DEVELOPMENT OF SP3 RAIL WITH EXCELLENT WEAR AND ROLLING CONTACT FATIGUE RESISTANCE FOR HEAVY HAUL RAILWAYS

Authors: Ryo Matsuoka *1, Mineyasu Takemasa *1, Tatsumi Kimura *2
Affiliations: *1 Shape Sec., Products Design & Quality Control for Steel Product Dept., West Japan Works, JFE Steel Corp.
*2 Plate & Shapes Res. Dept., Steel Res. Lab., JFE Steel Corp.

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Abstract

JFE Steel Corporation has newly developed high performance premium rail (SP3) with excellent wear and rolling contact fatigue (RCF) resistance for heavy haul railways. SP3 was manufactured with suitable alloy design and optimized production technology including thermomechanical control process (TMCP). SP3’s pearlite lamellar spacing at rail head was extremely fine to be 0.07μm and surface hardness achieved HB440. In addition, SP3 showed high internal hardness of HB390 at one-inch depth from the surface of rail head. SP3 has been laid and tested in actual track curves of BNSF Railway in North America. In this test, rail head profiles were periodically measured to calculate lost area of rail head and also to estimate rail life. Furthermore, by periodical rail surface observation, comparison of rail wear and RCF resistance between SP3 and AREMA premium grade rail (HB370) was conducted. SP3 showed 22% better wear resistance than AREMA premium grade rail and satisfactory RCF resistance of SP3 was obtained with no severe surface flaking of rail head surface at 230 mgt. In conclusion, SP3 showed 28% longer life than AREMA premium grade rail.

1. INTRODUCTION

In heavy haul railway, freight car load is over 150 ton. Wear is a dominant factor determining service life of rails in curve. Increased rail wear require more frequent rail exchanges and impose heavier maintenance. To improve wear resistance, rail head hardness is higher. JFE steel has manufactured wear resistant rails since 1978 developed New Head Hardened ; NHH rail by offline heat treatment. In 1992, JFE steel introduced online heat treatment equipment, and developed Thicker Head Hardened ; THH rail. THH rail was improved wear resistance and has stable quality due to the online heat treatment. In 2000, JFE steel developed Super Pearlite ; SP rail. Surface head hardness of SP rail was improved from 370 HBN of THH rail to
In order to respond to demand for rails with higher wear resistance, JFE steel recently developed a new high wear resistance rail called SP3, in which high hardness is achieved by refining the pearlite lamellar microstructure to its ultimate limit. This paper describes the basic properties of SP3, and the performance of SP3 on the actual rail road.

![Fig.1 Transition of JFE steel rails](image)

### 2. IMPROVEMENT OF WEAR RESISTANCE

#### 2.1 Effects of Hardness on Wear Resistance

The relationship between the hardness and wear resistance of pearlitic steels is shown in Fig. 2. The y-axis shows the weight loss due to wear in a two-cylinder type wear test. Smaller numbers indicate higher wear resistance. Increase in the hardness of pearlitic steel are improved the wear resistance. So, to improve rail’s wear resistance, it is important that not only surface but also internal hardness of rail head are higher.

![Fig.2 Relationship between hardness and wear resistance](image)

#### 2.2 High Hardness of Pearlitic Structure Rails

Pearlite structure is hardened by refinement of the lamellar structure. Photo.1 shows pearlite lamellar structure at 2/5in. (10mm) under head surface of 340 HBN and 370 HBN rails. The lamellar spacing of the 370 HBN rail is much finer than that of the 340HBN. The relationship between pearlite lamellar spacing and the hardness was shown in Fig. 3. High hardness can be achieved by refinement of this lamellar structure.

