High Strength Bainitic Steel Rails for Heavy Haul Railways with Superior Damage Resistance

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NKK has developed high strength bainitic steel rails with superior flaking resistance for heavy haul railways. In this paper, rolling contact fatigue and wear behavior in bainitic and pearlitic rail steels with various tensile strengths were studied. Emphasis was placed on examining the formation behavior of the WEL(White Etching Layer) in bainitic and pearlitic steels, and its effect on flaking resistance. Advantages of the newly developed high-strength bainitic steel with superior flaking resistance, good wear resistance and excellent weldability have been also discussed.

1. Introduction

In North America, railways play a very important role in freight transportation of minerals and crops. In recent years, increased loads per freight car, increased speed, and longer freight trains have caused increasing demand for the efficiency of freight transportation. So, what is called the “mile train”, with a formation of more than one hundred freight cars in a train, intersects the land like cobwebs. In addition, the axle load (**Footnote 1**) on rail has exceeded 35 tons. The increase in the axle load induces degradation of rail life. This leads a strong demand from overseas heavy haul railways for the development of rails that have superior wear resistance and rolling contact fatigue resistance.

As for the rolling contact fatigue that appears on the surface of rails, flaking occurs particularly near the center of the head portion of inner rail of curved track section and becomes a dominant factor determining the service life of rails. **Photo 1** shows an example of flaking. On the inner rail of curved section of track, the running direction of the wheel and the tangential direction of the rail do not agree with each other, thus a lateral force is induced generating significant sideslip of the wheel. The sideslip is identified as one of the causes of flaking on the rail.

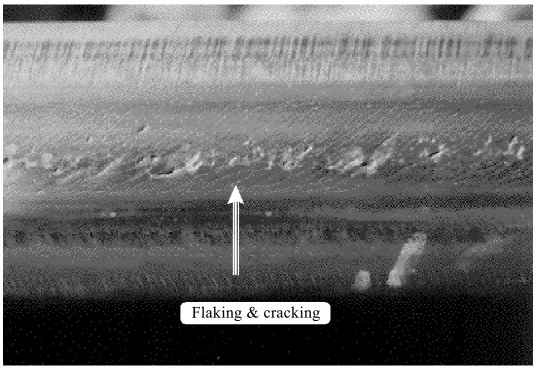

Photo 1 Appearance of flaking

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Footnote 1, Axle load: Load applied to a single axle.

NKK developed a heat-treated pearlite rail Series THH370 (1300 MPa class of tensile strength), which has 0.2 μ m or less distance between pearlite layers (interlamellar spacing) controlled by on-line heat treatment for services of overseas heavy haul railways. The developed THH370 Series has received high evaluation from users. The improvement in characteristics of the pearlitic steel rails is achieved mainly by narrowing the distance between pearlite layers. Since, however, the refined interlamellar spacing achieved in THH370 Series is already close to the theoretical limit[1)], the pearlitic steel rails are probably nearing their limit of development[2)–4)] .

As a next generation of rails, the bainitic steel rails have attracted a great deal of attention. With a specific alloy design, the bainitic steel rails attain strength beyond that of heat-treated pearlitic steel rails. Accordingly, the bainitic steel rails have a potential to provide unique characteristics different from those expected in the development of conventional pearlitic steel rails.

General phenomena observed from the comparison of characteristics of bainitic steel rails and pearlitic steel rails are summarized below.

(1) Generally, pearlitic steel rails have superior wear resistance to bainitic steel rails[2), 4)–8)].

(2) Bainitic steel rails have higher fatigue strength than pearlitic steel rails[8), 9)].

(3) Bainitic steel rails have fracture toughness (K_{IC}) almost double that of pearlitic steel rails[8)].

(4) No significant difference in fatigue crack propagation behavior appears between bainitic steel rails and pearlitic steel rails[8)].

The above-described phenomena suggest that, regarding the generation of rolling contact fatigue such as flaking and fracture, bainitic steel rails have material characteristics equivalent to or better than those of pearlitic steel rails. Consequently, improvement of wear resistance should make the bainitic steel rails the long service life rails having excellent wear resistance and rolling contact fatigue resistance.

