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# Development of SP3 Rail with High Wear Resistance and Rolling Contact Fatigue Resistance for Heavy Haul Railways†

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***Abstract:***

*JFE Steel has developed high performance pearlitic steel rail (SP3) with excellent wear resistance and rolling contact fatigue (RCF) resistance for heavy haul railways. To obtain excellent wear and RCF resistances, SP3 rail was manufactured by the suitable alloy design and optimum production conditions including the thermo-mechanical controlled process (TMCP). The lamellar spacing of SP3 was extremely fine of 0.07 μm near the rail surface, with the surface hardness of 420 in Brinel scale (HB420) or higher. In addition, SP3 showed high hardness over HB370 even at 1-inch depth (25.4 mm-depth) from the rail head surface. The excellent wear and RCF resistances of SP3 have been demonstrated by the actual performance tests at heavy haul railway in North America. At approximate 100 mgt from the installation, SP3 showed 10% better wear resistance comparing with the conventional HB390 grade heat treatment rail at the test, without showing any fatigue damage on the rail head surface, such as flaking and shelling.*

## 1. Introduction

Accompanying the economic growth the emerging nations of China, Brazil, and Russia, logistics is expanding at the global scale. In these circumstances, the importance of railroad transportation is being reviewed, as railroad transportation was established at an early date as a means of transporting passengers and freight in large volume with high efficiency.

Railroad transportation can be broadly divided into freight transportation and passenger transportation. From the viewpoint of realizing further improvements in efficiency in freight transportation, adoption of heavier loading capacities ("heavy haul") and larger freight cars is progressing. In particular, the transcontinental railroads in North America may be mentioned as typical freight transportation routes. The loading capacity on these routes is several times heavier than that in Japan. This increasingly severe transportation environment is the same on railroads used to transport mining products in countries such as Australia, Brazil, etc. On the other hand, in Japan, where passenger service is the main function of railroads, rail companies attach greater priority to high speed.

As a result of these increasingly difficult transportation environments, the condition of rolling contact between rolling stock wheels and rails has also become more severe. Increased rail wear and increased fatigue damage in the form of shelling, flaking, etc. require more frequent rail exchanges and impose heavier maintenance loads. JFE Steel had previously developed a high performance heat-treated rail (Super Pearlite rail: SP rail) utilizing alloy design and thermo-mechanical controlled process (TMCP)[1,2]. In order to respond to demand for rails with even higher wear resistance and improved fatigue damage properties, the company recently developed a new high wear resistance and rolling contact fatigue (RCF) resistance rail (SP3), in which

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high hardness is achieved by also refining the pearlite lamellar microstructure to its ultimate limit. This new rail has already been laid on heavy freight railroads in North America, where it is demonstrating excellent performance. This paper describes the microstructure control guideline and basic properties of the developed SP3 rail.

## 2. Basic Design for Improvement of Rail Wear Resistance and RCF Resistance

### 2.1 Effects of Hardness and Microstructure on Wear Resistance

**Figure 1** shows the relationship between the hardness and wear resistance of pearlitic steel. The y-axis shows the weight loss due to wear in a two cylinder type wear test (Nishihara type wear test). Smaller numbers indicate higher wear resistance. Wear resistance improves as the hardness of the steel increases. Furthermore, wear resistance also depends on the microstructure of the steel, improving in the order of bainite, tempered martensite, and pearlite[3]. **Photo 1** shows cross-sectional microstructures of the surface layer of two pearlitic steels after wear tests. Because the plastic deformation of the surface layer becomes shallower with increasing hardness, higher hardness can be judged to be effective for reducing fatigue damage of rail surface.

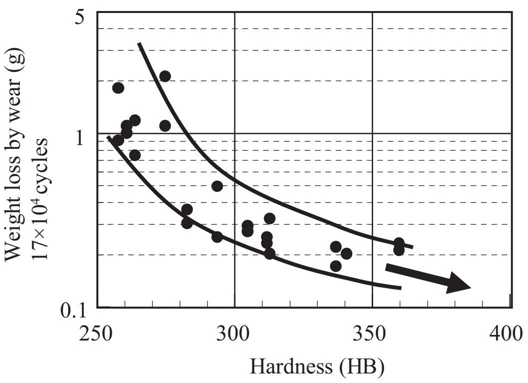
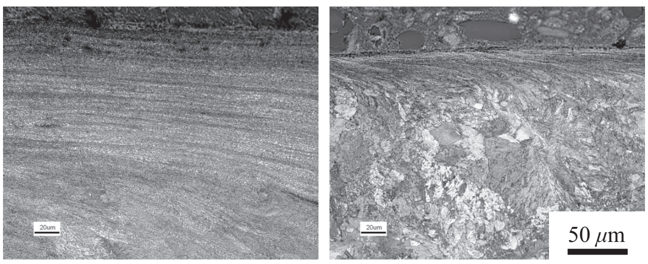



