RESIDUAL STRESS EVALUATION OF RAILWAY RAILS

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ABSTRACT
Various stresses add to the railway rails and accumulate fatigue damage due to daily use. Fracture mechanics clarification concerning the growth behavior of cracks is needed, in order to decide the inspection period and the cycle [1], [2]. Though the crack progression and influence of residual stress on fatigue strength has been researched [3] for many years, they are not clear now. The aims of this research are the assistance of the inspection period and the cycle decision of the rail maintenance. For these purposes, the residual stress distribution in the railway rails was measured by using the X-ray diffraction method, the strain gauge method and FEM analysis respectively.

INTRODUCTION
Rolling contact fatigue is one type of fatigue damage of railway rails. A lot of research has been done about rolling contact fatigue based on fracture mechanics. Rolling contact fatigue occurs by repeated contact stress at the railhead running wheels. Contact stress generally forms compressive stress. Tensile stress helps to progress the fatigue failure and it decreases rapidly under the contact surface, so a lot of cracks usually stop at the depth of several millimeters. However, the rails finally break when the crack propagation in the rail changes direction toward the bottom of the rail. This is because the crack receives the cyclic bending stress of the rail and the influence of the tensile residual stress. In order to obtain the crack growth rate, the measurement of the residual stress distribution is needed. Fracture mechanics clarification concerning the growth behavior of cracks is needed, in order to decide the inspection period and the cycle. The crack progression and influence of residual stress on fatigue strength has been researched [3] for many years. It is well-known the compressive residual stress improves the fatigue strength of the material.

The method of stress measurement can be divided into two methods. One is destructive and the other is nondestructive. The former is done by calculating the residual stress from the strains released after cutting the blocks into small pieces upon which the strain gauges are attached beforehand. The latter is the nondestructive method which measures the change of the lattice spacing of the material’s structure using X-rays or neutrons. From
the change of the lattice spacing, residual stress can be determined. It is known that the internal residual stresses of the rail plays an important role in propagation of cracks in the rails\cite{1,2}. However, it is difficult to measure the state of internal residual stress of large engineering parts such as the railway rails. It becomes impossible to obtain enough diffraction intensity such as rails for the flight path of the neutron beam, due to these large engineering parts, though there is a technique that uses neutron diffraction as a method of residual stress measurement in the material. The authors are measuring residual stress in railway rails; it was difficult to measure the whole of the rail due to the constraint of the measuring instruments. Therefore, small samples should be taken, and the stress relaxation should be measured from these samples\cite{4}. A definite technique for measuring internal residual stress of large engineering parts does not exist now. This research is examined on combines the strain gauge method with FEM analysis; it aims at internal residual stress measurement of railway rails.

RESIDUAL STRESS MEASUREMENT
Residual Stress Measurement of Rails with Strain Gauge

The residual stress measurement of rails with a strain gauge was done by UIC/WEC Joint Research\cite{5}, and the residual stress of a rail vertical centerline\cite{5} is calculated from the amount of relaxation of the residual stress. This research was performed using the UIC/WEC technique. The strain gauges were attached as shown in Fig. 1, it was No.1 from the rail head, and used 12 gauges in total. Fig. 2 was the first cut, Fig. 3 was the second, and Fig. 4 was the third. The amount of relaxation of the strain was measured by cutting the rail. At this time, the strain gauge measured the amount of relaxation in the longitudinal direction and the direction of the outer tangent (hereafter, hoop direction) with a two axis gauge. Before and after railway rail cutting using the saw machine, the relaxation value was measured. The rail tested is the commonly used 60kg rail designated in the Japan Industrial Standard as JIS E 1101. The rail was un-used, and the heat treatment and the roller-straightening were finished.

Residual Stress Measurement of Rails with FEM Analysis

Using FEM analysis software (ABAQUS ver. 6.6), the state of the internal residual stress is presumed by using the residual strain measured using the section sample. A model was created from an elastic body, and Young's modulus was defined at 206GPa and the Poisson's ratio was defined at 0.3. The FEM model was symmetrical and used a two dimensional plane strain model as shown in Fig. 5, mesh was 4 node two dimension elements, the numbers of nodes are 4323, and the numbers of elements are 1348. The residual strain value measured using the section sample was linear interpolated (Figure 6).
The stress was given to each element of the surface as an initial condition at each position, and the stress was calculated by the elastic analysis.

Fig. 1. Strain gauge locations. 
Fig. 2. Scheme of first cut.

Fig. 3. Scheme of second cut. 
Fig. 4. Scheme of third cut.

Fig. 5. FEM mesh of rail.
Residual Stress Measurement of Rails with X-ray Method

Residual stress of the rail was measured using the $\sin^2 \psi$ method that is a standard method of X-ray residual stress measurement. The measurement point is as shown in Fig. 7. The longitudinal residual stress of the rail was measured. The X-ray stress measurement conditions as shown in Table 1.

Table 1. X-ray stress measurement conditions.