In this paper, flaking and wear behavior in bainitic and pearlitic steels with various tensile strengths have been evaluated by lab-scale rolling contact fatigue and wear tests. Emphasis was placed on comparatively examining the formation behavior of the WEL(White Etching Layer) (**Footnote 2**) both in bainitic and pearlitic steels. Subsequently, the mechanical characteristics and the welded joint characteristics were introduced for high strength bainitic steel rails developed upon the above-given basic findings. The rolling contact fatigue resistance was also evaluated for the developed rails determined using a rolling contact testing apparatus which was developed by NKK to reproduce the actual contact conditions at curved section of rail tracks.

2. Experimental method

2.1 Tested steels

Table 1 shows the chemical composition of the sample steels. As for the bainitic steel, the carbon content was varied in a range from 0.20–0.55 wt%, and the tensile strength was varied in a range from 810–1430 MPa by adjusting the addition of alloying elements such as Cr, Mo, and Nb. About 50 kg of bainitic steel was prepared by melting in a laboratory scale furnace, which was then heated to 1250℃. The prepared ingot was hot-rolled under a rolling condition (980℃ finish temperature)simulating actual rolling to form a steel plate of 12 mm in thickness. Specimens were prepared by cutting from the steel plate.

For the pearlitic steel, specimens were prepared by cutting from commercially manufactured rails which were varied in the tensile strength in a range from 900–1300 MPa by adjusting the contents of alloying ingredients and the cooling speed after hot-rolling.

2.2 Test method

2.2.1 Rolling contact fatigue test

Fig. 1(a) shows a schematic drawing of a specimen used to evaluate the rolling contact fatigue resistance. A rail disk having a curvature on the surface contacting with a wheel (370 of Vickers hardness (Hv)) was

Table 1 Ranges of chemical composition of steels studied

(wt%)

Steel	C	Si	Mn	Cr	Mo	Nb	V
Bainitic	0.20/0.55	0.40/0.45	0.40/2.10	0/2.0	0/2.0	0/0.15	0/0.10
Pearlitic	0.65/0.80	0.25/0.95	0.75/1.45	0/0.50	0	0	0/0.10

Footnote 2, WEL (White Etching Layer) is understood as a martensitic phase generated from friction between wheel and rail. The WEL is considered as an origin of rolling contact fatigue[10)].

rolled to contact each other. The contact load and slip ratio were 980 N (2.8 GPa of contact pressure) and –20% (**Footnote 3**) under a condition of oil-lubrication, and 490 N(2.2 GPa of contact pressure) and –10% under a condition of water-lubrication. The rotational speed of the wheel was 800 rpm. The contact pressure applied in the test was significantly higher than the condition (about 1.25 GPa of contact pressure) that actually induces flaking on the inside rail of curved section of tracks. Thus, the test was an accelerated test. The appearance of the contact surface was visually observed at every 30 minutes. The rolling contact fatigue life was determined as the time of occurrence of rolling contact fatigue damage.

2.2.2 Behavior of WEL (White Etching Layer) formation

Fig. 1(b) shows an illustration of test method relating to the formation behavior of WEL. A pin type rail specimen of 6 mm in diameter and 15 mm in length was brought to contact with a wheel rotating at 800 rpm under the condition of 1470 N of contact load for 3 seconds in a dry state. After grinding the longitudinal cross section of the rail specimen, the ground surface was etched by nital. The white etched layer generated near the contact face was examined using a light-microscope.

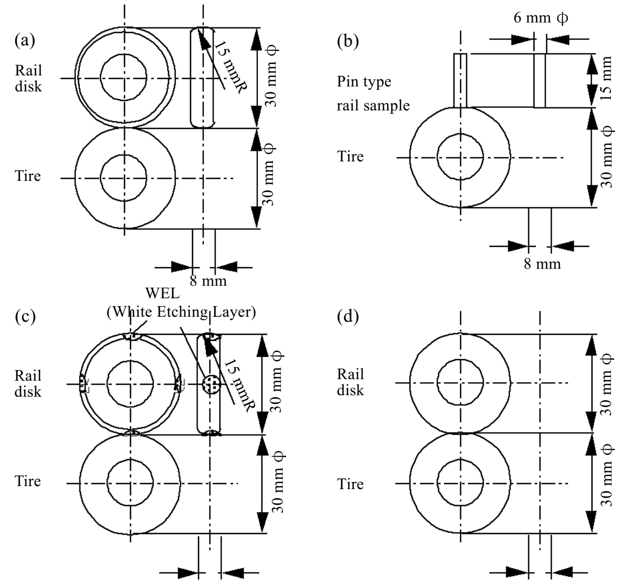

Fig. 1 Schematics showing of testing configuration;
(a) Flaking test (b) WEL formation test
(c) Flaking test using samples with WEL
(d) Wear test

