Test and application of 60 kg·m^{-1} bainite rails for heavy-haul railway

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Abstract

Purpose – In order to develop high-strength, high-toughness and high-wear-resistance rails suitable for the development and application of heavy-haul railways.

Design/methodology/approach – Based on the trial production of 60 kg·m^{-1} bainite rails, the Zeiss inverted optical microscope, transmission electron microscope and static hydraulic universal tester were used to test the microstructure and property of rail base metal and welded joints. Meanwhile, a trial laying of rails, wing rails of frogs and switch rails for turnouts was performed to systematically analyze their strength, toughness and wear resistance.

Findings – The results show that the base metal of 60 kg·m^{-1} bainite rail is of a uniform microstructure, with a carbide-free bainite matrix, a few of stable residual austenite and M/A islands, and it features high hardness, good wear resistance and good strength-toughness balance. The welded joint is of a uniform microstructure and has good properties.

Originality/value – A bainite rail, laid in a curve section of heavy-haul railway is able to serve for 48 months with a gross traffic tonnage of nearly 600 million tons, whose service life is more than one time longer than that of pearlite rail; the service life of the wing rail of frog and the switch rail for turnout with 60 kg·m^{-1} bainite rails is 3–4 times longer than that with U75V rails, and no serious damage occurs. The bainite rails also have strong peeling and spalling resistance.

Keywords Heavy-haul railway, 60 kg·m^{-1}, Bainite rail, Residual austenite, Base metal, Welded joint

Paper type Research paper

1. Introduction

In recent years, with the development of railway in China toward heavy-haul and high-speed modes, especially with the increase of the train axle load, the improvement of the operating speed and the increasingly complex operating environment, higher requirements have been put forward for the service conditions of rails (Tan *et al.*, 2018). High strength, high toughness, high wear resistance and good peeling and spalling resistance of rails have gradually become the necessary conditions for the development of railway, especially the heavy-haul. With the increase in transportation volume and axle load of the Daqin Railway, rail damage is becoming increasingly serious, and improving the service life of the Daqin heavy-duty railway rail has become an urgent and important research topic (Zhou, Zhang, Guo, Xi, & Gao, 2010). The frequency of peeling, hidden defects and even breaking caused by wear and fatigue of existing pearlite rails has increased significantly, resulting in a sharp increase in the maintenance cost of heavy-haul railways (Chen & Zhou, 2002; Davis & Sawley, 1998; Liu, Chen, Zhang, Zhou, & Tian, 2011). The bainite rail has high strength, good plasticity,

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good balance between strength and toughness/plasticity and better toughness, which is 2–5 times that of pearlite rail; and it has excellent contact fatigue resistance and wear resistance. Known as the “rail steel in the 21st century”, it has become the research and development focus and direction of the new-generation high-strength rails for heavy-duty railway (Chen, Jin, Liu, Yang, & Zhao, 2008; Kern, 1998; Sawley & Sun, 1997; Sawley, 1998). In China, the steel sector has been cooperating with the railway sector in researching bainite rails for nearly 20 years. After continuous innovation, 60 $kg \cdot m^{-1}$ and 75 $kg \cdot m^{-1}$ bainite rails have been successively developed, in which the trial laying of 60 $kg \cdot m^{-1}$ bainite rails was conducted for the first time on a main railway line in operation in China. Up to now, there are few reports on the research of the microstructure, property and application of bainite rails.

The Zeiss inverted optical microscope, transmission electron microscope and static hydraulic universal tester in this paper were used to test the microstructure and comprehensive mechanical property of base metal, and the flash weldability of 60 $kg \cdot m^{-1}$ bainite rail, and a trial laying of rails and wing rails of frogs and switch rails for turnouts was performed for application analysis, in order to further verify the strength, toughness and wear resistance of 60 $kg \cdot m^{-1}$ bainite rail.

2. Trial production of base metal and its microstructure and property

2.1 Chemical composition, smelting and trial production of bainite rail

In order to optimize the screening of chemical composition and range of 60 $kg \cdot m^{-1}$ bainite rail and ensure that its property indicators meet the standards, a multitude of smelting and rolling simulations were performed in lab to determine the smelting composition for trial production on site. Then the samples from all heat ranges were selected for the analysis of the chemical composition. The results are shown in Table 1.