<table>
<thead>
<tr>
<th>Characteristic X-ray</th>
<th>Cr-Kα</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube current (mA)</td>
<td>6</td>
</tr>
<tr>
<td>Tube voltage (kV)</td>
<td>30</td>
</tr>
<tr>
<td>Diffraction angle 2(\theta) (deg.)</td>
<td>156.4</td>
</tr>
<tr>
<td>Stress constant K (MPa/deg.)</td>
<td>-318</td>
</tr>
<tr>
<td>Fixed time (sec.)</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 7. Measurement locations of un-used rail using X-ray method.
RESULTS
Residual Strain Measurement of Rails Using Strain Gauge

Fig. 8, Fig. 9 and Fig. 10 show the strain relaxation value from cutting. The data of Fig. 10 (No. 1 and No. 12) cannot be acquired because the strain gauge was disconnected after being cut with a saw. Fig. 11 shows strain distribution obtained; (a) is longitudinal direction and (b) is hoop direction. After the first cut, the strain relaxation value was larger in the longitudinal direction than in the hoop direction, as shown in Fig. 8. Roughly, the strain relaxation value from the first cut shows approximately 90% of the amount of the strain relaxation value obtained from the final cut and it is shown that the amount of relaxation of the residual stresses is remarkable in the vicinity of the cutting surface. The longitudinal residual strain distribution was similar to the UIC/WEC report [5]. In detail, the rail head was compressive and the web was tensile. According to the UIC/WEC report, the bottom was strain-free or had low tensile strain. In this research the bottom of the rail had high compressive strain. It is possible that the residual strain occurred from roller straightening. The third cut is thought to have relaxed the strain in the hoop direction the most. After the third cut, the positive and the negative were reversed by No. 5 and No. 7, and the compressive strain increased at No. 6. It seems that the specimen curved by the influence of the residual stress caused the positive and the negative to reverse by No .5 and No. 7.

Fig. 8. Strain distribution after the first cut. Fig. 9. Strain distribution after the second cut.

Fig. 10. Strain distribution after the third cut.
Residual Strain Evaluation of Rail using FEM Analysis

Fig. 12 (a), (b) and (c) show the internal residual strain distribution by FEM analysis, using the residual strain value obtained from cutting with the saw. The figures show the residual stress distribution $\sigma_{11}$, $\sigma_{22}$ and $\sigma_{33}$ respectively. It was similar to the result of Luzin [6]; the residual stress value of each stress component is low. For an un-used rail, the influence of the universal rolling [7] and the heat treatment, etc. can be supposed to be very small, though residual stress is created through these methods. It is uncertain whether it is possible to apply the test specimen with a high residual stress distribution such as used rails. In particular, it is thought that internal stress cannot be accurately evaluated because this analysis is a technique that balances the stress only on the surface. Therefore, it is necessary to examine the state of the internal residual stress of the test specimen with a high residual stress distribution in the future. It seems that the internal residual stress measurements by rod gauge and inherent strain method etc. improve accuracy.

![Fig. 11. Strain distributions of rail during cutting.](image)

![Fig. 12. Contour plots of residual stress distributions in the transverse direction of rail.](image)
Residual Stress Measurement of Rail using X-ray Methods

Fig. 13 shows the residual stress measurement result in the longitudinal direction of the rail. Comparing X-ray method with FEM analysis in the rail head part, the error margin was about 10%, and there was excellent agreement between the two values. Thus, it is thought that the residual stress distribution on the surface of the rail head part can be presumed by the FEM analysis. We can see the difference in the rail bottom from 100MPa to 300MPa. The following things are thought about the reason why there is a difference in the bottom of the rail. At present, we are examining this. The X-ray method measures residual stress in the surface of material. Thus, this method affects the surface finishing condition. The external force may often load the bottom of rail when the rail is kept. There is a possibility that the surface condition influenced the difference in the data. The FEM analysis does not receive the influence of the surface condition because the calculation is based on the value of the strain gauge. This difference was caused so that the influence of the surface condition on the X-ray method could be seen. Moreover, internal residual stress distribution will be evaluated using the neutron diffraction method in the future.

CONCLUSIONS
This research suggests of combining the strain gauge method with the FEM analysis. To sum up this research, the main conclusions are as follows;
(1) It was similar to the result of Luzin; the residual stress value of each stress component is low. For un-used rail, the influence can be supposed to be very small though the residual stress is formed by the universal rolling and the heat treatment, etc.

(2) There are good prospects of evaluating the state of the rail residual stress before the rail is destroyed by using both the strain gauge and the FEM analysis. It will be necessary to examine the state of the internal residual stress of the test specimen with a high residual stress distribution in the future.

(3) The FEM analysis result indicated an excellent agreement in the rail head with that of X-ray measurement. It is thought that the residual stress distribution of the material surface can be presumed by FEM analysis. The neutron diffraction method can evaluate internal residual stress distribution. The validity of the internal residual stress distribution by the FEM analysis can be evaluated effectively with the neutron diffraction method. This is what we will focus on in future research.

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REFERENCES