2.2.3 Influence of WEL (White Etching Layer) on rolling contact fatigue damage

To validate that the WEL can become the origin of rolling contact fatigue damage, a WEL was forcefully formed on a rail disk, and the rolling contact fatigue test was carried out. **Fig. 1**(c) shows an illustration of the test method. A WEL was formed on the rail disk using TIG spot welding. Specimens were prepared, each including the WEL. The shape of each specimen was the same as given in **Fig. 1**(a). The test conditions were oil-lubrication, 980 N of contact load (2.8 GPa of contact pressure), –20% of slip ratio, and 800 rpm of rotating speed. The appearance of the contact surface was visually observed every 30 minutes. The rolling contact fatigue life was determined as the time of occurrence of surface damage.

2.2.4 Wear test

The evaluation of wear resistance was also conducted by the method of rotating a wheel in contact with a rail disk. **Fig. 1**(d) shows an illustration of the test method. Both the rail disk and the wheel had smooth contact face on every specimen. The test conditions were –10% of slip ratio, 490–2450 N of contact load, and 800 rpm of rotational speed. The mass loss caused from wear was determined at every 5 x 10^5 turns.

3. Result and discussion

3.1 Rolling contact fatigue resistance

Fig. 2 shows the influence of tensile strength on the flaking life of bainitic steel rails and pearlitic steel rails. Comparison at 1300 MPa of tensile strength showed that the bainitic steel rails gave better flaking resistance than the pearlitic steel rails under the condition of both water-lubrication and oil-lubrication. Increase in strength increased the time for generation of flaking. That is, the bainitic steel rail having 1400 MPa tensile strength showed more than twice the flaking resistance compared with the 1300 MPa class pearlitic steel rail.

Photo 2 shows the appearance of specimens after testing for 6 hours under oil-lubrication condition. The pearlitic steel rail showed distinctive rolling contact fatigue damage. However, the bainitic steel rail did not show damage on its surface. **Photo 3** shows microstructures of rail cross sections. On the pearlitic

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Footnote 3, Slip ratio: (Rotating speed of rail disk–Rotating speed of wheel) / (Rotating speed of wheel).

Ex. Slip ratio –10% means that the rail disk rotates 90 turns during the period that the wheel rotates 100 turns.

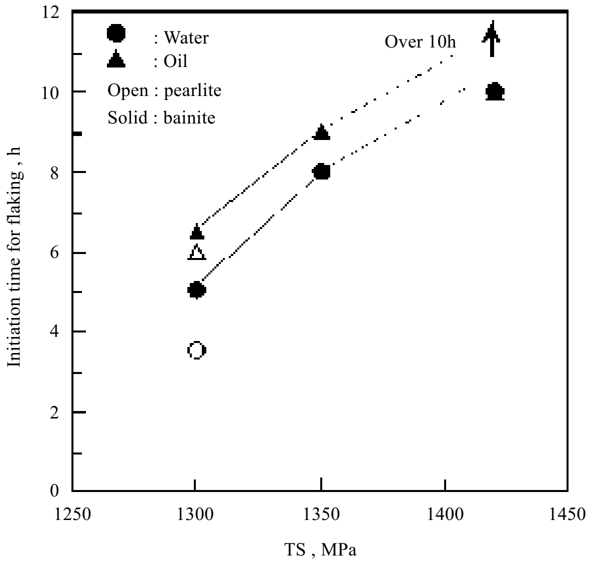

Fig. 2 Flaking resistance in bainitic and pearlitic steels

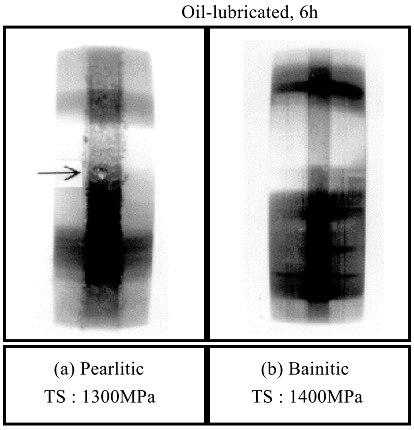

Photo 2 Appearance of samples after flaking test for 6h

steel rail, significant crack generation as well as plastic flow near the contact face was observed. However, the bainitic steel rail showed only slight plastic flow, and did not show any significant crack generation.

