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Strain Measurement in the Depth of the Order of Millimeter Using High Energy White X-rays

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Abstract. The strain in the bulk of material was evaluated using high energy white X-rays from a synchrotron radiation source of SPring-8 in Japan. An austenitic stainless steel (JIS-SUS304L) was used for a specimen. The specimen of 5 mm thickness was subjected to the bending. The internal strain of it could be measured using white X-rays which range of energy from 60 keV to 125 keV. The measurement of the internal strain with a high accuracy was accomplished using the strain data from several lattice planes of γ-Fe simultaneously. Furthermore, the measurement error of strain could be decreased by using the diffracted beam with high energy, high peak count and the similar profile with the Gaussian distribution. The results showed that the high energy white X-rays is effective for the internal strain measurement in the depth of the order of millimeter.

Introduction

White X-ray beam has a wide wavelength range. The shorter wavelength X-rays will penetrate deeper below the surface. Therefore, information of interplanar spacing from the surface to the deeper layers can be obtained simultaneously. The energy dispersive method using white X-rays may be very useful for a nondestructive evaluation of residual stress along the depth direction in a subsurface layer. We have been developed residual stress measurement methods using relatively low energy white X-rays [1]. In resent years, G. Brusch *et al*. [2] and W. Reimers *et al*. [3] have reported the measurement of residual stress in materials by diffracted X-ray transmitted through the specimen using high energy white X-rays. Although the measurement using high energy white X-rays is very useful for a nondestructive evaluation of stress in the bulk of material, it has not been established yet. This paper presents a basic research on the measurement of strain in the depth of the order of millimeter of material by using high energy white X-rays from a synchrotron radiation source of SPring-8 in Japan. An austenitic stainless steel is used for the specimen that is subjected to bending. The bending strain of the specimen is obtained directly from a rate of change of peak energy of diffracted X-rays transmitted through it.

Energy Dispersive Method

Because white X-ray beam has a wide energy range, an interplanar spacing *d* of crystal should be measured under the fixed diffraction angle 2θ. Therefore, the fundamental equation of energy dispersive method is expressed as Eq.1 based on the Bragg law.

$$d = \frac{hc}{2\sin\theta}\frac{1}{E_n}, \qquad (1)$$

where h is the Planck's constant, c is the velocity of light and E_n is the energy value of diffracted X-ray. Differentiation of Eq.1 gives Eq.2 because the Bragg angle θ is constant in this method.

$$\Delta d = -\frac{hc}{2\sin\theta \cdot E_n^2}\Delta E_n . \qquad (2)$$

Combination of this equation with Eq.1 shows that

$$\frac{\Delta d}{d} = -\frac{\Delta E_n}{E_n} = \frac{E_n^0 - E_n}{E_n}, \qquad (3)$$

where E^0_n is the peak energy value of the diffracted beam profile of a non-strained specimen and E_n is that of a strained specimen respectively. The strain ε is therefore obtained from Eq.3 using the diffracted X-ray energy.

Equation 3 demonstrates that the accuracy of strain measurement increases with the energy of X-ray and is independent of the diffracted angle 2θ. These are major characteristics of energy dispersive method differing from the angle dispersive method.

Experiment Procedure with High Energy White X-rays

An austenitic stainless steel (JIS-SUS304L) was used for a specimen as shown in Fig.1. Grain size of it was 30μm or more. A beam of the specimen, which has a thickness of 5 mm, a width of 10 mm and a length of 20 mm, was bent by clamp load of bolt. It was then subjected to a bending moment and a little tension. Surface strains of the beam were measured by strain gauges. Maximum strain of tension side was 770×10^{-6} and that of compression side was -740×10^{-6}.

The strain in the beam was measured using high energy white X-rays from a synchrotron radiation source of BL14B1 of SPring-8 in Japan. The white X-ray beam, which has a height of 50μm and a

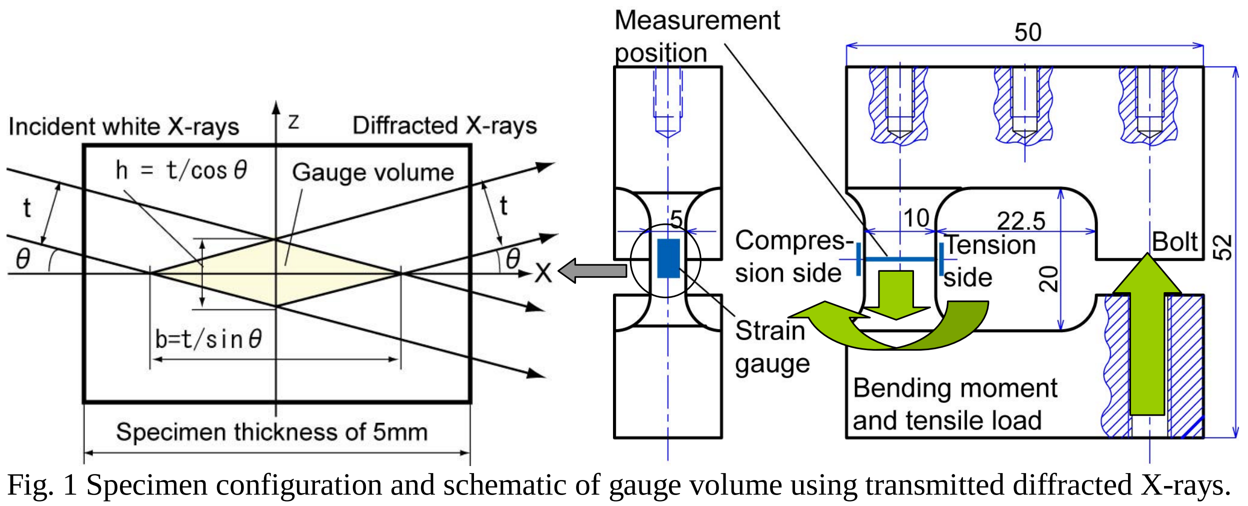

Fig. 1 Specimen configuration and schematic of gauge volume using transmitted diffracted X-rays.

