Development of SP4 Rail with High Performance Pearlitic for Heavy Haul Railways

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Abstract
JFE Steel has developed a high performance pearlitic rail (SP4) with excellent wear resistance and rolling contact fatigue (RCF) resistance for heavy haul railways. Excellent wear and RCF resistances were realized in SP4 rail with a suitable alloy design and optimum production conditions, including the thermo-mechanical controlled processing. The microstructure in the rail head is fully pearlite with an extremely fine lamellar spacing. Features of the SP4 rail were the surface hardness of 450 in Brinell scale (HB450) and the higher level of hardness than HB400 even at a depth of 0.9 inches from the rail head surface. The tensile and 0.2% yield strengths were approximately 1500MPa and 1000MPa respectively, which were higher than HB370 heat-treated class rail (HB370 class rail). In addition, the elongation of SP4 rail was approximately 12%, which was on the same level as that of HB370 class rail.

1. Introduction
In heavy haul railway, freight consists mainly of grains and mineral ores. Recently, the weight and composition of freight trains on heavy haul railways has increased year by year with the aim of achieving higher transportation efficiency. Under these conditions, the rails used on heavy haul railways must provide high wear resistance. To improve wear resistance, we manufactured New Head Hardened (NHH) rail using offline heat treated equipment since 1978. In 1992, Thicker Head Hardened (THH) rail with a hardness of 370 in Brinell scale was developed with the introduction of online heat treatment equipment. THH rail had improved wear resistance and has had stable quality due to the online heat treatment. In 2000, we developed Super Pearlite (SP) rail which improved the rail head hardness. Recently, we developed a SP3 (Super Pearlite Type 3) rail with high rail head hardness and enhanced...
wear resistance. SP3 is highly-regarded as a rail with performance in the top group of the premium rails. However, further improvement of wear resistance and RCF resistance is required to cope with severe service conditions and to reduce rail maintenance costs.

In this research, we developed a new rail, SP4, with higher hardness by refining the pearlite lamellar spacing to the ultimate limit. This paper describes the microstructure control guidelines and performance of the base material of the newly-developed SP4 rail.

2. Microstructure control of developed SP4 rail

2.1 Effect of Hardness on Wear Resistance

Figure 2 shows the effect of hardness on wear resistance. The wear test was carried out using a twin disk type rolling contact test machine. The wear test was performed with a contact stress of 1.2 GPa (Hertz stress) and a slip ratio of 10% in a non-lubricated (dry) environment. Wear resistance was evaluated by weight loss at a total of $1.6 \times 10^5$ revolutions. Accompanying the increased hardness, weight loss due to wear decreased and wear resistance improved.

2.2 Increased Hardness of Pearlitic Rail

Increasing the hardness of pearlite is effective for improving wear resistance of the rail. Pearlite has a layered structure consisting of sheet-like layers of ferrite and cementite. The pearlite lamellar spacing...
is well known as a microstructural factor in the hardness of eutectoid steel \(^7\)\(^8\). Therefore, high hardness can be achieved in eutectoid steel by refining the pearlite lamellar spacing. Photo 1 shows the pearlite lamellar structure at the head surface of HB340 heat-treated rail (HB340 class rail) and HB370 class rail. The lamellar spacing (\(\lambda\)) of the HB370 class rail is much more refined than that of the HB340 class rail. Thus, the hardness of the rail can be increased by refining the pearlite lamellar structure.

![Photo 1 Pearlite lamellar structure of rail heads](image)

### 2.3 Refinement of Pearlitic Lamellar Spacing

Figure 3 shows a schematic diagram of a continuous cooling curve (CCT). In this figure, the degree of supercooling (\(\Delta T\)) is defined as the difference between the equilibrium transformation temperature (TE) which is determined by chemical composition and the calculated pearlite transformation temperature. Pearlitic structure becomes more refined as the \(\Delta T\) value increases in number. Photo 2 shows the pearlite lamellar structures after accelerated cooling and air cooling. The pearlite lamellar structure was more refined due to an increase of \(\Delta T\) by accelerated cooling. To maximize \(\Delta T\), it is effective to increase TE by optimizing the chemical composition and decreasing the pearlite transformation start temperature (\(Ps\)) by accelerated cooling after hot rolling.

![Figure 3: Schematic diagram of a continuous cooling curve (CCT)](image)
2.4 Influence of alloy element on equilibrium temperature

Figure 4 shows the results of a Thermo-Calc® calculation of the effects of Si, Mn and Cr on TE in an Fe-0.8%C steel. In comparison with the base steel, TE increased 2.4°C, and 1.0°C per 0.1% of added Si and Cr, respectively. On the other hand, the addition of Mn resulted in a decrease of 1°C per 0.1%.