Fig. 1 Relationships between hardness and wear resistance




(a) HB275 (b) HB337

Photo 1 Cross sectional microstructures near wear surface after the wear tests (Hardness (HB) of sample: (a) HB275 and (b) HB337)

### 2.2 Refinement of Pearlite Lamellar Spacing

Pearlite has a layer structure (lamellar structure) consisting of sheet-like layers of ferrite and cementite. High hardness can be achieved by refinement of this lamellar structure[4,5]. Volumetric free energy decreases when pearlite is formed from austenite. However, the increase in interfacial energy for forming ferrite/cementite interfaces becomes larger with increasing refinement of the lamellar spacing. Consequently, there is a limit to the refinement of the lamellar structure. The limit of the fine lamellar spacing which can be obtained industrially is considered to be 0.05 $\mu$m[6].

Because the energy available for ferrite/cementite interfacial energy depends on the magnitude of the driving force of the pearlite transformation, the magnitude of the chemical driving force is proportional to the super cooling temperature ($\Delta T$) from the equilibrium transformation temperature ($T_E$) of pearlite. This means that increased refinement of the pearlite lamellar spacing is possible by increasing $\Delta T$[7]. The concept employed in maximizing $\Delta T$ is shown in **Fig. 2**. In the design of the chemical composition, the pearlite transformation temperature and $T_E$ calculated by Thermo-Calc® are

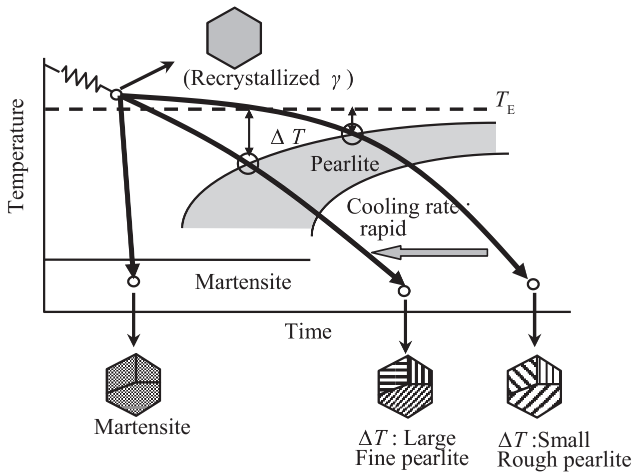
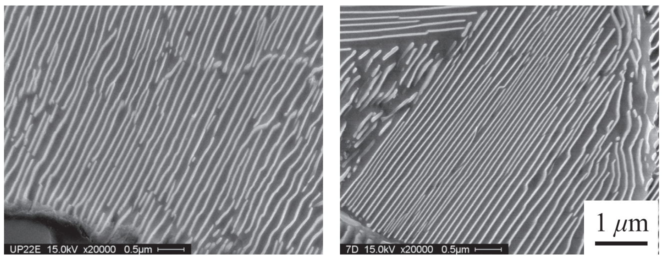



Fig. 2 Schematic illustration showing maximum super cooling ($\Delta T$) for formation of fine pearlite microstructure




(a) Conventional heat treatment rail (b) Developed rail

Photo 2 Pearlite lamellar structures of (a) Conventional heat treatment rail and (b) Developed rail obtained, and the pearlite transformation temperature is lowered by optimizing the TMCP conditions such as the cooling rate and cooling stop temperature after rolling in order to maximize $\Delta T$. As shown in **Photo 2**, a technology for stably refining the pearlite lamellar spacing of the developed rail was developed through this design of the chemical composition of the rail and optimization of the TMCP conditions.