Consequently, the bainitic steel rails having 1400 MPa of tensile strength have a remarkably superior rolling contact fatigue resistance to the heat-treatment type pearlitic steel rails having 1300 MPa.

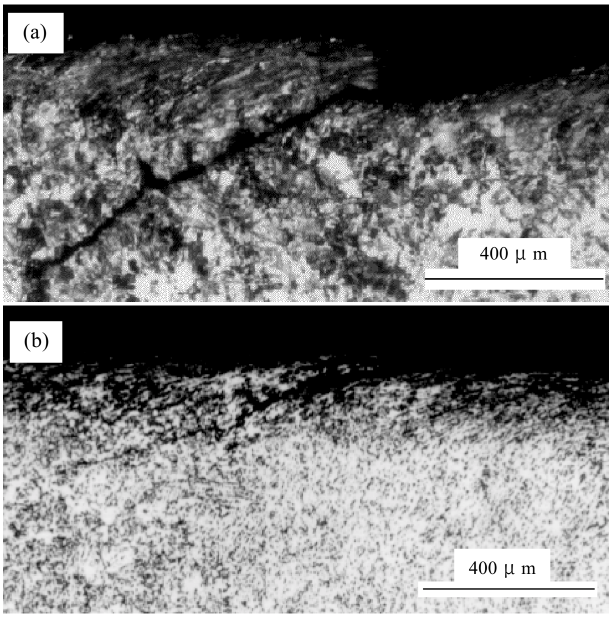

Photo 3 Cross-sectional microstructure of samples after flaking test; (a): pearlite (b): bainite

3.2 Formation behavior of WEL (White Etching Layer)

Photo 4 shows cross sectional microstructures of specimens with varied carbon content. The photographs of 0.3% C and of 0.42% C are bainitic steel rails, and the photograph of 0.65% C is pearlitic steel rail. These photographs show that the thickness of the WEL increases simply by increasing the carbon content independent of the type of structure.

As previously described, the WEL is presumably a martensitic phase requiring that the material should once be austenized. **Fig. 3** is a calculated phase diagram of Fe-0.25%Si-0.80%Mn-C system[11]. The transformation temperature (Ae_3) in equilibrium state gives the minimum eutectoid composition, which temperature increases with the decrease in the C content.

With the assumption that the temperature of the surface layer of rail rises above the transformation point due to friction with the wheel, low carbon material having a higher transformation point provides a thin-

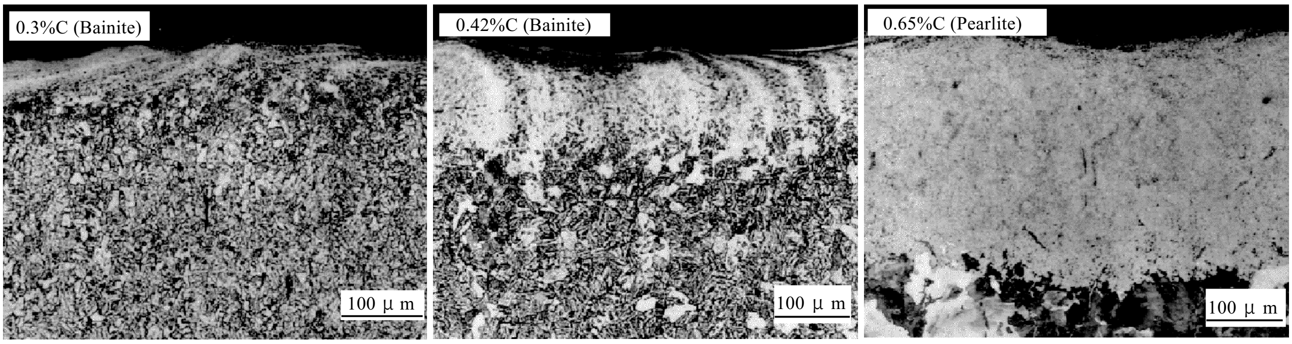

Photo 4 Cross-sectional microstructures of pin-type specimens showing variation in WEL thickness with carbon content