3. Manufacture and basic performance of SP4 rail

3.1 Manufacture of rails

Table 1 shows the typical chemical composition of the developed SP4 rail (SP4) in comparison with that of the HB370 class rail. The C content was set at 0.8% considering elongation and toughness. The chemical composition was designed in terms of optimizing ΔT. After converter refining and the RH degassing process, the steel was cast into blooms by continuous casting and hot-rolled to 141-pound rails. Following hot rolling, TMCP was performed by accelerated cooling using slack quenching to produce SP4 with a refined pearlite lamellar microstructure.
Table 1  Typical chemical composition of SP4 rail (mass%).

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn (decrease)</th>
<th>P</th>
<th>S</th>
<th>others</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP4</td>
<td>0.8</td>
<td>0.31</td>
<td>1.14</td>
<td>≤0.02</td>
<td>≤0.005</td>
<td>Cr and V</td>
</tr>
<tr>
<td>HB370 Class rail</td>
<td>0.8</td>
<td>0.31</td>
<td>1.14</td>
<td>≤0.02</td>
<td>≤0.005</td>
<td>Cr</td>
</tr>
</tbody>
</table>

3.2  Microstructure and Lamellar Spacing

Figure 5 shows the rail head microstructures of SP4 and the HB370 class rail. All rails showed a fully pearlitic microstructure. Figure 6 shows the pearlite lamellar microstructures of SP4 and the HB370 class rail. The lamellar spacing of SP4 was 68nm at the railhead surface and 81nm at a depth of 1in. (25.4mm). The lamellar spacing of the HB370 class rail was 90nm at the railhead surface and 130nm at a depth of 1in. (25.4mm). Thus, the pearlite lamellar spacing of SP4 was more refined compared to that of the HB370 class rail.

Fig. 5 Optical micrographs of railhead of SP4 and HB370 class rail.

Fig. 6 Pearlite lamellar structures of SP4 and HB370 class rail.

3.3  Distribution of Rail Head Hardness

Figure 7 shows the hardness distributions of SP4 and the HB370 class rail. The hardness of SP4 was approximately HB450 at the railhead surface and HB400 at a depth of 25.4mm. Compared to the
HB370 class rail, the hardness of SP4 was increased by HB65 or more by refining the pearlite lamellar spacing.

![Hardness distributions of SP4 and HB370 class rail](image)

**Fig. 7** Hardness distributions of SP4 and HB370 class rail

### 3.4 Tensile strength and toughness

Figures 8, 9 and 10 show the tensile test results of SP4 and the HB370 class rail. The yield strength (0.2%YS) and tensile strength of SP4 were 1033MPa and 1499MPa, respectively, which were higher than those of the HB370 class rail. Although SP4 displayed high strength compared with the HB370 class rail, the average elongation of SP4 was on the same level as that of the HB370 class rail. Thus, SP4 has excellent ductility.

![0.2% Yield strength of HB370 class and SP4 rail](image)

**Fig. 8** 0.2% Yield strength of HB370 class and SP4 rail.
3.5 Residual stress

Figure 11 shows results of residual stress measurement of SP4 and the HB370 class rail. Residual stress was evaluated by a web saw-cut in reference to AREMA standards Chapter 4 2.1.13.2 2015. The result of SP4 satisfied the range of ±3.75 as described by AREMA standards. The mean value of SP4 is -2.6mm, which is at the same level as that of the HB370 class rail (-2.5mm).

3.6 Wear resistance and RCF resistance

A wear test and RCF test were carried out using a twin disk type rolling contact test machine. The wear test was performed with a contact stress of 1.2GPa (Hertz stress) and a slip ratio of 10% in a non-lubricated (dry) environment. Wear resistance was evaluated by weight loss at a total of $1.6 \times 10^5$ revolutions. The RCF test was performed with a contact stress of 2.8GPa and a slip ratio of 20% in a lubricated (oil) environment. RCF resistance was evaluated by rotational contact until initiation of flaking. The samples used in the wear test and RCF test were taken from the rail head as shown in Figure 12. Figures 13 and 14 show the results of the wear test and RCF test of SP4 and the HB370 class rail. In the laboratory test, the wear resistance and RCF resistance of SP4 were 43% and 2.6 times higher than those of the HB370 class rail, respectively.
4. Conclusion
The SP4 rail (Super Pearlite Type 4: SP4) was developed as a new rail with high hardness, wear resistance and RCF resistance. In particular, the pearlite lamellar spacing of SP4 was refined to the ultimate pearlite lamellar spacing. The high performance of SP4 was realized by optimizing the chemical
composition design to increase the equilibrium transformation temperature, using the optimized TMCP conditions after hot rolling. As the pearlite lamellar spacing of the SP4 rail is extremely fine, at 68nm, SP4 displays a surface hardness of HB450 and a high hardness of HB400 or more even at a depth of 0.9 inches from the rail head surface. In spite of its high strength, the elongation of SP4 is similar to that of the HB370 class rail. Residual stress meets AREMA standards. In laboratory tests, the wear resistance and RCF resistance of SP4 were 43% and 2.6 times higher than those of the HB370 class rail, respectively.