## 3. Manufacture of High Hardness/ High Hardening Depth SP3 Rail

### 3.1 Chemical Composition and Manufacturing Process

The typical chemical composition of the developed SP3 rail is shown in **Table 1.** The carbon content is 0.81%. A design of chemical composition which maximizes $\Delta T$ was adopted in order to achieve high hardening from the rail head surface to the interior. After the converter and the RH degassing process, slabs were cast by continuous casting and then hot rolled. Following hot rolling, TMCP (heat treatment) was performed by accelerated cooling under slack quenching conditions, in which the air pressure and cooling time were optimized, and 141 lb (approximately 70 kg) rails were produced.

### 3.2 Performance of Base Material

#### 3.2.1 Microstructure and cleanliness

The typical microstructures of the developed SP3 rail are shown in **Photo 3**. The microstructure is a pearlite structure in which no formation of martensite could be observed. A comparison of the pearlite lamellar spacing of the SP3 rail and a conventional HB390 class heat-treated rail (hereinafter, "heat-treated rail") is shown in **Photo 4**. The lamellar spacing of the SP3 rail was extremely fine, being 0.07 $\mu$m at the railhead surface and 0.09 $\mu$m at the 1 inch (25.4 mm) depth. From the fact that the lamellar spacing of the conventional heat-treated rail was 0.09 $\mu$m at the railhead surface, it can be understood that the developed rail has maintained a fine, dense pearlite lamellar structure further into the interior than in the conventional rail.

**Table 2** shows the results of an investigation of the metallurgical cleanliness of the SP3 rail in accordance with the AREMA standard (AREMA: Abbreviation of American Railway Engineering and Maintenance-of-Way Association). The number of nonmetallic inclusions is sufficiently small and satisfies the AREMA standard.

Table 1 Typical chemical composition of developed SP3 rail

(mass%)

| | C | Si | Mn | P | S | Others |
|---|---|---|---|---|---|---|
| SP3 | 0.81 | 0.55 | 0.55 | 0.014 | 0.005 | Cr, V |

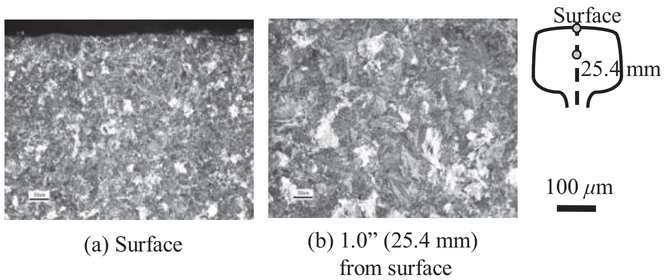



Photo 3 Microstructures of SP3 rail; (a) surface and (b) 1.0" (25.4 mm) from surface

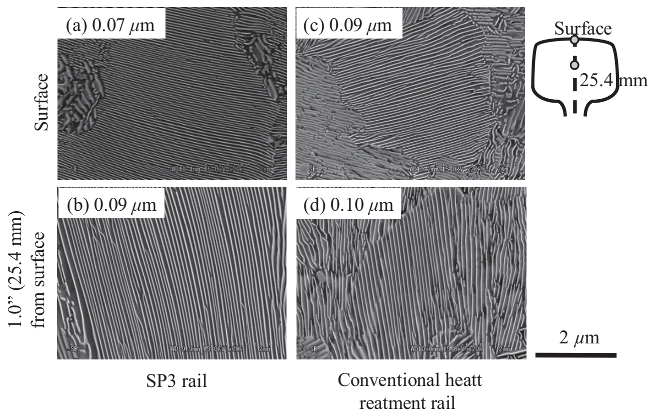



Photo 4 Pearlite lamellar structures of surface and 1.0" (25.4 mm) from surface ((a), (b): SP3 rail, and (c), (d): Conventional heat treatment rail)

Table 2 Metallurgical cleanliness test results of SP3 rail

(According to ASTM E45-Method A)

| | Type A | | Type B | | Type C | | Type D | |
|---|---|---|---|---|---|---|---|---|
| | Thin | Heavy | Thin | Heavy | Thin | Heavy | Thin | Heavy |
| Developed SP3 rail | 0.5 | 0.5 | 0 | 0 | 0.5 | 0 | 0.5 | 0 |
| Conventional heat treatment rail | 1.0 | 0.5 | 1.0 | 1.0 | 0.5 | 0 | 0.5 | 0 |
| AREMA Spec. | Average ≤ 2<br>Individual ≤ 3 | | Average ≤ 2<br>Individual ≤ 3 | | Average ≤ 2<br>Individual ≤ 3 | | Average ≤ 2<br>Individual ≤ 3 | |