![Photo.1 Pearlite lamellar structure of rail heads](image)
2.3 Refinement of Pearlite Lamellar Spacing

Fig. 4 shows a schematic diagram of continuous cooling curve (CCT) with 0.8% carbon eutectoid steel. The degree of supercooling (ΔT) is defined as the difference between the equilibrium transformation temperature (TE) determined by chemical contents and the actual pearlite transformation temperature. Pearlite structure becomes refiner as ΔT value increases in number. Refiner pearlitic structure increases the hardness of steel. That is, maximizing ΔT is an efficient means of improving rail wear resistance. For maximizing ΔT value, it is important to make equilibrium transformation temperature higher by designing chemical compositions and to make actual pearlite transformation temperature lower by accelerate cooling after hot rolling (TMCP).

In development SP3 rail having higher hardness, maximum ΔT is achieved by optimizing the content of chromium which raise TE, and by lowering actual pearlite transformation temperature by accelerating cooling after hot rolling.

The typical chemical composition of the developed SP3 rail is shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP3</td>
<td>0.83</td>
<td>0.55</td>
<td>0.55</td>
<td>0.014</td>
<td>0.005</td>
<td>Add.</td>
<td>Add.</td>
</tr>
</tbody>
</table>

3. PERFORMANCE OF SP3 RAIL
3.1 Microstructure and Lamellar Spacing

The typical microstructures of the rail head of the SP3 rail and a 390 HBN class conventional heat-treated rail (herein-after, noted “conventional rail”) are shown in Photo. 2.

The microstructures from surface to one-
inch depth of rail head are shown fully pearlitic structure in which no formation of martensite can be observed. The results which observed pearlite lamellar spacings in SEM are shown in Photo.3. The pearlite lamellar spacings of SP3 rail at the surface and the interior are extremely fine compared with the conventional rail.

3.2 Distribution of Rail Head Hardness

Fig. 5 shows the distribution of the rail head hardness of SP3 and the conventional rail. SP3 rail has 430HBN at the surface and 390HBN at one-inch depth position. In comparison with the conventional rail, the hardness of SP3 is HB40 points higher at the rail head surface and approximately HB20 points higher at a depth of one-inch.

Fig. 5  Hardness distributions of SP3 and conventional rail

<table>
<thead>
<tr>
<th>Surface</th>
<th>1/2 in. (12.7mm)</th>
<th>1 in. (25.4mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP3</td>
<td>100 μm</td>
<td>100 μm</td>
</tr>
<tr>
<td>Conventional rail</td>
<td>100 μm</td>
<td>100 μm</td>
</tr>
</tbody>
</table>

Photo.2 Microstructure of SP3 and conventional rail

<table>
<thead>
<tr>
<th>Surface</th>
<th>1/2 in. (12.7mm)</th>
<th>1 in. (25.4mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP3</td>
<td>2 μm</td>
<td>2 μm</td>
</tr>
<tr>
<td>Conventional rail</td>
<td>2 μm</td>
<td>2 μm</td>
</tr>
</tbody>
</table>

Photo.3 Lamellar structure of SP3 and conventional rail
3.3 Mechanical Properties

The typical tensile properties of the SP3 and the conventional rail are shown in Table 2. The SP3 shows yield strength (YS) of 141ksi (975MPa) and tensile strength (TS) of 205ksi (1415MPa), thus realizing high strength approximately 5ksi (50MPa) superior to that of the conventional rail. Although SP3 is high strength compared with the conventional rail, obviously no decrease in elongation can be observed.

<table>
<thead>
<tr>
<th>Type of rail</th>
<th>Tensile Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield strength</td>
</tr>
<tr>
<td>SP3</td>
<td>141 ksi (975 MPa)</td>
</tr>
<tr>
<td>Conventional rail</td>
<td>131 ksi (903 MPa)</td>
</tr>
<tr>
<td>AREMA standard, High-strength</td>
<td>minimum</td>
</tr>
<tr>
<td>SP3</td>
<td>120 ksi (827 MPa)</td>
</tr>
</tbody>
</table>

3.4 Metallurgical Cleanliness

The metallurgical cleanliness of the SP3 and the conventional rail are shown in Table 3. The metallurgical cleanliness conformed to the AREMA standard (AREMA: American Railway Engineering and Maintenance-of-Way Association), and was measured. The number of nonmetallic inclusion in the SP3 is sufficiently small and satisfies the AREMA standard.

