Effect of Rail/Wheel Rolling Contact on Microstructure in Surface Layer of Rail

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The rail/wheel rolling contact affects the microstructure of rail steel in the surface layer of rail. The microstructure was investigated from a point of view of the crystal orientation by means of X-ray inverse pole figure measurement and EBSP analysis. The specific condition that the {111} crystallographic plane of the constituent grains is oriented in parallel to the running surface in the surface layer of a rail used in service for 16 years is confirmed through the analysis of X-ray inverse pole figure and EBSP orientation image map. The degree of orientation evaluated by the axis density of the 111 crystallographic axis varies in the direction of depth from the running surface giving a maximum at about 100 µm from the surface. Based on the results, it is conceivable that the 111 axis density could be a potential parameter to evaluate the degree of rolling contact damage accumulated in the surface layer of used rails.

Keywords: rail, rolling contact fatigue, crystal orientation, inverse pole figure, EBSP

1. Introduction

One of the major types of damage of rail used for high-speed and high-density traffic lines is the fatigue damage due to the repeated rolling contact of wheels of rolling stock on the running surface of rail. The grinding of the running surface has been studied from theoretical and experimental viewpoints as one of the effective means to prevent such serious damages and to extend the service life of rails. In order to optimize the grinding condition, it is important to find the depth which the influence of the rolling contact reaches. It is also important to design methods to evaluate the fatigue level before the damage becomes visible.

In the previous studies into the metallographic and crystallographic characterization of rails from Shinkansen and narrow-gauge lines in Japan, we confirmed that a plastic flow pattern and a preferred crystallographic orientation of ferrite developed in the close vicinity of the running surface through optical microscopic observation and X-ray pole figure measurement of the (110) crystallographic plane of ferrite in the pearlitic steel of rail over a range from the surface to a depth of about 800 µm. Following our previous studies, this study focuses on the damage caused by the rolling contact with wheels, and investigates the crystallographic orientation conditions by means of X-ray inverse pole figure measurement, Electron Back Scattering Pattern (EBSP) analysis with a Field Emission electron gun – Scanning Electron Microscope (FE-SEM) apparatus.

2. Samples

2.1 Rail

Two Japanese Industrial Standards (JIS) 50kgN (JIS E 1101) type rails were examined in this study. One was an used rail and the other was a new rail. The former was in use for 16 years on a straight segment of a ballasted double-track section on a narrow-gauge line. Its accumulated service tonnage was about 160 Million Gross Tonnage (MGT). A typical damage observed on the running surface of the rail is shown in Fig. 1. A new JIS 50kgN rail was used as a reference. The chemical compositions of the two rails conformed to the specification given in JIS as shown in Table 1.

The symbols for the three axes of a coordinate system used in this study are given in Fig. 2. The direction normal to the running surface of the rail is ND; the rolling direction is RD (RD is chosen as the train running direction); and the transverse direction is TD.

![Fig. 1 Typical damage observed on the running surface of an used rail](image)

Table 1 Chemical compositions of rails (mass %)

<table>
<thead>
<tr>
<th>Rail</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Used</td>
<td>0.69</td>
<td>0.24</td>
<td>0.85</td>
<td>0.013</td>
<td>0.008</td>
</tr>
<tr>
<td>New</td>
<td>0.71</td>
<td>0.23</td>
<td>0.92</td>
<td>0.023</td>
<td>0.007</td>
</tr>
<tr>
<td>JIS specification</td>
<td>0.63 ~ 0.75</td>
<td>0.15 ~ 0.30</td>
<td>0.70 ~ 1.10</td>
<td>&lt; 0.030</td>
<td>&lt; 0.025</td>
</tr>
</tbody>
</table>
2.2 Sample position

The position for sampling in the RD direction was chosen as shown in Fig. 3. If the sample position was on the side leaving from the damage, any extra effect such as vertical dynamic force generated by wheels passing over the damage might occur and overlap with the original damage which had been accumulated by the rolling contact with wheels. In order to prevent such a condition, the sample position was chosen on the side approaching the damage.

The position in the TD direction was chosen by taking the following discussion into consideration. A wheel of a rolling stock has a gradient on the wheel tread in order to stabilize vehicle motion. As a result, the length of the circumference of the tread varies depending on the position on the tread. The difference in the circumferential length causes a differential slip between the tread and the running surface, and induces a non-uniform dis-
tribution of tangential force in the contact area of the running surface. In order to investigate the effect of rolling contact itself and to compare the magnitudes of the effect on several rails used under different service conditions, it is important to minimize the extra turbulence yielded by the tangential force which could be different in different service conditions.