A: MnS  B: Chain of $Al_2O_3$ and/or TiN  C: $SiO_2$  D: Grain of $Al_2O_3$ and/or TiN

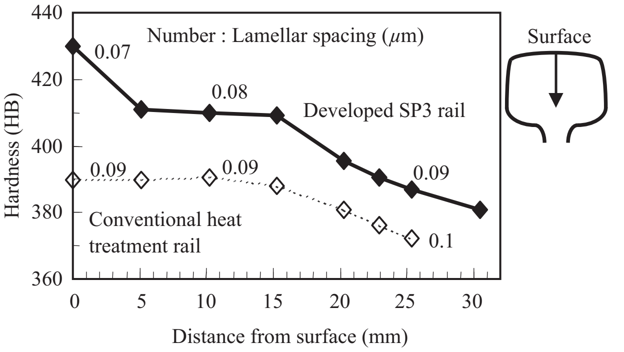



Fig. 4 Hardness distributions of SP3 rail in rail head comparing with conventional heat treatment rail

Table 3 Typical tensile properties of SP3 rail

| | 0.2% YS (MPa) | TS (MPa) | El (%) | RA (%) |
|---|---|---|---|---|
| Developed SP3 rail | 967 | 1 409 | 14 | 37 |

YS: Yield strength TS: Tensile strength
El: Elongation RA: Reduction of area

### 3.2.2 Hardness distribution and mechanical properties

The hardness distribution of the SP3 rail is shown in **Fig. 4** in comparison with that of the conventional heat-treated rail. In comparison with the conventional heat-treated rail, the hardness of the SP3 rail is HB40 points higher in the Brinel scale (HB) at the rail head surface and approximately HB20 points higher at a depth of 1 inch (25.4 mm), being HB390 or higher at the 1 inch depth. The typical tensile properties of the SP3 rail are shown in **Table 3**. The rail possesses 0.2% yield strength (0.2% YS) of 967 MPa and tensile strength (TS) of 1 409 MPa, thus realizing high strength approximately 100 MPa superior to that of the conventional heat-treated rail. In spite of the high strength achieved in the developed rail, virtually no decrease in elongation can be observed.

### 3.2.3 Wear resistance and rolling contact fatigue resistance

Next, specimens were taken from the rail head part of the developed SP3 rail and the conventional heat-treated rail, and wear resistance and rolling contact fatigue (RCF) resistance were investigated. Cylindrical wear test pieces with a diameter of 30 mm (inner diameter: 16 mm) and thickness of 8 mm were taken from the rail head surface and a depth of 0.75 inches (19.1 mm), and a wear test was performed. Quenched and tempered steel with a Vickers hardness of HV370 was used as the simulated wheel material. The wear test was performed with a Nishihara type wear test machine under conditions of contact stress: 1.5 GPa, rotational speed : 800 rpm, slip ratio: –10%, and an non-lubricated environment. The results of the test are shown in **Fig. 5**. The y-axis shows the weight change of the test pieces converted to rail wear depth (mm) per 100 million gross tons (MGT). Smaller values indicate higher wear resistance. A wear resistance improvement effect of 10% or more was confirmed with the developed rail in comparison with the conventional heat-treated rail at both the rail head surface and the interior.

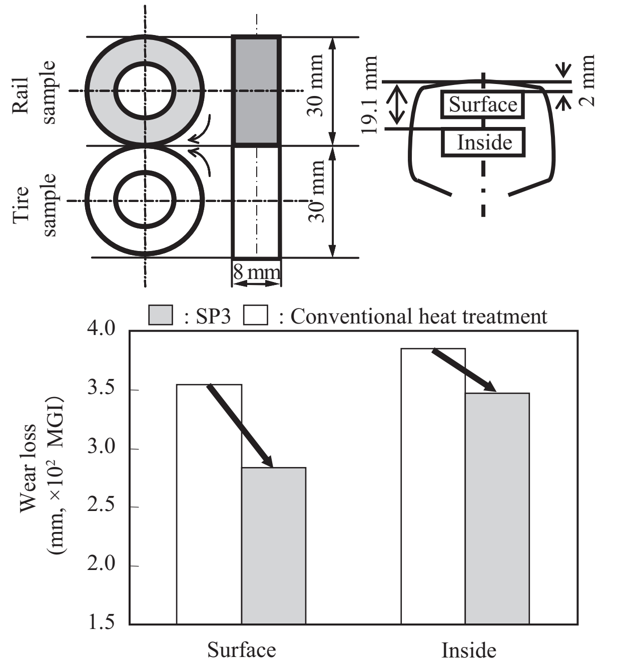



Fig. 5 Wear resistance of SP3 rail comparing with conventional heat treatment rail