The procedure of trial production of 60 $kg \cdot m^{-1}$ bainite rail is as follows: Continuous casting of large square billet → heating by walking beam furnace → descaling with high-pressure water → cogging → rough rolling → secondary descaling with high-pressure water → universal rolling → thermal printing → hot sawing → hot pre-bending → slow cooling in cooling bed → horizontal–vertical composite straightening → straightness inspection → eddy current surface flaw detection → ultrasonic flaw detection → traversing and steel splitting → online inspection → four-side pressure straightening → processing by saw-drill combined machine tool → collection and warehousing.

2.2 Decarburized layer, nonmetallic inclusions and structural characteristics of bainite rail

The samples of the 60 $kg \cdot m^{-1}$ bainite rail from three heat ranges were selected and numbered as 1#, 2# and 3#, respectively, to inspect and analyze the decarburized layer for decarburization stability. According to the specification of *Technical Conditions for Ordering 43–75 kg·m*$^{-1}$ *Rails* (TB/T 2344-2012), the samples were taken at the railhead fillet and the center of the tread. The inspection results of the decarburized layer are shown in Table 2.

It can be seen from Table 2 that the depth of the decarburized layers of bainite rails from the three heat ranges is very shallow, meeting the ≤0.5 mm requirement in TB/T 2344-2012.

	Chemical composition (wt%)/%						
Specification of rail	C	Si	P	S	Cr + Mo + Mn	V + Nb	Fe
60 $kg \cdot m^{-1}$	0.1–0.3	1.0–2.0	≤0.020	≤0.015	3.0	Appropriate	Others

Source(s): Author’s own work

Table 1. Chemical composition of bainite rail

The nonmetallic inclusions of 1#, 2# and 3# rail samples were sampled, respectively, according to TB/T 2344-2012, and then the nonmetallic inclusions of all samples were rated according to the *Steel – Determination of Content of Nonmetallic Inclusions – Micrographic Method Using Standards Diagrams* (GB/T 10561-2005). See Table 3 for the results and standards.

It can be seen from Table 3 that the nonmetallic inclusions of bainite rails of the three heat ranges meet the relevant requirements of TB/T 2344-2012.

The metallographic samples of 1#, 2# and 3# rail samples were taken, respectively, according to TB/T 2344-2012. After grinding, polishing and etching with 4% nitric acid alcohol solution, the metallographic structure was observed under the optical microscope. The results are shown in Figure 1, from which it can be seen that the microstructure of each sample is stable and evenly distributed, composed of carbide-free bainite and a small amount of massive ferrite, indicating that the microstructure of 60 kg·m^{-1} bainite rail embodies good stability.

For a more accurate analysis of the structural morphology and composition of bainite rail, 1# sample was further observed and analyzed by the field emission transmission electron microscope (JEM-2010F), and the results are shown in Figure 2, from which it can be seen that

Table 2. Inspection results of decarburized layer of railhead of 60 kg·m^{-1} bainite rail

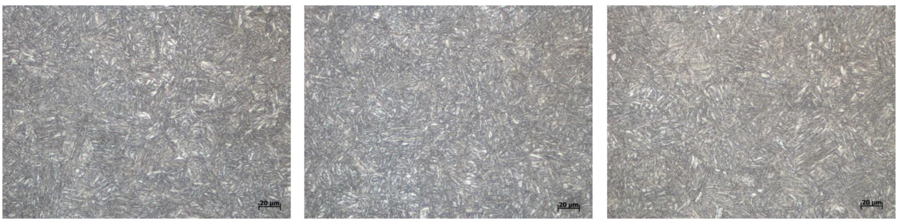
Sample no.	Depth of decarburized layer/mm Center of railhead tread	Railhead fillet
1$^{\#}$	0.025	0.028
2$^{\#}$	0.030	0.032
3$^{\#}$	0.040	0.045

Source(s): Author's own work

Table 3. Rating results and standards of nonmetallic inclusions of 60 kg·m^{-1} bainite rail