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Development of SP4 Rail with High Performance Pearlitic for Heavy Haul Railways

Ryo Matsuoka
JFE Steel Corporation
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1. History of JFE’s rail

2. Basic study on improved rail endurance

3. Manufacture and basic performance of developed rail

History of JFE’s rail

We have been developing SP4 rail with an excellent wear resistance and rolling contact fatigue (RCF) resistance.

Effect of hardness on wear resistance

The wear resistance was improved by increasing hardness.

Increase of hardness in pearlitic rail

Bright phase: Ferrite
Dark phase : Cementite

Hardness of rail was increased by refining pearlite lamellar structure.
Relation between pearlite lamellar spacing and hardness

Refining lamellar spacing ⇒ High hardness


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Refinement of pearlite lamellar spacing

£: Equilibrium transformation temp. (depend on the chemical composition)
P: Pearlite transformation temp. (depend on the cooling condition)
ΔT: Supercooling

T (SP4)

To increase ΔT, the chemical composition and the cooling condition of SP4 was optimized.

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Influence of alloy element on equilibrium transformation temperature (£)

Base steel: Fe-0.8%C

(Components of Fe-0.8%C: 760°C)

Fig. Effects of Si, Cr and Mn content on £

○ Addition of Si and Cr ⇒ Increase of £
○ Addition of Mn ⇒ Decrease of £

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Chemical composition of SP4 (mass%)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>others</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP4</td>
<td>0.8</td>
<td>add.</td>
<td>decrease</td>
<td>≤ 0.02</td>
<td>≤ 0.005</td>
<td>Cr and V</td>
</tr>
<tr>
<td>Conventional rail (HB 370 class rail)</td>
<td>0.8</td>
<td>0.3</td>
<td>1.14</td>
<td>≤ 0.02</td>
<td>≤ 0.005</td>
<td>Cr</td>
</tr>
</tbody>
</table>

SP4 optimized the chemical composition and the accelerated cooling condition (Slack quenching) to refine lamellar spacing.

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Microstructure

SP4 as well as Conventional rail has fully pearlitic microstructure.

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Pearlite lamellar structure

Elongation of 0.2% yield and tensile strengths of SP4 were 150ksi and 217ksi, respectively, which were higher than those in Conventional rail. Elongation of SP4 was the same level to that of Conventional rail.

Residual stress measurement

Residual stress of SP4 was almost the same level as that of Conventional rail.

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Tensile properties

<table>
<thead>
<tr>
<th>SP4</th>
<th>Conventional rail (HB370 class rail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2%YS (ksi, MPa)</td>
<td>150, 1033</td>
</tr>
<tr>
<td>TS (ksi, MPa)</td>
<td>217, 1499</td>
</tr>
<tr>
<td>El(%)</td>
<td>12</td>
</tr>
</tbody>
</table>

0.2% yield and tensile strengths of SP4 were 150ksi and 217ksi, respectively, which were higher than those in Conventional rail. Elongation of SP4 was the same level to that of Conventional rail.

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Wear resistance

Wear resistance of SP4 ⇒ 43% higher than that of Conventional rail

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Residual stress measurement

Residual stress measurement test result.

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Summary

- JFE steel successfully developed the new high performance steel rail (SP4), having high hardness over 400HB at 0.9 inches below the rail head surface.
- SP4 rail is eutectoid carbon rail (0.8%C level) and the rail has an extremely fine lamellar spacing.
- SP4 has high strength compared with Conventional rail.
  (HB370 class rail)
  (SP4 : 0.2% yield strength =150ksi, Tensile strength=217ksi)
- Elongation of SP4 is the same level as that of Conventional rail.
  (HB370 class rail)
- SP4 showed much better wear resistance and RCF resistance than Conventional rail in the laboratory test.
  (HB370 class rail)