Application of Neutron Diffraction Technique to Industrial Materials

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Abstract. As an important industrial problem, the rolling contact fatigue damage is accumulated in rails during the repeated passage of trains over the rails, and rail failures may occur from the cracks grown in the rails. In order to prevent such rail failures, the estimation of the behavior of internal rail cracks is required based on the exact engineering analysis model as well as conducting rail test to search rail defects. The purposes of this paper are to apply the neutron stress measurement to rails, and to obtain residual stress state in the rails for the above purpose. The rail samples used were those that have been used in service line in Japan for about six years (222 million gross tons). The neutron measurement was conducted using the Residual Stress Analyzer (RESA) of the Japan Atomic Energy Agency (JAEA). The present measurement of stresses in rails by the neutron diffraction method was the first attempt in Japan.

Introduction

It is known that the rolling contact fatigue damage is usually accumulated in the railway rails during the repeated passage of trains over the rails, and sometimes cracks are initiated and propagate in the damaged layer of the rail. These rolling contact fatigue cracks may cause rail failures and influence the life of rails. In order to prevent these rail failures effectively, the rail defect management based on the engineering analysis is required. For this purpose, the growth rate of the internal crack in rails as a faction of contact stress due to the wheel, bending stress due to the train, thermal stress due to the change in the temperature and residual stress due to the manufacturing and the use in-service should be estimated accurately. Among these factors, the determination of residual stress, which has been performed destructively using the strain gauge method in general, is difficult to obtain entirely satisfactory result. However, the most promising method for measuring residual stress in rails is the method of neutron stress measurement that has been developed around 1990s. The method of X-ray stress measurement is also useful for the similar purpose, but it is limited to obtain only surface stresses. The penetration depth of neutrons is nearly 1000 times than that of X-rays so that the method of neutron stress measurement is useful to investigate on the stress state inside of materials. The purposes of this study are to apply the neutron stress measurement to rails, and to obtain residual stress state in the rails. The rail samples used were those that have been used in service line in Japan for about six years (222 million gross tons). The neutron stress measurement was conducted using the Residual Stress Analyzer (RESA) of the Japan Atomic Energy Agency (JAEA), Tokai, Japan. The measurement of neutron stresses in rails is the first attempt in Japan.

Experimental method

The rail specimens used were sampled from a straight line in a service line used in Japan for about 6 years (222 million gross tons). The rail steel was the JIS E 1101 60 kg normal rail. The chemical compositions and the mechanical properties are listed in Table 1. Considering the possible shape and weight of the sample to be measurable with the neutron facility used in this

Table 1, Chemical compositions and mechanical properties of railway rails used in this study.

Chemical composition (mass%)					Mechanical properties		
C	Si	Mn	P	S	Tensile strength (MPa)	Elongation (%)	Hardness (HB)
0.63〜0.75	0.15〜0.30	0.70〜1.10	0.030 under	0.025 under	800 over	10 over	235 over

Table 2, Neutron diffraction conditions.

Diffraction line	α-Fe110	α-Fe211
Wavelength of neutrons (nm)	0.2072	
Slit size (mm×mm)	3×3	
Distance from specimen to detector (mm)	50	
Lattice spaching in stress free d_0 (nm)	0.2027	0.117
Scanning range of 2θ (deg)	60 - 63	122.8 -126.4
Step width (deg)	0.1	0.1
Fixed time (sec)	15	60

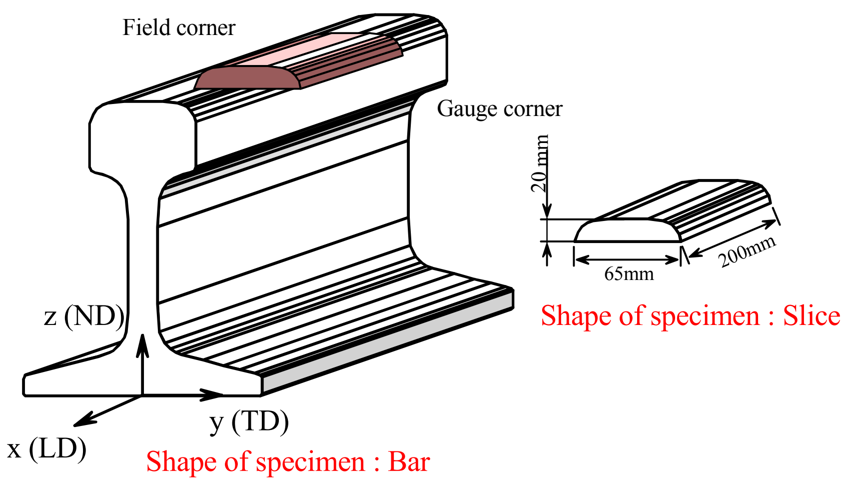


Fig. 1, Sampling of rail specimen used for the neutron stress measurement.