Table 3 Metallurgical cleanliness

(According to ASTM E45-Method A)

<table>
<thead>
<tr>
<th>Type of rail</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
<th>Type D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thin</td>
<td>Heavy</td>
<td>Thin</td>
<td>Heavy</td>
</tr>
<tr>
<td>SP3</td>
<td>0.5</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Conventional rail</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

A: MnS, B: chain of Al₂O₃ and/or TiN, C: SiO₂, D: grain of Al₂O₃ and/or TiN
4. EVALUATION TEST ON ACTUAL RAIL ROAD

SP3 were actually laid in a curved part of a freight railroad in a heavy haul environment in North America, and the wear behavior and rail head fatigue damage were observed. The details of the curve are shown in below.

- Curvature : 7° 40′
- Curve detail : Up grade sharp curve
- Passing tonnage : 104MGT/year
- Grinding : Every 20-40MGT/1-3pass
- Medium lubrication
- Average rail life : 18 months with AREMA premium grade rail

SP3, a conventional heat-treated rail (JFE SP), and other AREMA premium grade rails were laid alternately in the same curve.

4.1 Observation of Rail Head Surface

The rail surfaces of the preceding mentioned rails were observed. The rail surface of SP3 after passing 230MGT is shown in Photo 4. No surface defects were found on the high rail surface.

Photo 4 The high-rail surface of SP3 after passing 230MGT

Fig.6 Comparison of rail-head profiles in low-rail at 230MGT
4.2 Comparison of Rail head Profile (Low-Rail)
The rail head profiles of SP3 and the AREMA premium grade rail after 230MGT are shown in Fig. 6. Large deformations can be seen at the gauge corner (G.C.) side and field corner (F.C.) side of the rail head. Heavy wear loss was found in the AREMA premium grade rail in comparison with SP3. The wear ratio of the low rail of SP3 was reduced by 22% in comparison with that of the AREMA premium grade rail (Fig.7).

\[
\text{SP3 Wear ratio (%) = } \frac{\text{Wear area of SP3 rail}}{\text{Wear area of AREMA premium grade rail}}
\]

![Fig. 7 Comparison of wear resistance of SP3 and AREMA premium grade rail in actual track in service (low-rail)](image)

The initial rail head profiles and profiles after 230MGT of the AREMA premium grade rail and SP3 are shown in Fig. 8. The worn areas of the AREMA rail were W1=0.819in.(20.8mm) and W3=0.965in. (24.5mm), whereas those of SP3 were W1=0.669in.(17.0mm) and W3=0.673in. (17.1mm).

4.3 Comparison of Rail Head Profile (High-Rail)
Assuming the wear rate of the high rail of the AREMA premium grade rail is 100, the wear rate of the SP3 rail is reduced by 8% (Fig. 9).

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The initial rail head profiles and profiles after 230MGT of the AREMA premium grade rail and SP3 are shown in Fig. 10. The worn areas of the AREMA premium grade rail were $W_1=0.291\text{ in.}(7.4\text{ mm})$ and $W_3=0.401\text{ in.}(10.3\text{ mm})$, whereas those of SP3 were $W_1=0.283\text{ in.}(7.2\text{ mm})$ and $W_3=0.370\text{ in.}(9.4\text{ mm})$.

### 4.4 Rail Life

The rail life of the SP3 is shown in Fig. 11 (low rail) and Fig. 12 (high rail), when the rail life limit is defined as $W_1=0.875\text{ in.}(22.2\text{ mm})$.

In the low rail, the SP3 life is 30.1 months, that of the AREMA premium grade rail is 23.6 months. This means the rail life of the SP3 is 28% longer than that of the AREMA premium grade rail.

