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R&T Results of AAR Developed J6 Bainitic Type Rail Steel

by Joseph Kristan

Summary

Early results of J6 bainitic steel (developed by the Association of American Railroads) showed superior performance in rolling contact fatigue (RCF), with comparable wear performance to premium pearlitic rail steels available at that time. The development and testing of this alloy spurred three rail manufacturers to produce bainitic rail steel for prototype testing. One manufacturer tested its prototype bainitic rail at the Facility for Accelerated Service Testing (FAST), along with AAR's J6 rail.

The J6 bainitic rail steel, which is a low carbon-carbide free type, showed that this microstructure can be produced to hardness well over 400 BHN by air-cooling the appropriate chemistry without additional treatment. The fracture toughness of the bainitic steel tested is significantly above that of the conventional (350 BHN) head-hardened pearlitic steel rails. This increased toughness increases the critical crack size before sudden fracture, potentially allowing less frequent in-track ultrasonic inspection of the rail to identify crack propagation.

The latest pearlitic rails have equivalent RCF resistance and better wear performance based on laboratory and track testing. Thus, the reduced or negated gain in rail surface performance from the J6 bainitic rail, in comparison to the modern head-hardened rails, along with welding issues and difficulty manufacturing 141-RE section, have led to AAR's discontinuing the J6 research effort in regard to the application as premium rail. However, the use of J6 bainitic rail for special track work applications may provide performance advantages. The J6 rail used in high angle crossing diamonds has shown improved performance in comparison to conventional materials (see TD02-024: "Advanced Design Bainitic Steel Rail Crossing Diamonds under HAL Service").

The impetus of TTCI's rail steel research effort has changed with the goal of gaining a better understanding of the rail steel fundamentals in regard to the microstructure to mechanical and micromechanical property relationships ultimately leading to improved wear and RCF performance. The intent is to use this information to promote further accelerated rail steel development. This research effort is being jointly funded by the AAR and Federal Railroad Administration and is scheduled for completion this year.



DEVELOPMENT HISTORY AND FINDINGS

The AAR initiated the bainitic rail steel research program in the 1980s. Comprehensive research and development was performed by Oregon Graduate Institute over several years using small-scale laboratory testing. During this time, bainitic test alloys J1 through J6 were developed and tested with J6 being found to possess a near order of magnitude superior wear performance as tested using Amsler test equipment. The J6 steel had a laboratory wear performance 60 to 80 times better than premium head-hardened rail produced at the time. In 1996, TTCI chose to proceed with full-scale trials of the J6 test material. J6 rail in the 136-RE profile was first produced in 1997. The steel was manufactured by Ellwood City Forge with the rail rolled by Pennsylvania Steel Technologies (PST).

The initial J6 bainitic 136-RE test rail was thoroughly tested in the laboratory at TTCI to evaluate service worthiness. Subsequent to the laboratory investigation of the J6 test rail, the rail was installed as part of the rail evaluation test at FAST in 1997, with the following results:

- J6 high-rail wear rate was approximately 50 percent higher than the average premium head-hardened rail in test.
- Surface performance appeared to be superior to that of the pearlitic rails.
- No rail fractures occurred during more than 450 MGT of testing.

Spurred by the initial results of the J6 rail surface performance at FAST, a J6 test site was installed in 1999 on the Norfolk Southern line near Roanoke, Virginia (rail from the first 136-RE heat of steel). Additionally, testing of J6 bainitic rail for special track work applications began shortly thereafter. Results of this test include:

- J6 high rail wear rate was nearly identical to the 360 BHN PST control pearlitic rail.
- J6 low rail wear rate was approximately 50 percent less than the control rail (due significantly to inhibited deformation and flow).
- J6 rail surface performance was substantially superior to that of the control rail (especially so for the low rail).
- Both thermite and flash-butt weld performances were poor mainly because J6 welding parameters were not optimized.
- Two flash-butt fractures occurred.
- Two thermite fractures occurred.