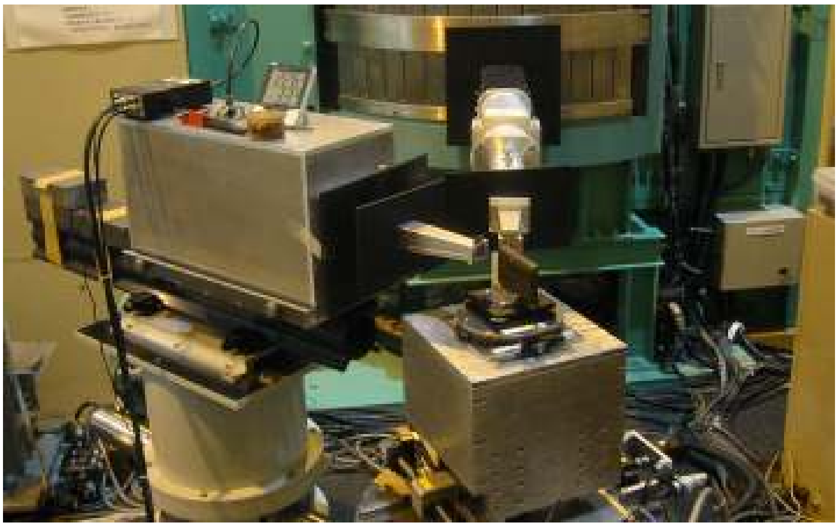


Fig. 2, Example of experimental set-up for neutron stress measurement of lattice spacing in transverse direction with RESA.

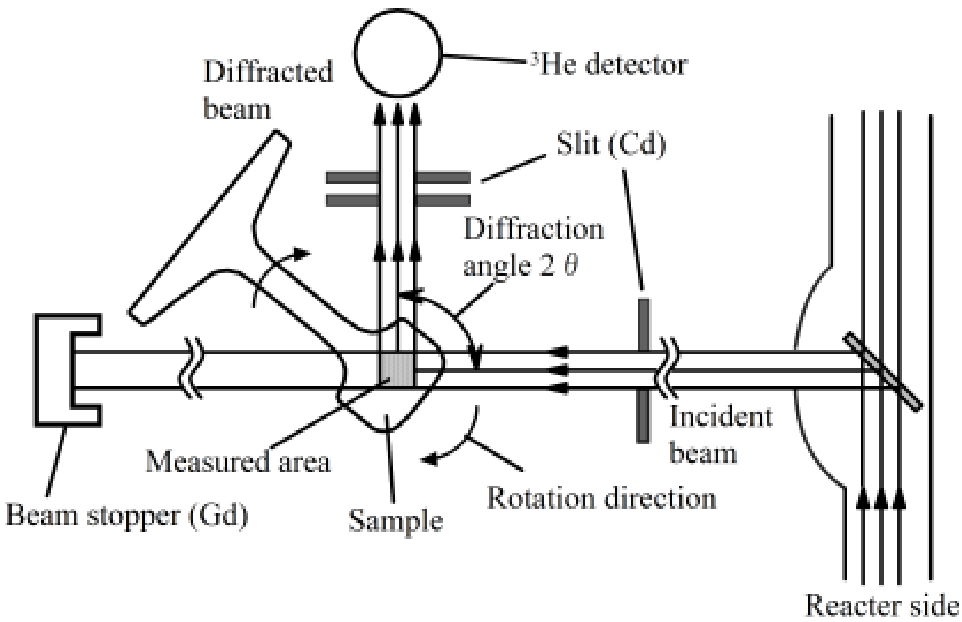


Fig. 3, Neutron optics used in this study.