Sample no. and standard names	Category/grade of nonmetallic inclusion A		B		C		D	
	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
1$^{\#}$	1.0	0	1.0	0	1.0	0	0.5	0
2$^{\#}$	1.5	0	1.0	0	0.5	0	0.5	0
3$^{\#}$	1.0	0	1.5	0	0.5	0	0.5	0
TB/T 2344-2012	≤2.5	≤2.5	≤1.5	≤1.5	≤1.5	≤1.5	≤1.5	≤1.5

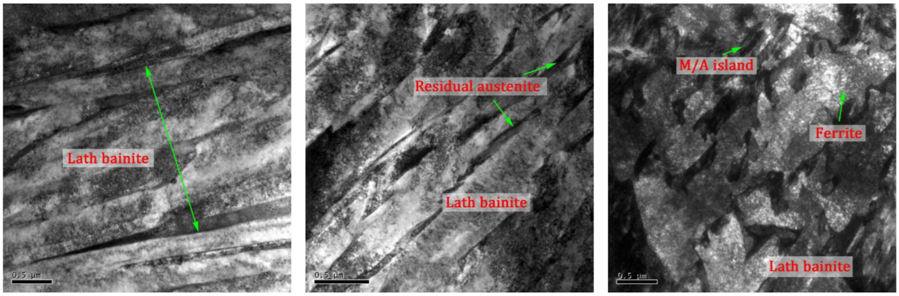
Source(s): Author's own work



1# sample (a) 2# sample (b) 3# sample (c)

Source(s): Authors own work

Figure 1. Metallographic structure of 60 kg·m^{-1} bainite rail (500× magnification)



Carbide-free lath bainite
(a)

Carbide-free lath bainite + residual austenite
(b)

M/A structure + ferrite + carbide-free lath bainite
(c)

Source(s): Authors own work

Figure 2. TEM structural morphology of 1# sample

the 60 kg·m^{-1} bainite rail is composed of carbide-free lath bainite, plate-like ferrite, a few of residual austenite and M/A islands (island-shaped parts surrounded by lath ferrite, and composed of residual austenite and high-carbon martensite); the residual austenite is distributed between the laths of lath ferrite; the volume fraction of carbide-free lath bainite is more than 85%, meeting the requirements for the matrix structure of bainite rail.

2.3 Property of base metal of bainite rail

The base metal of 60 kg·m^{-1} bainite rail was sampled for testing its regular and special properties according to the sampling requirements of TB/T 2344-2012. The regular properties include the hardness and tensile property of railhead tread, while the special properties include residual stress, fracture toughness, crack growth rate and sample fatigue life. The test results are shown in Tables 4–6, respectively. It can be seen from Tables 4–6 that the hardness and tensile property of the bainite rail tread are stable and reach a high level, and the elongation after fracture is more than 12.5%; the residual stress and fatigue crack growth rate are good; and in particular, the fracture toughness index at −20°C reaches a high level, resulting in an excellent strength-toughness balance and plasticity index, meeting the technical requirements.

3. Microstructure and property of welded joint

The flash welding test of 60 kg·m^{-1} bainite rail was carried out with GASS80/580 welder in a rail welding base. According to the characteristics of bainite rail such as high content of alloy elements, high thermal strength and poor thermal conductivity, an optimal welding scheme was determined, and the drop weight test and static bending test for the welded joint were carried out after welding. According to the quality requirements for welded joints in the

Table 4. Hardness of railhead tread of bainite rail

Rail specifications and technical requirements	Brinell hardness/HBW Measuring point value										Average
60 kg·m^{-1}	385	384	386	385	384	385	384	386	386	385	385
Technical requirements	360~430										

Source(s): Author's own work

Rail specifications and technical requirements	Sampling position	Yield strength, $R_{P0.2}$/MPa	Tensile strength, R_m/MPa	Elongation after fracture, A/%	Reduction of area, Z/%
60 kg·m^{-1}	Center of 1/2 railhead	1 160	1 300	13.0	50.0
	Center of 1/2 railhead	1 150	1 300	12.5	51.0
	Center of railhead	1 110	1 280	13.0	43.0
	Rail web	1 140	1 260	12.5	50.5
	Rail base center	1 170	1 320	12.5	52.0
Technical requirements		Railhead $R_m \geq$ 1 250 MPa			

