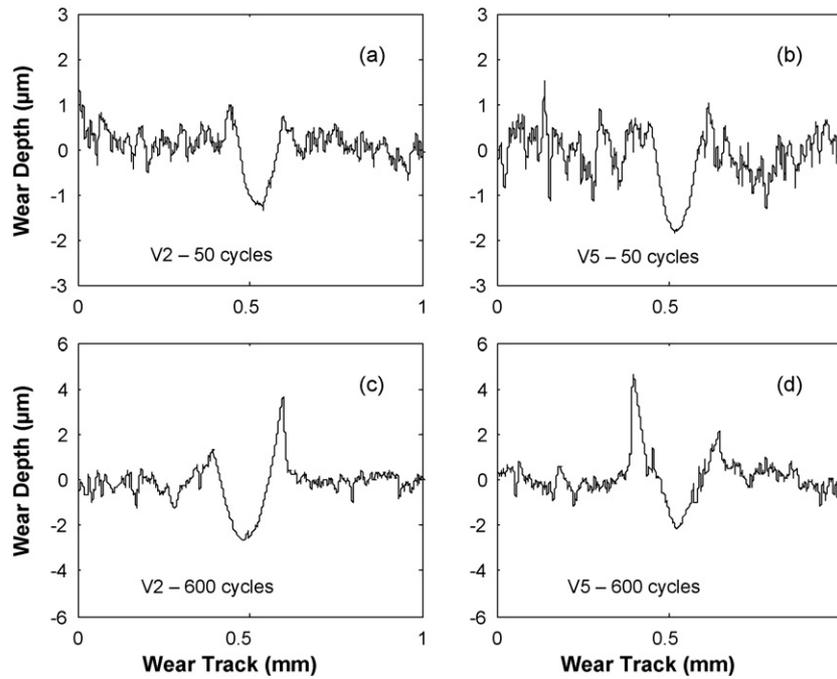


Fig. 8. Representative wear track scans: (a) V2 at 50 cycles, (b) V5 at 50 cycles, (c) V2 at 600 cycles, and (d) V5 at 600 cycles.

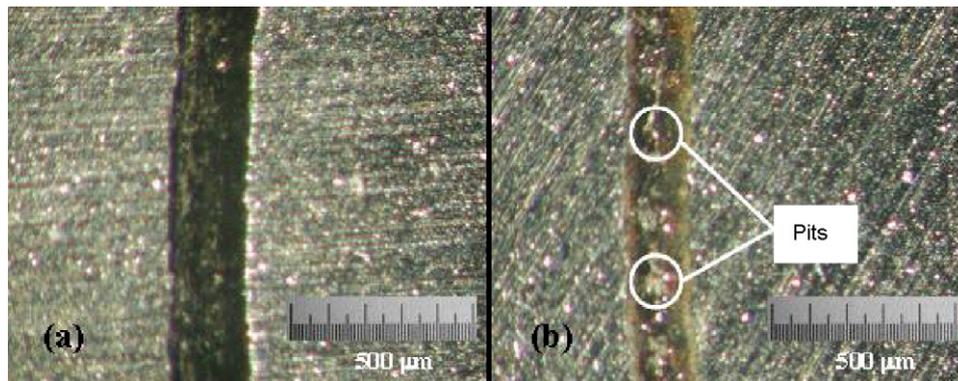


Fig. 9. Typical micrographs of rail samples subjected to testing: (a) uniform wear track, (b) wear track with pits and material removal.

Fig. 9 illustrates some of the ball-on-disk tested samples showing pits, thus, excessive material removal that can affect the profilometric measurements inside the wear track.

Fig. 9a shows low magnification picture of a sample with a relatively uniform wear track. In this case, each profilometric wear measurement was very similar for the same number of cycles on the wear track. Fig. 9b shows pictures of another sample with pits and some oxidation on the wear track, which can influence the profilometric wear measurements. To minimize this inherent variability, four different locations (line scans) on each disk were measured and average wear values in terms of depths are reported. It should also be noted that a few of the ruby balls fractured during tests causing larger contact area and wear tracks. In such cases, both, samples and ruby balls were excluded from the analyses.

Fig. 10 summarizes the average wear depths for all of the new rails samples (V1 through V6) showing that initially samples V1 through V3 appear to have less wear than samples V4 through

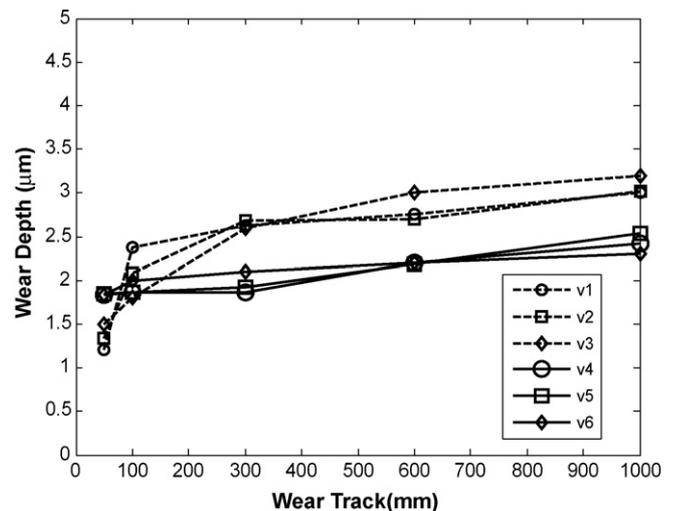


Fig. 10. Summary of ball-on-disk sliding wear experiments for new pearlitic samples.

V6. However, as the number of cycles for samples V1 through V3 increases, wear also increases. The difference in wear depth becomes apparent after 600 cycles. Samples V4 through V5 seem to have a slow gradual increase in wear as the number of cycles increase, but in comparison to samples V1 through V3, the wear at all cycles is comparable. Final conclusions of the results among the full scale and the ball-on-disk test will be included in future research publications.

4. Conclusions

The wear results obtained from the full scale and ball-on-disk tests are in agreement. The two major findings were obtained with the use of the ball-on-disk test that are the identification/determination of the most suitable rail microstructure for premium rails (pearlitic) and the better wear performance of the latest generation (higher hardness) of premium rails (classified as V). Since the two generations of premium rails have pearlitic microstructure it can be said that the higher wear performance of the latest generation of premium rail is attributed to its higher hardness. The lower wear performance of the bainitic rail (J6) is presumably due to its poor work hardening ability. In this paper, it is clearly shown the potential for implementation of the ball-on-disk test as a screening method to pre-select the rails with higher wear performance for full-scale applications including FAST and revenue service. This can be of significant importance since the method can be directly used by the railroad industry.

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