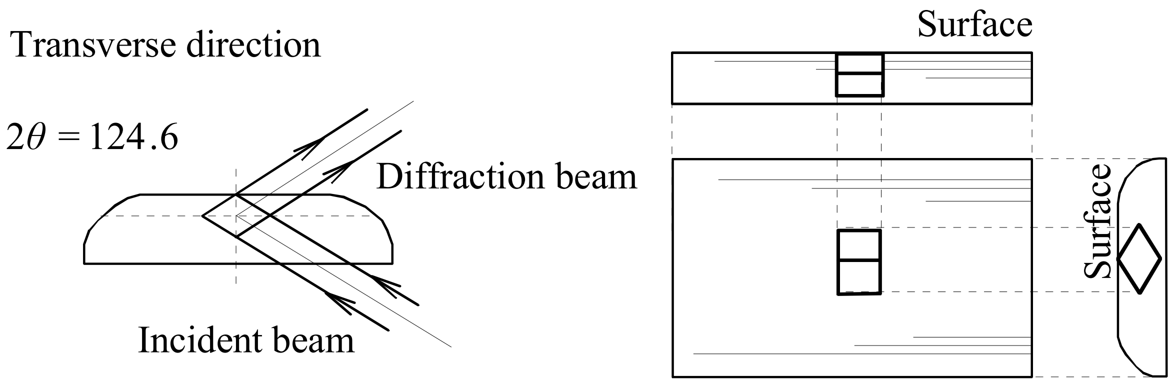


Fig. 4, Schematic of gauge volume for neutron stress measurement.

study (RESA), the specimen geometry was determined as shown in Fig.1. The neutron stress measurement was conducted with the residual stress analyzer, RESA, installed in the research reactor, JRR-3, of the Japan Atomic Energy Agency (JAEA). Fig. 2 shows a photograph of the experimental set-up for the present neutron stress measurement for rails. Fig. 3 shows the neutron optics used in this study. Fig. 4 shows the gauge volume in the sample where neutron diffract. The experimental conditions used in this study are listed in Table 2. Strains in three directions were measured by the neutron diffraction method. The first direction, the longitudinal direction (LD, parallel to x axis), was parallel to the rail. The second one, the normal direction (ND, parallel to z axis), was normal to the top surface of the rail. The third one, the transverse direction (TD, parallel to y axis), was normal to the other two directions (see Fig. 1). The diffraction lines used were 211 for both LD and TD directions, and 110 for ND direction in order to decrease the difference among their gauge volumes. The size of the slits used was 3 mm x 3 mm for both incidence and reflection beams (see Fig. 4). The size of the gauge volume was about 3.0 mm in the depth direction (ND), 5.0 mm in the direction of LD and 3.0 mm in the direction of TD. Diffraction profiles obtained were fitted by the Gaussian function to determine their peak positions, which correspond to the diffraction angle, 2θ. Then they converted to strains, ε, using the Bragg equation,

$$\varepsilon = \frac{d - d_0}{d_0} = (\theta_0 - \theta)\cot\theta_0 \qquad (1)$$

where d is the lattice spacing of the sample, d_0 is that in stress free state and θ_0 is the diffraction angle in stress free state. In this study, the same rail steel as the sample rail was used to obtain θ_0. The Euler cradle was also used to measure θ_0.

Stresses were converted from strains using the following equations,

$$\begin{aligned} \sigma_x &= \frac{E}{(1+\nu)(1\ \ 2\nu)}\left[(1\ \ \nu)\varepsilon_x + \nu(\varepsilon_y + \varepsilon_z)\right] \\ \sigma_y &= \frac{E}{(1+\nu)(1\ \ 2\nu)}\left[(1\ \ \nu)\varepsilon_y + \nu(\varepsilon_z + \varepsilon_x)\right] \\ \sigma_z &= \frac{E}{(1+\nu)(1\ \ 2\nu)}\left[(1\ \ \nu)\varepsilon_z + \nu(\varepsilon_x + \varepsilon_y)\right] \end{aligned} \qquad (2)$$

where ε_x is the strain in LD direction, ε_y is that in TD direction and ε_z is that in ND direction, E is Young's modulus, and ν is Poisson's ratio. In this study, theoretical values calculated by the Kröner model, E=224 GPa and ν=0.28, were used.

Experimental results

Fig. 5 shows an example of diffraction profile obtained from the rail sample. The true lines in the figure are Gaussian curve fitted to determine the diffraction angle. In the figure, two data are plotted, one was obtained from the annealed rail steel in which residual stress was released, the other was obtained from the rail sample. It is found that the Gaussian fitting is effective to the present neutron diffraction data. The similar good tendency was also seen at the other diffraction data. It is also seen that the both diffraction profiles have a gap in the transverse axis, 2θ, which means the existence of residual strain in the corresponding gauge volume measured. The similar data analysis was conducted to other measuring directions, TD and ND, and normal stress components were calculated with Eq. 1. Fig. 6 shows an example of residual stresses obtained. It is found that the three normal stresses are compressive all over the range in the figure, and have similar values each other without a part of σ_z. Residual normal stress components are compressive near the surface of the rail, and they decrease inside to compressive side in almost proportion to the depth after showing the peak at the depth of 2.5 mm.