Source(s): Author's own work

Table 5.
Tensile property of bainite rail

Rail specifications and technical requirements	Residual stress at rail base/MPa	Fracture toughness at −20°C/ (MPa·m$^{1/2}$)		Crack growth rate in case of different stress intensity factors/ (μm·cycle^{-1})		Fatigue life of sample /(10,000 rounds)
		Min.	Average	10.0 MPa·m$^{1/2}$	13.5 MPa·m$^{1/2}$	
60 kg·m^{-1}	295.8	47.2	51.9	10.6	22.2	500
Technical requirements	≤330	≥35	≥40	≤15	≤50	500

Source(s): Author's own work

Table 6.
Special property of bainite rail

Rail Welding – Part 2: Flash Welding (TB/T 1632.2-2014), 25 consecutive tested welded joints passed the falling weight impact test, in which no breaking of welded joint was found for two blows from a drop height of 3.1 m; and 15 consecutive tested welded joints passed the static bending test, in which no welded joint was broken when the compression test load of the railhead reached 2,300 kN or the tensile test load of the railhead reached 2,000 kN; no welded joint was broken under the fatigue test condition of the minimum bending fatigue load of 95 kN, the maximum load of 470 kN and the offset of 1 m after 2 million rounds. The results show that bainite rail passed the falling weight impact test and static bending test with excellent performance.

The tensile property, impact property, hardness and metallographic structure of the welded joint of 60 kg·m^{-1} bainite rail were tested according to the *Rail Welding – Part 1: General Technical Conditions* (TB/T 1632.1-2014); the hardness test mainly includes the tread hardness test of the welded joint and the hardness test of the longitudinal section. See Table 7

Rail specifications and technical requirements	*Average* R_m/MPa	*Average* $R_{P0.2}$/MPa	*Average* A/%	Average of impact absorbing energy, A_{ku}/J
60 kg·m^{-1}	1 255	1 004	7.1	35.9
Technical requirements	≥1 080	≥800	≥6.0	≥30.0

Source(s): Author's own work

Table 7.
Tensile property of welded joint of bainite rail

for the test results of tensile and impact properties; Table 8 for the test results of the tread hardness and longitudinal section hardness, and Figure 3 for their distribution; Figure 4 for the metallographic structure test.

According to the results of welding test, the welded joint of bainite rail has good tensile stability, good strength-plasticity balance and high impact energy absorbing capability at room temperature. In terms of the hardness distribution, the hardness of the flash welding joint of bainite rail conforms to $1.10H_P \geq H_J \geq 0.85H_P$ and $H_{J1} \geq 0.8H_P$ specified in the *Rail Welding – Part 2: Flash Welding* (TB/T 1632.2-2014). In terms of the metallographic structure, the structure of the flash welding joint of bainite rail is composed of carbide-free bainite and very few granular ferrite, meeting the requirements of the metallographic structure.

Rail specifications and technical requirements	Position	Average hardness of base metal, H_P	Average joint hardness, H_J	Average hardness of soft spot, H_{J1}	H_J/H_p	H_{J1}/H_p	Width of softening zone, w/mm Left	Right
60 $kg \cdot m^{-1}$	Longitudinal section	40.0 HRC	38.2 HRC	35.0 HRC	0.95	0.88	13	15
	Tread	388.5 HBW	355.0 HBW	331.0 HBW	0.91	0.85		
Technical requirements			$1.10H_P \geq H_J \geq 0.85H_P$, $H_{J1} \geq 0.8H_P$, $w \leq 20$					