The tangential force gives rise to a plastic surface flow of material in the layer just below the the running surface of an used rail. Therefore, it is reasonable to observe the plastic flow patterns in the layer to determine a suitable sample position. A series of microscopic observation of the plastic surface flow was performed on the vertical sections parallel to the RD direction as shown in Fig. 4 following the evaluation procedure proposed by Sugino et al. 8). Some optical micrographs are shown in Fig. 5 for the sections at 5mm from the center toward the field corner side (FC5mm), at the center (C) and at 5mm from the center toward the gauge corner side (GC5mm). The plastic flow directs in the train running direction at FC5mm and directs opposite to that at GC5mm, while no plastic flow pattern is evident at the center. The observation resulted in that the RD component of the tangential force vanishes at the center.

Based on the vanishing of the plastic surface flow in the RD direction, the center in the TD direction can be regarded as the position with the minimum effect of the tangential force. Therefore, the center is chosen as the sample position in the TD direction. The position is referred to as the contact center (CC) position in this study. The same position is used also for the new rail.

3. X-ray inverse pole figure measurement

3.1 Measurement

An inverse pole figure of a sample gives information on the orientation of constituent crystals in the sample through an evaluation of the ratio of the crystals which have the crystallographic axis in question parallel to the reference direction 4). The crystals of ferrite in the pearlitic steel of rail are used as the material for the inverse pole figure measurement in this study. The ND direction is chosen as the reference direction. The ratio of the X-ray diffraction intensity from a sample to the intensity from the standard material which has a random orientation of ferrite is evaluated as the axis density of the crystallographic axis in question, and plotted on a stereographic projection plane in general presentation. It is noted that the axis density 1 means a condition in which there is no preferred orientation with respect to the crystallographic axis, or the axis is randomly oriented in the sample.

The inverse pole figure measurement was carried out for the crystallographic axes 110, 100, 211, 310, 111 and 321 under the measurement conditions summarized in Table 2. In order to observe the variation of the inverse pole figure in the direction of depth from the running surface, measurement was repeated in the following way. The inverse pole figure of the running surface was measured; and then the material between the running sur-

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>Mo</td>
</tr>
<tr>
<td>Filter</td>
<td>Zr</td>
</tr>
<tr>
<td>Voltage</td>
<td>60 kV</td>
</tr>
<tr>
<td>Current</td>
<td>200 mA</td>
</tr>
<tr>
<td>Dispersion Slit</td>
<td>0.5 deg</td>
</tr>
<tr>
<td>Scattering Slit</td>
<td>1 deg</td>
</tr>
<tr>
<td>Receiving Slit</td>
<td>0.15 mm</td>
</tr>
</tbody>
</table>

3.2 Inverse pole figure at various depths

The inverse pole figures of the used rail are shown in Fig. 7 for the running surface and the depths of 10, 100 and 1000 μm. Each three-digit number hkl in the triangular inverse pole figure represents the crystallographic index of the axis for the cubic class, and the numerical value in parentheses near the crystallographic index gives the value of the axis density.

All of the four inverse pole figures show the maximum axis density at the 111 axis. This result shows that a large part of ferrite in the surface layer has the [111] crystallographic plane parallel to the running surface of the rail. Since the value of the 111 axis density varies depending on the depth of measurement, the detail of the variation of each axis density with depth is examined below.

3.3 Variation of axis density with depth

The variation of axis density in the direction of the depth of measurement is shown in Fig. 8 for each of the crystallographic axes 110, 100, 211, 310, 111 and 321. The values of axis density of the used rail are shown in the Figure by filled squares and those of the new rail are by...
The axis density of the new rail characteristically varies with the depth layer of the new rail. On the other hand, the axis density of the used rail is 1 or in the close vicinity of 1 throughout the range of measurement. This result suggests that there is no preferred orientation of ferrite in the surface layer of the new rail. Based on these results, the 111 axis density can be regarded as one of the potential parameters to evaluate the degree of rolling contact damage accumulated in the surface layer of the used rail.