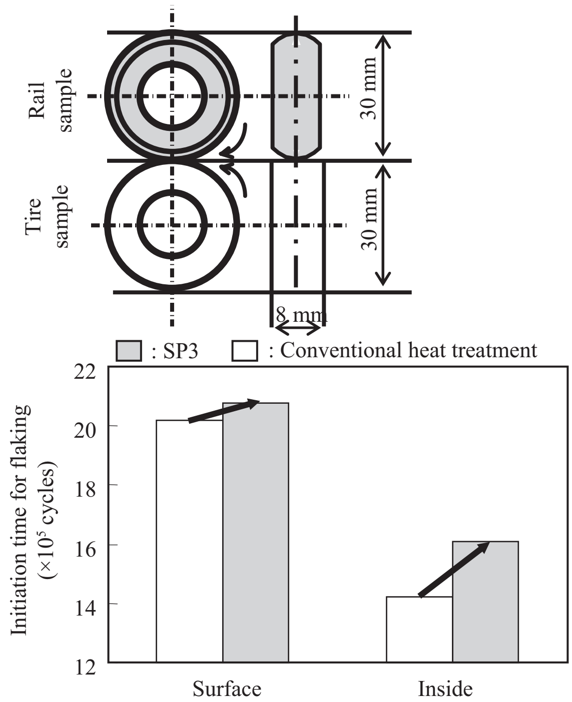



Fig. 6 Rolling contact fatigue test results of SP3 rail comparing with conventional heat treatment rail

Rolling contact fatigue resistance was also evaluated. As test specimens, cylindrical test pieces having curvature in the contact surface were taken from the same positions as in the wear resistance test, and a RCF test was performed under conditions of contact stress: 2.2 GPa, rotational speed : 800 rpm, slip ratio: –20%, and an oil lubricated environment. The results are shown in **Fig. 6**. A RCF resistance improvement effect of 3–13% was confirmed with the SP3 rail at both the rail head surface and a depth of 0.75 inches (19.1 mm). It is considered that the higher strength of the material and reduction in nonmetallic inclusions[8)] contributed to this improved performance.

### 3.3 Performance of Weld Joints

The typical microstructures of flash butt welded joint of SP3 rails are shown in **Photo 5**. No defects such as cracks, unbonded parts, or the like could be observed in the weld, and the microstructure displayed a pearlite structure. The hardness distribution at a depth of 5 mm below the railhead surface of flash butt welded joints is shown in **Fig. 7**. The developed rail shows a satisfactory hardness distribution of welded joint similar to that of the conventional heat-treated rail. **Table 4** shows the results of a slow bend test in accordance with the AREMA standard of welded joints for developed SP3 rail. Welded joint of SP3 rails have sound bending performance which amply satisfies the requirements of the standard for both fracture load and deflection.

### 3.4 Evaluation Test on Actual Railroad

SP3 rails have already been actually laid in the curved part of a freight railroad in a heavy haul environment in North America, and the wear behavior and occurrence of rail head fatigue damage accompanying use were observed. **Figure 8** shows the wear resistance of the SP3 rail obtained from the rail wear profile in comparison with that of the conventional heat-treated rail. When the wear of the conventional heat-treated rail is assumed to be 100, the specific wear rate of the SP3 rail was reduced by 10% or more. This effect is generally similar to the results of the two cylinder type wear test, and confirmed that the developed rail also has an substantial improvement effect in actual service envi-

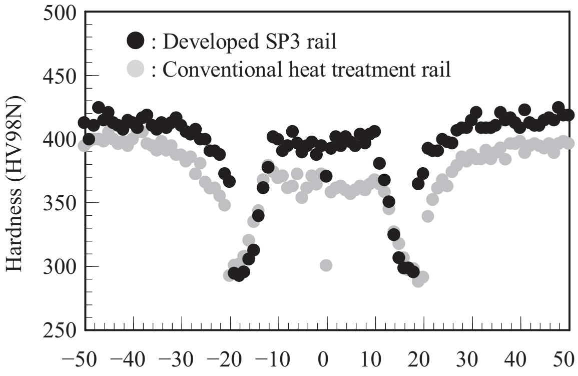



Fig. 7 Hardness distributions of flush butt weld joints in SP3 rail and conventional heat treatment rail