Source(s): Author's own work

Table 8. Hardness of welded joint of bainite rail

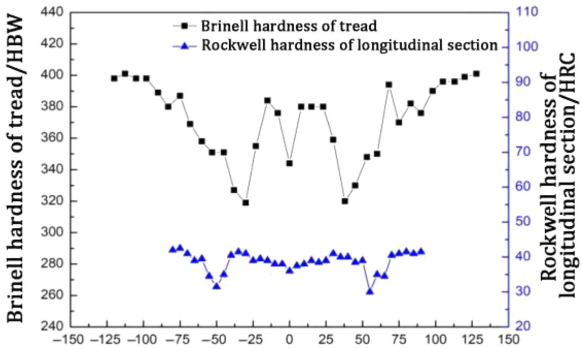


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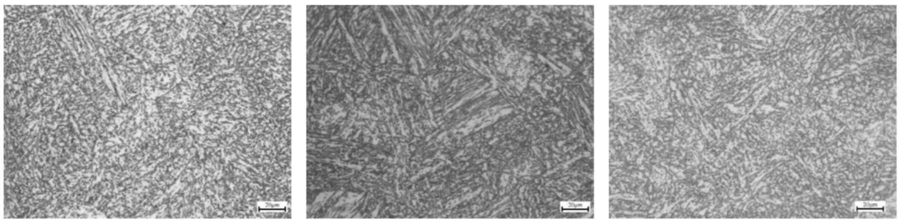
Figure 3. Hardness distribution of welded joint of 60 $kg \cdot m^{-1}$ bainite rail



Source(s): Authors own work

Figure 4. Metallographic structure of welded joint of 60 $kg \cdot m^{-1}$ bainite rail

4. Laying and service of bainite rails

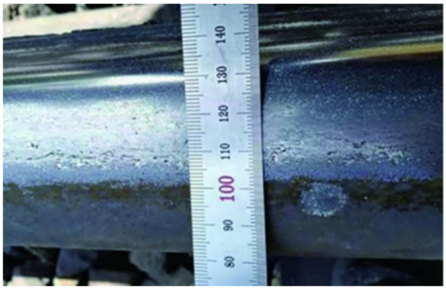
The 60 kg·m^{-1} bainite rails were laid on three track sections for trial operation: the first was a 1.66 km long curve section of the CWR up track of Shenyang–Shanhaiguan Railway under the administration of China Railway Shenyang Bureau Group Co., Ltd. for nearly 48 months, during which the gross traffic tonnage was nearly 600 million tons; the second was a curve section of the up track from Harbin West Railway Station of Wanggang–Sunjia Railway with 13-month service life; and the third was a curve section of the spiral-curve up track at K496 of the border section of Harbin–Suifenhe Railway with 42-month service life. The 60 kg·m^{-1} bainite rails were made into more than 6,000 wing rails of frogs by Qiqihar Track Maintenance Machinery Factory under China Railway Harbin Bureau Group Co., Ltd., and those wing rails were laid for service, with a gross traffic tonnage of 300 million tons. In addition, the AT switch rails made from 60 kg·m^{-1} bainite rails passed the tests such as trial laying on track by Beijing Baoding Turnout Factory, Wuhu Turnout Factory and Beijing Nankou Turnout Factory in succession. The surface conditions of bainite rails in service are shown in Figure 5.

According to the results of tracking analysis, the 60 kg·m^{-1} bainite rails laid for trial operation show excellent wear, peeling and spalling resistance, and the service life on the same curve is more than double than that of heat-treated pearlite rails. The wing rails of frog made from 60 kg·m^{-1} bainite rails also show excellent wear, peeling and spalling resistance, and good comprehensive service performance. The AT switch rails made from 60 kg·m^{-1}

Curve section of the up track from Harbin West Railway Station of Wanggang-Sunjia Railway

(a)

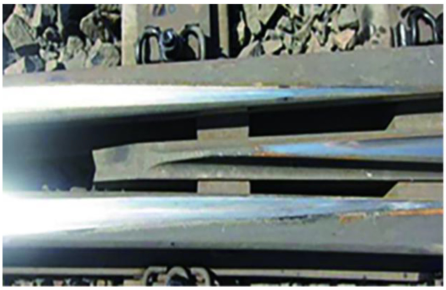
(After 13 months of service, the surface is smooth and free of peeling or spalling)



Curve section of the spiral-curve upper track at K496 of the border section of Harbin-Suifenhe Railway

(b)

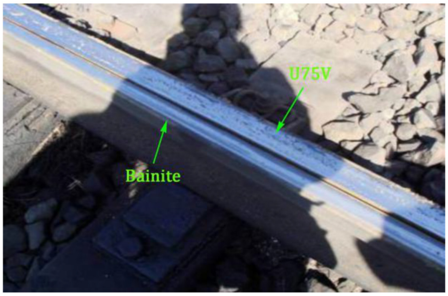
(After 42 months of service, the surface is smooth and free of peeling or spalling)