4. Orientation analysis with EBSP

4.1 Measurement

By means of Electron Back Scattering Pattern (EBSP), it is possible to determine the orientational distribution of the constituent crystals in a sample at a microscopic level. The procedure is based on the theory of back-scattering Kikuchi patterns created by inelastic scattering of electrons in a crystal of a thick sample irradiated by an electron beam.

The EBSP measurement was carried out in a Field Emission electron gun - Scanning Electron Microscope ((FE-SEM) apparatus at the electron beam acceleration voltage of 25kV with a scanning interval of 0.5 µm. on an area of 80 µm (ND direction) x 350 µm (RD direction) on the vertical section shown in Fig. 9. The vertical section was prepared at CC position in the TD direction and finished by emery paper and electrolytic polishing to remove the possible strain imposed during the preparation. The EBSP data were analyzed with Orientation Imaging Microscope software OIM™ supplied by TexSEM Laboratories. In the analysis, the raw orientation data were directly used to synthesize the orientation image maps with no misorientation angle threshold.

4.2 Orientation image analysis

The orientation image maps of the used rail and the new rail are shown in Fig. 10 taking the ND direction as the reference direction. At each point on the map, the crystallographic axis parallel to the reference direction can be identified with the help of the color key in the original color mapping.
Based on the orientation image map of the used rail, it is reconfirmed by means of EBSP that there is a strong orientation of the [111] crystallographic plane parallel to the running surface in the surface layer at the microscopic level as confirmed by the X-ray inverse pole figure measurement at the macroscopic level in the previous section. While the new rail can be characterized by no preferred orientations.

Unlike the X-ray inverse pole figure measurement, EBSP analysis can give the morphological information such as size and shape of the constituent grains as well as the crystallographic orientation. The orientation image map of the used rail consists of a large number of very small grains which elongate in the RD direction. On the other hand, the map of the new rail consists of a small number of coarse grains.

It is suggested by the characteristics of the morphology and orientation of the constituent grains that the original large grains are broken down into a large number of small and elongate grains by the repeated rolling contact with wheels during a long-term service. It is also suggested that the [111] crystallographic plane of the resultant small grains becomes parallel to the running surface during the process.

Some parts in the orientation image map of the used rail are very obscure and consist of a number of small spots. It is known in the field of EBSP analysis that imperfections and distortions of crystals and/or accumulation of dislocations in crystals can produce such a lack of clarity in the orientation image map. Using an image quality map is helpful for examining the condition of the obscure area. An image quality map gives the distribution of the so-called image quality of each point in the area of analysis by the brightness of the point. The image quality represents the sharpness of the detected Kikuchi lines. Low image quality implies the existence of any imperfections, distortions and dislocations at the point in the irradiated crystal. The image quality maps of the used and new rails at a depth of 100 µm are shown in Fig. 11. In the image quality map of the used rail, some areas are very dark and the grain boundaries are not clear in such areas. In contrast, the grains in the

Fig. 10  Orientation image maps (ND)

Fig. 11  Image quality maps at a depth of 100 µm
image map of the new rail are relatively bright and reveal well-defined grain boundaries. This observation might suggest that the constituent grains of the surface layer not only break down in size but also distort and/or suffer from the accumulation of dislocations during service.

5. Conclusions

The crystal orientation in the surface layer of a rail used on a narrow-gauge line for 16 years with an accumulated service tonnage of 160 Million Gross Tonnage (MGT) and damaged by the repeated rolling contact with wheels of rolling stock during the service period was analyzed by means of X-ray inverse pole figure measurement from the macroscopic viewpoint, and by EBSP analysis from the microscopic viewpoint. The following conditions were confirmed.

The specific orientation that the {111} crystallographic plane of the constituent crystal grains is arranged in parallel to the running surface in the surface layer is confirmed through the analyses of X-ray inverse pole figure and EBSP orientation image map. The degree of orientation evaluated by the axis density of the 111 crystallographic axis varies with the depth from the running surface giving the maximum at about 100 µm from the surface. Based on the result, the 111 axis density can be regarded as a potential parameter to evaluate the degree of the rolling contact damage accumulated in the surface layer of used rails. Other crystallographic axes also show characteristic variations with depth. A further study on the relationship among the variations of axis density values is required to build a fuller picture of the orientation process.

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References

9) TexSEM Laboratories, Inc., 226 W. 2230 North, #120, Provo, UT 84604, USA.