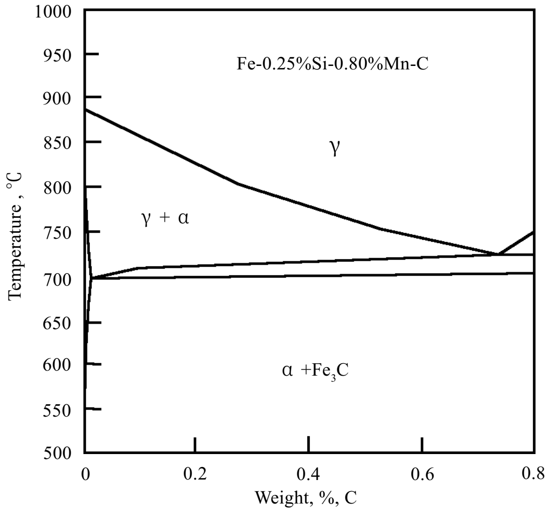

Fig. 3 Calculated phase diagram for Fe-0.25%Si-0.80%Mn-C system

ner austenized portion, (**Fig. 4**). Accordingly, a bainitic steel having less C content is presumably more difficult to form WEL, (**Photo 4**).

Furthermore, since the hardness of martensite mainly depends on the C content, the hardness of formed WEL also varies with the C content. **Fig. 5** is a graph of the hardness of WEL plotted against the C content. The figure shows the increase in the hardness of WEL along with the increase in C content.

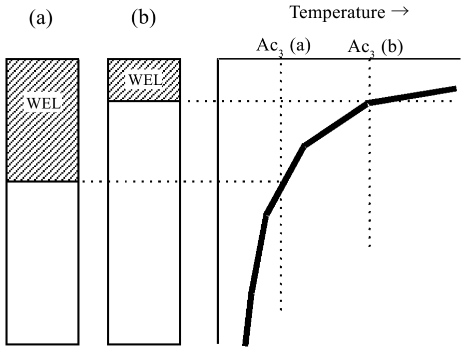

Fig. 4 Effect of Ac$_3$ temperature on thickness of WEL (a) High carbon steel, (b) Low carbon steel

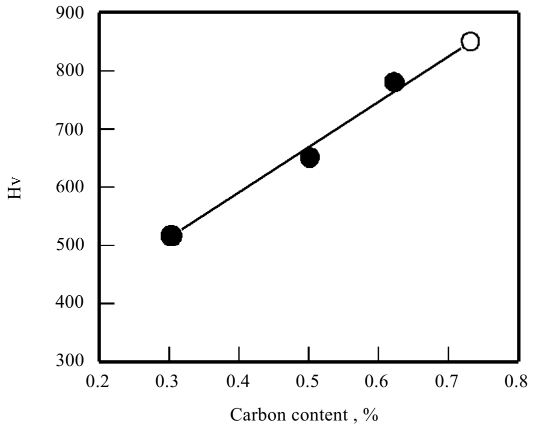

Fig. 5 Relationship between carbon content and hardness of WEL

As described above, bainitic steel rails having less C content are hard to form WEL, and, the hardness is low even when the WEL is formed. Therefore, the occurrence of rolling contact fatigue damage caused from the generation of cracks on the interface between the base material and the WEL should be suppressed.

3.3 Effect of WEL (White Etching Layer) on rolling contact fatigue

Photo 5 shows cross section macrostructure of specimens prepared from rail disks on which WEL was intentionally formed by TIG spot welding. The rolling contact fatigue test was carried out using these specimens. On the bainitic steel rail, distinct rolling contact fatigue occurred after 1.5 hours of test. On the pearlitic steel rail, however, only slight rolling contact fatigue occurred after 3.5 hours of test.

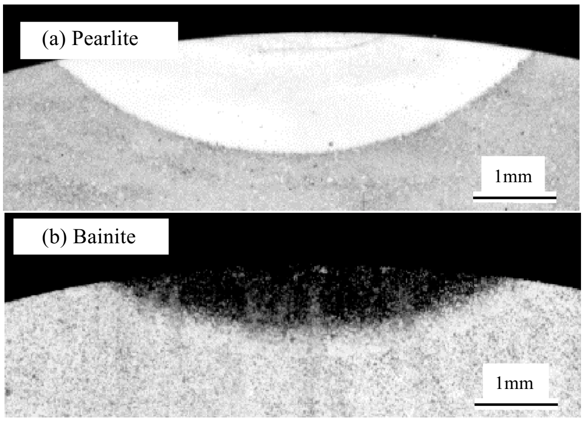

Photo 5 Macrostructures of samples before flaking test with artificially-made WEL