Bainitic wing rail of frog

(c)

(After 36 months of service, the surface is smooth and the wear is only about 3 mm)



Bainitic switch rail vs U75V switch rail

(d)

(Service life 1.75 times longer)

Source(s): Authors own work

Figure 5.
Surface conditions of bainite rails in different sections in service

bainite rails show outstanding wear resistance, and the service life is 3–4 times longer than that of U75V switch rails. It can be seen that 60 $kg \cdot m^{-1}$ bainite rail shows high strength, high toughness and high wear resistance in service, and has good comprehensive service performance, so that it is more suitable for laying and application of heavy-haul railway.

5. Analysis and discussion

5.1 Strength and toughness of bainite rail

Caballero, Bhadeshia, Mawella, Jones, and Brown (2001) and Bhadeshia and Edmonds (1983) suggested that for the research of high-strength and high-toughness bainite steel, a system design with appropriate alloy composition is the key to obtain the fine bainite structure. In the process of the research, in order to make the 60 $kg \cdot m^{-1}$ bainite rail embody high strength and high toughness, the C-Si-Mn-Mo alloy system was selected in the composition design, and the microstructure was composed of a carbide-free bainite matrix (for improving the strength), a few of residual austenite and M/A islands (for improving the toughness and plasticity).

Shen, Li, and Luan (2014) pointed out that Mn changes the shapes of the continuous and isothermal transformation curves of austenite when reaching a certain content, and reduces the bainite's transformation temperature (Bs point), so that austenite is transformed into bainite with good strength and toughness in the air-cooled state. The lower Bs point leads to inevitable existence of M/A islands in the bainite and can provide some plasticity. Si can inhibit the precipitation of cementite during austenite transformation, increase the stability of residual austenite and result in a carbide-free bainite structure to improve the strength and toughness of the rail. The addition of Mo can reduce or avoid the appearance of grain-like ferrite in the flash welding process on the basis of grain refinement, so as to improve the stability of welding structure and welding property.

5.2 Wear resistance of bainite rail

Huang, Fang, and Zheng (2003) found that two-thirds of the bainite strength came from the refinement of laths, and the rest from dislocation strengthening, matrix lattice strengthening and solid solution strengthening. For a 60 $kg \cdot m^{-1}$ bainite rail, due to the large deformation rolling and Si, the microstructure of bainite steel has many fine subunits (Xu, Zhou, Chen, Zhang, & Zhou, 2012) (see Figure 3c), and the carbide-free bainite laths are developed, with a large aspect ratio and a close arrangement between laths (see Figure 3a and b). The fine-grain strengthening and toughening effects are obvious, which significantly improves the wear resistance. In addition, the residual austenite can coordinate the deformation resistance, easily relieve the stress concentration in the microstructure, absorb certain impact energy and passivate the fatigue crack tip, so as to greatly improve the toughness and enhance the peeling and spalling resistance. Moreover, after large rolling deformation, a large number of dislocations are generated inside the lath bainite during bainite transformation (see Figure 3), further refining the grains. At the same time, the interaction between dislocations and deformation resistance as well as the cutting between dislocations increase the deformation resistance, which enhances the dislocation pileup and density, significantly improving the hardness, strength and wear resistance of bainite rail.

6. Conclusions

(1) The base metal of 60 $kg \cdot m^{-1}$ bainite rail has a uniform microstructure, with carbide-free bainite matrix, a few of stable residual austenite and M/A islands.

(2) The base metal of 60 $kg \cdot m^{-1}$ bainite rail has good strength-toughness balance, high hardness and good wear resistance.

(3) The stationary flash welded joint of 60 $kg \cdot m^{-1}$ bainite rail has a good microstructure and high performance, and there was basically no serious damage during the trial operation.

(4) A 60 $kg \cdot m^{-1}$ bainite rail laid in a curve section of heavy-haul railway is able to serve for 48 months with a gross traffic tonnage of nearly 600 million tons, which shows that its service life is more than one time longer than that of pearlite rail; the service life of the wing rail of frog or switch rail for turnout with bainite rails is 3–4 times longer than that with U75V rails. The bainite rails also have strong peeling and spalling resistance, and outstanding comprehensive service performance.

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