In the high rail, the rail life of SP3 is 57.1 months, while that of the AREMA premium grade rail life is 49.7 months. And, the life of SP3 is 14% longer than that of the AREMA premium grade rail.
5. CONCLUSION
A new rail (SP3) with high wear resistance and rolling contact fatigue (RCF) resistance was developed for heavy haul railways in North America and other countries.

The hardness of the SP3 is 440BHN at the rail surface and 370BHN at a depth of one-inch (22.9mm). The mechanical properties of SP3 rail are fully satisfied with the AREMA specification.

A test was conducted on an actual heavy haul railroad in North America. After 230MGT, no surface defects were found on the high or low rails. And the wear loss area of the low rail of SP3 was 22% superior to that of the AREMA premium grade rail. From the length of worn off at the top of head (W1) of each rail, the rail life of the SP3 is 28% longer than that of the AREMA premium grade rail.

6. ACKNOWLEDGEMENT
The performance confirmation test of the developed SP3 was carried out with the cooperation of the BNSF Railway, 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 an 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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Photo. 3  Lamellar structure of SP3 and conventional rail
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Development of SP3 rail with Excellent Wear and Rolling Contact Fatigue Resistance for Heavy Haul Railways

Ryo Matsuoka
JFE STEEL Corporation
Outline of presentation

- features of SP3
- mechanical properties of SP3
- test results of SP3’s rails performance
- conclusion
Concept of the SP3 rail

Online heat-treatment (air cooling)

Improved wear resistance with high hardness from the surface to the inside of the rail head.
Effects of hardness on wear resistance

The wear resistance improves as the hardness of the steel increases.
High hardness of pearlitic structure rails

340HB rail
Bright phase: Ferrite
Dark phase: Cementite

370HB rail

The lamellar spacing of 370HB rail is much finer than that of the 340HB.
High hardness of pearlitic structure rails

Refining lamellar spacing ⇒ High hardness

LV = 58 + 86 × (LPS)^{-1/2} ± 18

Refinement of pearlite lamellar spacing

$T_E$: Equilibrium transformation temperature
$T$: Pearlite transformation temperature
$\Delta T$: Supercooling temperature

Pearlite structure is finer as the $\Delta T$ value increases

$\Delta T = T_E - T$
## Chemical composition of SP3

<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><strong>SP3</strong></td>
<td>0.83</td>
<td>0.55</td>
<td>0.55</td>
<td>0.014</td>
<td>0.005</td>
<td>Cr and V</td>
</tr>
<tr>
<td><strong>Conventional rail (SP)</strong></td>
<td>0.84</td>
<td>0.55</td>
<td>1.18</td>
<td>0.014</td>
<td>0.005</td>
<td>Cr and Nb</td>
</tr>
</tbody>
</table>
SP3 as well as conventional rail has fully pearlitic microstructure.

<table>
<thead>
<tr>
<th></th>
<th>SP3</th>
<th>Conventional rail (SP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface</td>
<td><img src="image1" alt="Surface SP3" /></td>
<td><img src="image2" alt="Surface SP" /></td>
</tr>
<tr>
<td>0.5 inch</td>
<td><img src="image3" alt="0.5 inch SP3" /></td>
<td><img src="image4" alt="0.5 inch SP" /></td>
</tr>
<tr>
<td>1.0 inch</td>
<td><img src="image5" alt="1.0 inch SP3" /></td>
<td><img src="image6" alt="1.0 inch SP" /></td>
</tr>
</tbody>
</table>

100 $\mu$m
### SEM observations

<table>
<thead>
<tr>
<th></th>
<th>SP3</th>
<th>Conventional rail (SP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>Ave. 0.074 $\mu$m</td>
<td>Ave. 0.087 $\mu$m</td>
</tr>
<tr>
<td>0.5 inch</td>
<td>Ave. 0.083 $\mu$m</td>
<td>Ave. 0.094 $\mu$m</td>
</tr>
<tr>
<td>1.0 inch</td>
<td>Ave. 0.089 $\mu$m</td>
<td>Ave. 0.099 $\mu$m</td>
</tr>
</tbody>
</table>

SP3 has finer lamellar spacing compared with conventional rail.