Photo 6 shows microstructure of cross sections at locations where rolling contact fatigue occurred. On the pearlitic steel rail, cracks occurred at the interface between the WEL and the base material and other portions, resulting separation of the WEL. In contrast, the bainitic steel rail incurred only a few cracks. Thus, it was clear that the WEL has the potential to become the origin of rolling contact fatigue. The bainitic steel rails having less expectation of forming WEL and giving low hardness are advantageous also from the viewpoint of suppressing the rolling contact fatigue caused from WEL.

3.4 Wear resistance

Fig. 6 shows the relation between the amount of wear and the tensile strength in both the pearlitic steel rail and bainitic steel rail under a contact pressure of 1.4 GPa corresponding to the condition of heavy haul railways, and with −10% of slip ratio. At the same tensile strength, the pearlitic steel rail was superior in

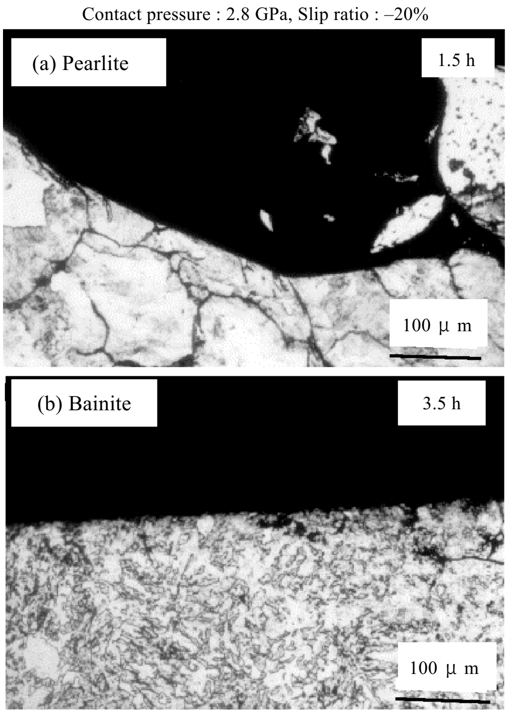

Photo 6 Microstructure of samples with WEL after flaking test

wear resistance to the bainitic steel rail. Nevertheless, the bainitic steel rail having 1400 MPa of tensile strength gave almost equal wear resistance to that of the heat-treated pearlitic steel rail having 1300 MPa of tensile strength.

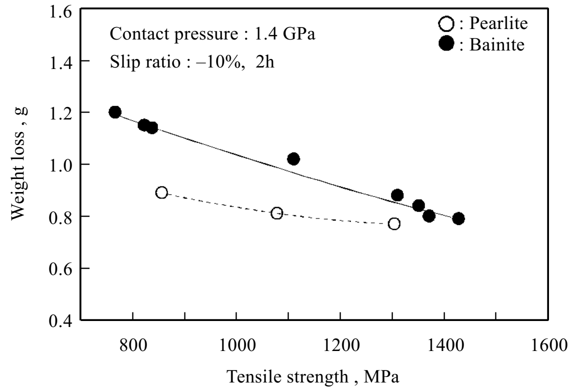

Fig. 6 Relationship between tensile strength and wear

4. Characteristics of materials manufactured by commercial apparatus

Based on the fundamental findings described above, an alloy design was conducted on the steel for high strength bainitic steel rails that have wear resistance equivalent to that of the heat treated pearlitic steel rails with at least twice the resistance to rolling contact fatigue than the heat-treated pearlitic steel rails. The steel was rolled in a commercial apparatus to manufacture rails. **Table 2** shows comparison with the heat-treated pearlitic steel rail in terms of mechanical test values at head portion of the rail. For both the tensile and the fatigue strength, the bainitic steel rail gave higher value by 100 MPa or more compared with the pearlitic steel rail. The bainitic steel rail gave 15% or higher elongation, and showed nearly twice the level of both the rupture toughness at room temperature and the u-notch Charpy impact absorption energy compared to those of pearlitic steel rail. The wear resistance is almost equal with that of pearlitic steel rail.