The test site was removed in August 2002 after approximately 135 MGT due to weld performance issues.

Another production (heat) of the J6 steel was commissioned in 2000 to allow additional testing of the alloy in special track work applications (136-RE and 136-RE thick web).

- The heat was mainly used for special track work.
- Rail was installed in the current rail evaluation test at FAST in late 2001.
- Two base fractures occurred in the J6 test rail.
- One detail fracture was caused by a titanium nitride inclusion. These inclusions are distributed throughout the rail matrix as a function of alloying.

In 2002, a third heat of J6 rail was commissioned in the 141-RE section for a grinding test at FAST as well as for test sites in revenue service (NS and UP). The production of the rail in the 141-RE profile was delayed due to rail rolling and straightening issues:

- Severe curvature of the rail occurred after hot rolling resulting from the differing rail section (141 RE) in comparison to previous heats (136 RE)
- Fracturing of several mill rollers occurred during roller straightening
- Fracture of one of the rails occurred during final manual hydraulic straightening

Several head web fractures subsequently occurred in the 141-RE rail likely due to extreme localized residual stress from the roller straightening process.

The improved performance of the modern 400 BHN head-hardened pearlitic rail, as evaluated in revenue service trials, led to laboratory RCF experiments to directly quantify the relative performance.

- Modern (400 BHN) head-hardened pearlitic rail was found to sustain 157,000 cycles at a test pressure of 1800 MPa (261.1 ksi) prior to the onset of detectable cracking while the J6 bainitic sustained 81,800 cycles (415 BHN)
- Previous generation head-hardened rail (350 BHN) sustained only 13,800 cycles before onset

The J6 bainitic rail requires special thermite welding kits as well as revised electric flash butt welding procedures for proper joining because of the alloy content.

The impetus of the rail steel SRI research project has changed with the goal of gaining a better understanding of the rail steel fundamentals in regard to wear and RCF. The intent is to gain a better understanding of rail steel mechanical and micromechanical performances as related to steel microstructure, and to use this information for enhanced rail steel development and provide improved laboratory testing techniques. This rail steel research is being jointly funded by the AAR and FRA.

BAINITIC RAIL STEEL PROPERTIES

Brinell hardness was measured on a full transverse section of J6 rail. The test rail had a near uniform hardness through the section, with typical hardness of 430 to 420 BHN in the head, 415 BHN in the web, and 420 BHN in the foot. This even distribution confirms that the hardness of J6 steel is relatively insensitive to cooling rate, and that the bainitic structure can be achieved without the need for accelerated cooling. Head-hardened pearlitic rail has typical head hardness in the range 340 to 400 BHN, with approximately 300 to 330 BHN in the web and foot.

Resistance of J6 rail steel to sudden brittle fracture was assessed using compact tension, fracture toughness specimens taken horizontally from the head of the rail. Average fracture toughness value for three tests of the J6 rail is 51.6 ksi (in^{1/2}). The average of two tests for the 350 BHN conventional head hardened rail is 41.7 ksi (in^{1/2}). Since critical crack size to fracture rises as the square of the toughness, this is an indication that J6 rail should sustain larger cracks than premium rail before failing by sudden brittle fracture.

Laboratory Rolling-Contact Fatigue Tests

A small number of laboratory tests were undertaken to examine the resistance of the J6 steel to RCF using the SUROS machine at the University of Sheffield. Like the Amsler machine, the SUROS machine is a twin-disc system that rolls a wheel disc against a rail disc under well-controlled loads. Unlike the Amsler machine, which has fixed gearing between the two test discs, the SUROS machine has independent drives for the two test discs, and this enables very close control of the applied creepage. The machine is equipped with a non-contacting eddy-current probe able to scan the disc surface during testing to detect small RCF cracks at the disc surface.