$2 \mu$m
Hardness distribution

Head surface: the hardness of SP3 was 40HB higher than that of conventional rail (SP).
At a depth of 1.0in (25.4mm): the hardness of SP3 was 20HB higher than that of conventional rail (SP).
### Mechanical properties

<table>
<thead>
<tr>
<th></th>
<th>Tensile Properties</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YIELD STRENGTH (ksi, MPa)</td>
<td>TENSILE STRENGTH (ksi, MPa)</td>
<td>ELONGATION (%)</td>
<td></td>
</tr>
<tr>
<td><strong>SP3</strong></td>
<td>141, 975</td>
<td>205, 1415</td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td><strong>Conventional rail (SP)</strong></td>
<td>131, 903</td>
<td>199, 1371</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td><strong>AREMA spec. (min.)</strong></td>
<td>120, 827</td>
<td>171, 1179</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Increase in elongation can be observed. 

*Conducted by AREMA spec*
# Metallurgical cleanliness

<table>
<thead>
<tr>
<th>Type</th>
<th>SP3</th>
<th>Conventional rail (SP)</th>
<th>AREMA spec. (max.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thin</td>
<td>Thin</td>
<td>Thin</td>
</tr>
<tr>
<td>A</td>
<td>0.5</td>
<td>1.0</td>
<td>average rating of 2</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>Heavy</td>
<td>individual rating of 3</td>
</tr>
<tr>
<td>B</td>
<td>0.0</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>C</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>D</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

SP3 is sufficiently small and meets the AREMA standard.
Evaluation test on actual rail road

- *curve* = 7° 40′
- Orange letters = AREMA premium grade rail
- Pink letters = Conventional rail (SP)
- Blue letters = SP3 rail

SP3’s deformations are smaller than the AREMA premium grade rail.

**Big deformation**

**Heavy wear loss**
Observation rail head surface

After 230 MGT passed rail surface

- No surface defect was found on SP3.
Comparison of railhead profile (low rail)

SP3 wear ratio(%) = 
wear area of SP3 rail / wear area of other AREMA premium grade rail

SP3 wear ratio(%) = +22%
Comparison of railhead profile (low rail)

- compared after 230 MGT passed

AREMA premium grade after 230 MGT passed

SP3 after 230 MGT passed

- SP3 shows better wear resistance
Comparison of railhead profile (high rail)

SP3 wear ratio(%) = wear area of SP3 rail / wear area of other AREMA premium grade rail

- 100% increase
Comparison of railhead profile (high rail)

- compared after 230 MGT passed

other AREMA premium grade after 230 MGT passed

- SP3 shows better wear resistance

SP3 after 230 MGT passed
Rail life (low rail)

- Rail life shown below
  - Rail life limit is $W_1 = 7/8$ in (22.2 mm)

SP3 rail life is 28% longer than the other premium grade rail.
Rail life (high rail)

- rail life shown below
  - rail life limit is W1 = 7/8in (22.2mm)

SP3 rail life is 14% longer than the other premium grade rail
Conclusion

1) JFE steel successfully developed SP3 for heavy haul railroad.
2) The hardness of SP3 is 440 HB at the surface and 370 HB at a depth of 1.0 in (25.4mm).
3) The mechanical properties of SP3 meets AREMA specification.
4) In actual heavy haul railroad, after 230 MGT
   a) No surface defects were found on high and low rails.
   b) Wear loss of area of the low rail of SP3 was 22% superior to that of the AREMA premium grade rail.
   c) The rail life of SP3 is 28% longer than that of the AREMA premium grade rail based on a set amount of wear W1 over time on the top of the railhead.
Appendix

- hardness distribution at a depth below 5mm below the railhead surface

- hardness distribution of welded joint → similar to that of the conventional heat treatment rail.
Appendix

- microstructures of flush butt welds

→ the microstructure displayed a pearlite structure