Fig. 7 shows the bending characteristics of flush butt-welded joints. Three kinds of joints were prepared: bainitic steel rail / bainitic steel rail; bainitic steel rail / pearlitic steel rail; and pearlitic steel rail / pearlitic steel rail. A load was applied to the head portion using a three-point bending device, and the deflection and rupture stress were determined until the

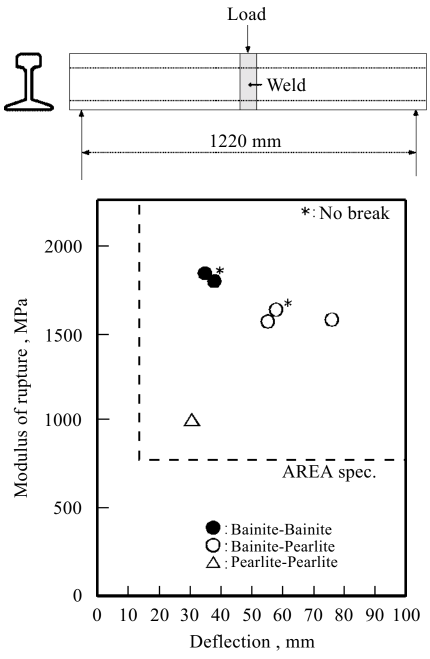

Fig. 7 Bending test results for flush-butt welded joints with developed bainitic steel rail

Table 2 Typical mechanical properties of developed bainitic steel rail

	Tensile strength (MPa)	Tensile elongation (%)	K_{IC} (MPa $\sqrt{}$ m)	Absorbed energy in the u-notch charpy test (20°C) (J)	Fatigue strength (MPa)	The amount of wear* (g/2h)
The developed bainitic steel rail	1420	15.5	98	39	870	0.77
The premium pearlitic steel rail	1300	13.5	43	20	750	0.76

* Evaluated by the test method described in the present paper

joint ruptured. Both joints of bainitic steel rail / bainitic steel rail and bainitic steel rail / pearlitic steel rail showed characteristics that fully satisfy the AREMA Standard, (**Footnote 4**).

Separately, a bloom prepared from a commercial apparatus was rolled in the laboratory. The prepared rolled steel was evaluated for its rolling contact fatigue resistance using a new type rolling contact fatigue test machine developed by the Research Laboratories of NKK.

As described in Chapter **1**, the wheel running direction differs from the tangential direction of the inner rail of curved section of track, (the angle between these directions is signified as "attack angle"), which is a main cause of flaking. The new type of rolling contact fatigue test machine can control the attack angle. **Photo 7** shows the appearance of the test machine.

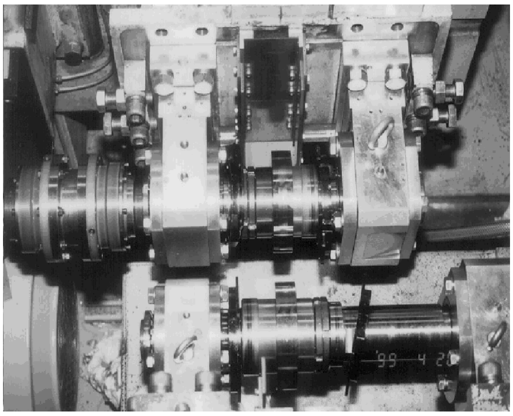

Photo 7 Appearance of newly developed rolling contact fatigue test machine

Fig. 8 shows the relation between the attack angle and the initiation time for flaking for both bainitic steel rail and pearlitic steel rail. With the increase in the attack angle, the initiation time for flaking decreases. Under all conditions tested, however, the bainitic steel rail gave at least twice the time for flaking than the pearlitic steel rail. The test conditions cover the conditions corresponding to the inner rail of curved track, where flaking is expected to be generated. Thus, the high strength bainitic steel rails are expected to assure excellent performance in actual railroads.

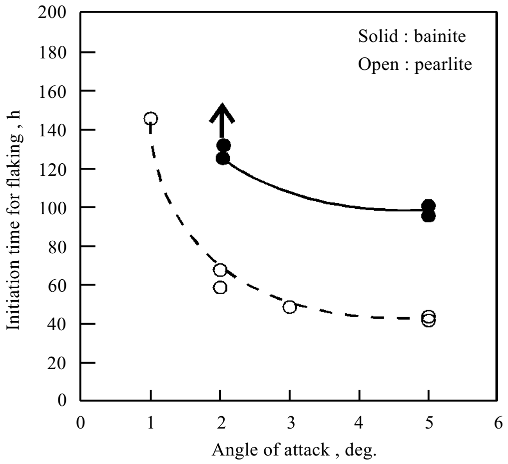

Fig. 8 Effect of angle of attack on flaking in bainite and pearlite

5. Conclusions

A high strength bainitic steel rail that has excellent resistance to rolling contact fatigue and favorable wear resistance which are required for the rails of high haul railways was developed.