All tests were conducted on 45 to 47 millimeter diameter discs machined from the heads of J6 and head-hardened pearlitic rails. These rail discs were rolled against discs machined from North American Class C wheels. Tests were done at nominal contact stresses of 1,500 (217.6 ksi) and 1,800 MPa (261.1 ksi).

Table 1 summarizes results of the SUROS testing. At a contact stress of 1,500 MPa, both of the conventional (350 BHN) head-hardened rail disc tests were stopped near

approximately 80,000 cycles when the eddy current system detected a surface breaking RCF crack. The two J6 tests at the same stress were stopped at run out after approximately 200,000 cycles without crack detection. A single specimen of modern 400 BHN head-hardened rail also went to run out at this stress level. At a stress of 1,800 MPa, the J6 test was stopped at about 82,000 cycles due to crack detection. In comparison, the conventional head-hardened rail test was stopped at about 14,000 cycles. The modern head-hardened rail sustained more than 157,000 cycles before crack initiation. Thus, the modern head-hardened rail likely possesses equivalent or superior RCF performance to that of the J6 bainitic rail based on this limited testing.

Table 1. Laboratory Rolling Contact Fatigue Tests

Contact stress: 1,500 MPa (217.6 ksi); Creepage: 1%					
Rail Disc	Hardness	Cycles	Weight Lost		Comment
			(g)	(oz)	
J6 1	415	200,283	0.164	5.78x10 ⁻³	Runout
J6 2	415	200,215	0.129	4.55x10 ⁻³	Runout
HH1	350	81,438	0.046	1.62x10 ⁻³	Crack detected
HH2	350	76,343	0.042	1.48x10 ⁻³	Crack detected
Modern1	400	200,536	0.145	5.11x10 ⁻³	Runout
Contact stress: 1,800 MPa (261.1 ksi); Creepage: 1%					
Rail Disc	Hardness	Cycles	Weight Lost		Comment
			(g)	(oz)	
J6 3	415	81,816	0.080	2.82x10 ⁻³	Crack detected
HH3	350	13,785	0.012	0.42x10 ⁻³	Crack detected
Modern2	400	157,013	0.172	6.07x10 ⁻³	Crack detected

SERVICE TRIALS

Tests at FAST

The performance of the J6 rails was compared with six head-hardened rail steels in two separate tests in a 5-degree curve with nominal 4-inch superelevation at FAST in the High Tonnage Loop. Data from these tests are from previous tests performed from 1997 to 2001 and the current test initiated in 2001, which is still ongoing.

Table 2 shows the relative wear performance of each of the rails from both the previous and current rail evaluation tests. Data is presented in wear rates (relative to the lowest wearing steel) with standard trucks and no direct wheel/rail lubrication. The inferior wear performance of the J6 steel is apparent, notwithstanding its higher hardness.

Table 2. Test Rail Wear Rates from TTC Test Site Covering Two Separate Rail Evaluation Tests

Rail Steel	Wear Rate 1997 to 2001	Wear Rate 1997 to 2001	Wear Rate 2001 to 2004	Wear Rate 2001 to 2004
	(in ² per 1000 MGT)	(relative)	(in ² per 1000 MGT)	(relative)
J6	2.409	1.67	1.46	1.76
HH-1	1.530	1.06	0.91	1.10
HH-2	1.936	1.34	1.00	1.20
HH-3	1.557	1.08	0.83	1
HH-4	1.643	1.14	no rail tested	
HH-5	1.632	1.13	0.92	1.11
HH-6	1.444	1	0.90	1.08
HH-7	no rail tested		0.92	1.11

Little evidence of RCF was seen on any of the rails throughout the test, possibly due to the dry environment at the test site and the conformal wearing of the wheels and rail because of the looped track. However, those cracks that did occur appeared only at the rail gage corner on the head-hardened pearlitic rails. Very little evidence of contact fatigue was seen on the J6 test rails.