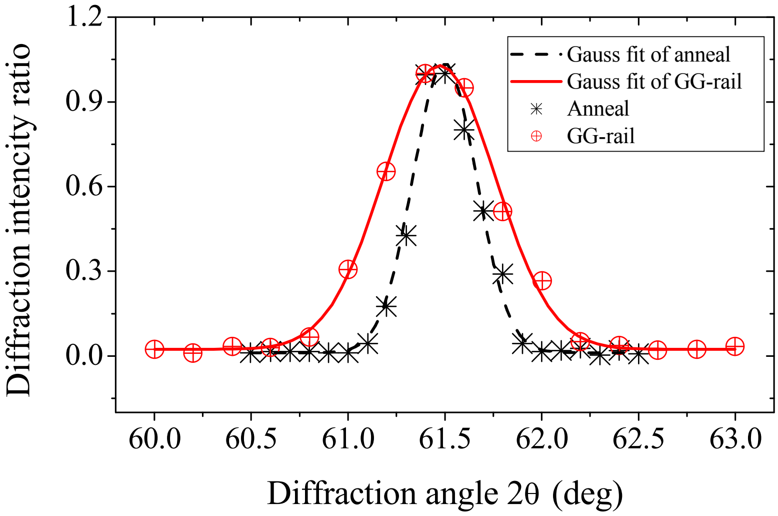
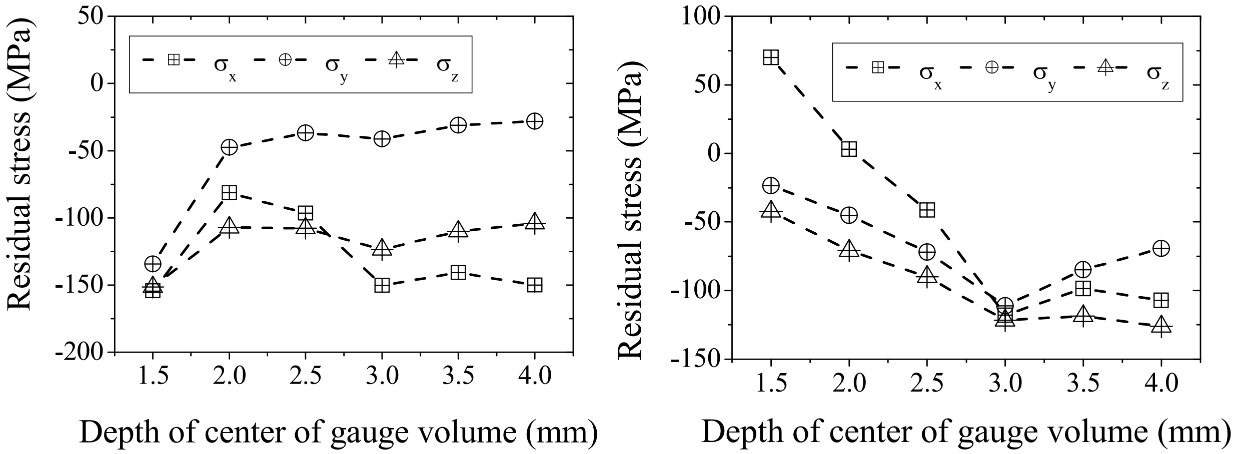


Fig. 5, Example of diffraction pattern obtained from rail at point P1 (z=2.0 mm) in LD direction.



(a) FC15mm of GG-rail. (b) GC15mm of GG-rail

Fig. 6, Residual stresses in rail obtained by the neutron stress measurement.

It is also seen that the normal stress components have similar values each other except a part of σ_Z. It is not clear why the residual stress state in the rail was a hydrostatic. More research needs to be conducted in order to answer that question. However, the fact that a compressive stress layer surrounding rail head with about 10mm thickness restricts inside deformation from three sides may be one of the reasons.

The similar neutron stress analysis was conducted at other locations in the transverse direction of the rail as shown in Fig. 6 (b). As a result, all stresses obtained were compressive ranged from 0 (MPa) to -200 (MPa). The distribution patters are different from the location in the transverse direction of the rail. This is because the influence of the contact condition between the rail and wheels of trains passing over the rail.

Conclusions

The objective of this research is to clarify the applicability of neutron rays to the measurement of residual stress of railroad rail nondestructively. The authors believe that the possibility was confirmed and future research is necessary to get more data about many rails used in various

conditions.
1. Residual stresses in the rail under the top surface were almost compressive without small exception where small tensile stresses were built up.
2. The depth profiles of residual stresses vary from the location in transverse direction. The steepest gradient of residual stress was observed at the location of 7.5 mm away from the center of the rail.
3. The residual normal stresses obtained from the rail have similar values each other almost over the area where the measurement was conducted in this study.

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