Regarding the characteristics of rolling contact fatigue resistance and wear resistance, the heat-treated pearlitic steel rail and the bainitic steel rail were primarily compared, with the following conclusions obtained.

(1) Comparison at a tensile strength level of 1300 MPa shows slightly better characteristics of rolling contact fatigue resistance for the bainitic steel rails than for the heat-treated pearlitic steel rails. The bainitic steel rail having 1400 MPa tensile strength gives at least twice the resistance to rolling contact fatigue than the heat-treated pearlitic steel rail having 1300 MPa of tensile strength.

(2) On the bainitic steel rails, the WEL which is understood as an origin of rolling contact fatigue damage is difficult to generate. The reason is presumably that the austenizing temperature during heating is high due to the low C content. Thus, only a very limited zone in the vicinity of contact face with wheel are austenized, which becomes the WEL (martensitic layer) by the succeeding rapid cooling.

(3) The WEL formed in the bainitic steel rails has low hardness with a small difference in hardness compared to the base material. The reason is that the hardness of the martensitic layer mainly depends on the C content. A rolling contact fatigue test was conducted using a rail disk on which the WEL was formed by TIG spot welding. In the pearlitic steel rail, rolling contact fatigue damage accompanied by crack generation at the

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Footnote 4, AREMA is abbreviation of "American Railway Engineering & Maintenance of Way Association", an American association relating to railway.

interface between the WEL and the base material occurred in a short time. In contrast, the bainitic steel rail showed at least twice the initiation time for flaking than that of the pearlitic steel rail.

(4) At the same level of tensile strength the pearlitic steel rails generally have better wear resistance than the bainitic steel rails. Nevertheless, the bainitic steel rail which was strengthened to 1400 MPa tensile strength gives equivalent wear resistance to that of the heat-treated pearlitic steel rail having 1300 MPa of tensile strength.

On the basis of the above-described findings, an alloy design was given to the bainitic steel rail of 1400 MPa class of tensile strength, and the steel was rolled in a commercial apparatus to prepare rails. The developed bainitic steel rails showed superior characteristics as described below.

(1) The bainitic steel rail showed higher values of yield strength, tensile strength, fatigue strength, elongation, rupture toughness at room temperature, and u-notch Charpy impact absorbed energy, compared to the heat-treated pearlitic steel rails. The wear resistance was similar in both rails.

(2) Flush butt-welded joint characteristics were also in very good condition.

(3) With a rolling contact fatigue-testing machine that can control the attack angle, the influence of attack angle on rolling contact fatigue life was investigated. Increase in the attack angle shortened the initiation time for flaking. Within the tested range, however, the bainitic steel rails showed at least twice the rolling contact fatigue life than that of the heat-treated pearlitic steel rails.

The developed high strength bainitic steel rail has at least twice the rolling contact fatigue characteristics and almost equal wear resistance to those of the heat-treated pearlitic rail, thus the developed high strength bainitic steel rail is expected to provide excellent performance in heavy haul railways.

References

1) Yamamoto Sadahiro. 161st and 162nd Nishiyama Memorial Technology Lecture Meetings. the Iron and Steel Institute of Japan(1996)
2) Sawley, K. J. et al. Railway Track & Structures. 1997–03.
3) Bramfitt, B. L. 39th Mechanical Working and Steel Processing Conference Proceedings(1998).
4) Sawley, K. J. et al. Ibid. 1007p.
5) Track Buyer’s Guide 1999. Railway Track & Structures(1999).
6) Clayton, P. et al. Wear, 200(1996).
7) Jin, N. et al. Wear, 202(1997).
8) Hofmann, C. et al. Eisenbahntechnische Rundschau, 38(1989).
9) Yokoyama, H. et al. in ref.4), 1023.
10) Dikshit, V. et al. Wear, 144(1991).
11) B. Sundman, B. Jansson and J. O. Andersson. CALPHAD 9(1985).