Revenue Service Trials

Rails were installed for test in a Norfolk Southern (NS) revenue service line near Roanoke, Virginia. Test J6 rails were installed in the high and low rails of a 5.5-degree curve with 4 inches of superelevation. The line carries mainly coal traffic with 35.75-ton axle-load cars traveling at about 40 mph. Head-hardened (350 BHN) pearlitic rails were installed on either side of the test rails for comparison.

Three points are noted from this testing. First, wear over the test period is linear for both the high and low rails and for both rail types. Second, unlike the results from the site at FAST, in the high rail of the curve there is little difference between the wear of the J6 rails and the head-hardened pearlitic rails. Third, the J6 low rails have worn significantly less than the head-hardened low rails. After 110 MGT of traffic, the J6 low rails showed almost exactly half the wear of the head-hardened control rails (significantly less deformation and flow).

There are several possible reasons for this change in relative wear performance in comparison to FAST. First, the better lubrication at the NS test site may have altered relative wear performance. Second, the track geometry and train operating speeds at the two sites resulted in different cant deficiencies. The loading on the high and low rails at the NS site is more evenly distributed than at FAST, which has higher loading on the high rail. Third, the wheel/rail contact conditions are less conformal than those at FAST.

While the J6 wear results at the NS test site were encouraging, the observations of RCF performance were

much more interesting. In the low rail of the curve, the J6 rails showed an almost complete absence of cracks and shelling (RCF). In comparison, the conventional head-hardened pearlitic rails showed widespread RCF damage, with extensive cracks and shelling, as Figure 1 shows.

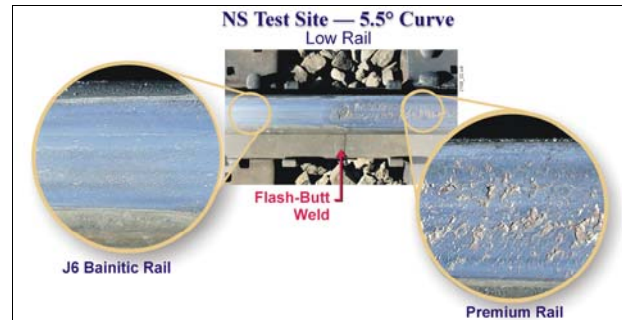


Figure 1. Surface Condition of Test Rail in Revenue Service at 110 MGT

CONCLUSIONS

The bainitic rail steel has shown that this microstructure can be produced to hardness well over 400 BHN by air-cooling the appropriate chemistry without additional treatment. The fracture toughness of the bainitic steel tested is significantly above that of the conventional (350 BHN) head-hardened pearlitic steel rails. This increased toughness increases the critical crack size before sudden fracture, potentially allowing more time for in-track ultrasonic inspection of the rail to identify crack propagation.

Laboratory and full-scale tests with axle loads up to 39.4 tons have shown the rolling contact performance of bainitic steel rails to be superior to that of conventional head hardened pearlitic rails. The high-rail wear performance of the J6 rail in comparison to conventional pearlitic rail ranged from nearly equivalent to approximately 50 percent more wear, depending on test conditions. However, the state-of-the-art 400 BHN head-hardened rails possess significantly improved RCF resistance in comparison to the conventional steel as evident in recent revenue service tests on the Union Pacific as well as the SUROS RCF laboratory tests (Table 1).

Thus, the reduced or negated gain in rail surface performance from the J6 bainitic rail, in comparison to the modern head-hardened rails, along with welding issues and difficulty manufacturing 141-RE section, have led to AAR's discontinuing the J6 research effort. However, work will continue on the use of J6 bainitic rail for special track-work applications.

The impetus of the rail steel research project has changed with the goal of gaining a better understanding of the rail steel fundamentals in regard to the microstructure to mechanical and micromechanical property relationships ultimately leading to wear and RCF performance. The intent is to use this information to promote further accelerated rail steel development and improved laboratory test techniques.

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