Table 4 Slow bend test results of weld portion for developed SP3 rail

| Flush butt weld joint | Modulus of rupture ($\times 10^5$ lbs/in$^2$ ) | Deflection (inch) |
|---|---|---|
| Developed SP3 | 1.97 (1.39×10$^4$ kg/cm$^2$) | 1.2 (3.0 cm) |
| | 2.07 (1.46×10$^4$ kg/cm$^2$) | 1.7 (4.3 cm) |
| AREMA spec. | Min.1.25 (8.8×10$^3$ kg/cm$^2$) | Min. 0.75 (1.9 cm) |

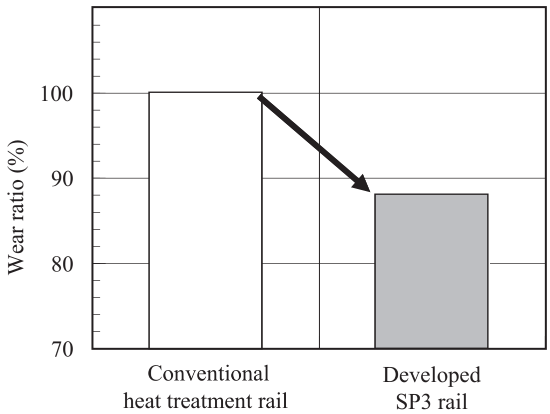



Fig. 8 Comparison of wear resistance in actual track in service, between the conventional heat treatment rail and SP3 rail, taking 100 for wear loss in the conventional rail

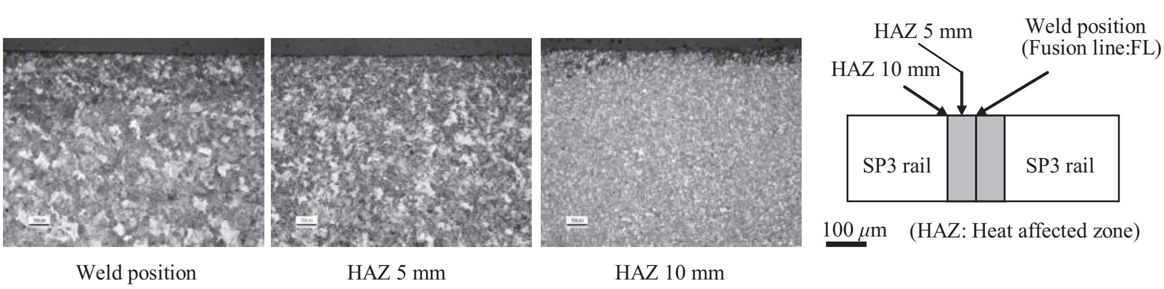



Photo 5 Microstructures of flush butt welds in SP3 rail

ronments. Satisfactory fatigue damage resistance was also obtained, as no flaking or shelling of the rail head surface was observed.

## 4. Conclusion

A new high wear resistance and RCF resistance rail (SP3) was developed for heavy haul freight railways in North America and other countries. Design of the chemical composition of the rail was performed and the TMCP conditions after rolling were optimized in order to refine the pearlite lamellar spacing of the developed rail to its ultimate limit. The pearlite lamellar spacing of the developed SP3 rail is extremely fine, at 0.07 $\mu$m, and hardness is also high, being HB420 points or higher in the Brinel scale at the rail head surface and HB370 or higher at a depth of 1 inch (25.4 mm). As a result, an improvement or 10% or more in wear resistance was confirmed in comparison with the conventional heat-treated rail in both laboratory tests and a performance confirmation test in which rails were actually laid. The welded joint performance of the developed rail is equal to that of the conventional rail, showing a satisfactory hardness distribution and performance in the slow bending test.

Because long rail life can be expected with the SP3 rail, JFE Steel believes that it can make an important contribution to reducing the rail maintenance costs of customers in the future by supplying this product for use in heavy haul freight lines.

## 5. Acknowledgement

The performance confirmation test of the developed SP3 rail was carried out with the cooperation of the Burlington North Santa Fe Railway (BNSF), which is a leading railway company in North America. As a result, it was possible to collect a large volume of valuable data on the developed rail in the actual service environment. The authors would like to express their heartfelt appreciation to all those concerned for their generous cooperation in this test.

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