width of 300μm, was incident in it with the Bragg angle θ of 5 degrees and fixed time of 500 second. In this case, a gauge volume for strain measurement was 574x50x300 μm^3. The interplanar spacing of the crystal in the measurement position indicated in Fig.1 was measured using diffracted X-rays transmitted through the beam of specimen. The Gaussian equation was used to decide on the peak energy of the diffracted beam profile at each lattice plane. The bending strain was calculated by Eq.3 using the peak energy obtained from the non-strained and the strained specimens respectively.

An energy calibration equation must be derived to convert a channel number into X-ray energy because the number of counts corresponding to the diffracted X-ray intensity is recorded at each channel of a multi channel analyzer (MCA). In this experiment, this equation was obtained from the measurement of five kinds of mono-energetic source of Mo, Ag, Ta, Pt and Pb, which was given by

$$E_n = 0.252334 + 0.042486 \times Channel\ number\ of\ MCA \quad \text{[keV]}. \tag{4}$$

Results and Discussion

A translatory oscillation of ±2 mm along the X-direction and a rotary oscillation of ±2 degree in the X-Z plane of the specimen were done simultaneously because the diffracted X-ray peak counts at each measurement position fluctuated with the relationship between the grain size and the X-ray gauge volume. Diffracted X-ray profiles at all measurement positions are shown in Fig.2. It was confirmed that the interplanar spacing of the crystal in the specimen of 5mm thickness can be measured using white X-rays which range of energy from 60keV to 125keV. In this experiment, W-Kα1 radiation was detected from a collimator made of tungsten steel. By reason that it has a constant energy value, measured values of peak energy of the diffracted X-ray must be modified so that the value of W-Kα1 coincides with the theoretical value.

Figure 3 indicates the strain distribution of the specimen using the strain data of γ-Fe(620) lattice plane as an example. The strain distribution measured by each lattice plane had large errors compared with the applied strain. When the peak count and the coefficient of determination of Gaussian fitting of the diffracted beam profile were low, the measurement accuracy almost decreased. Therefore, strain data of several lattice planes of γ-Fe were used simultaneously to determine the strain distribution. Furthermore, the diffracted beam with high energy, high peak count and the profile which is close to

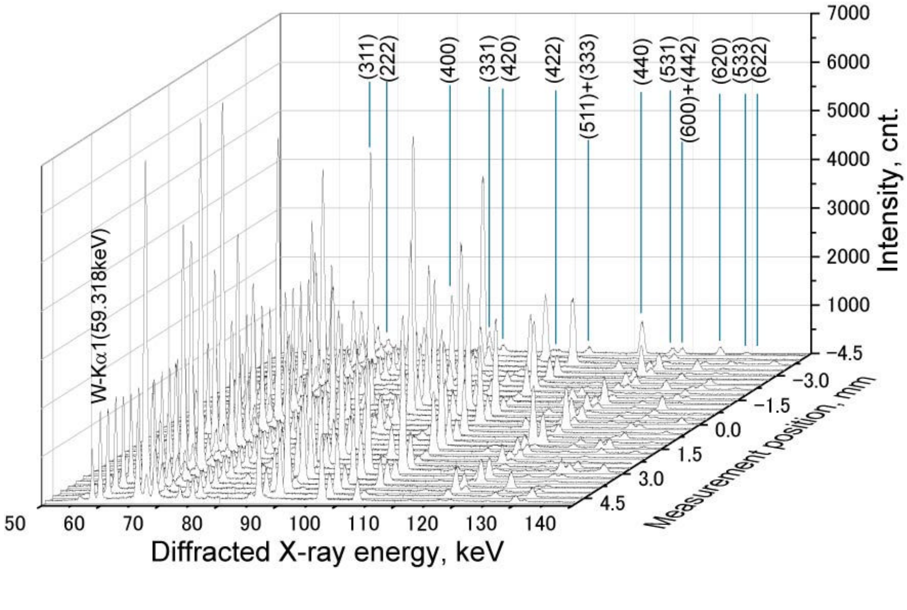

Fig. 2 Distribution of diffraction profiles of SUS304L by white X-rays.

the Gaussian distribution was used to calculate the measurement strain. Figure 4 shows the strain distribution obtained from strain data of four lattice planes. The close agreement between applied and measured strain distribution was obtained. The results showed that the high energy white X-rays is effective for the internal strain measurement in the depth of the order of millimeter of the material.

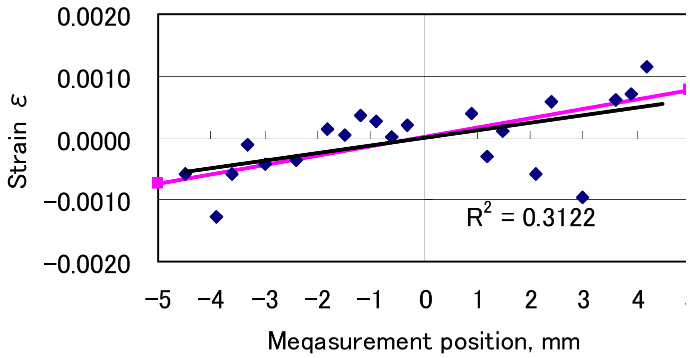

Fig. 3 Strain distribution of SUS304L under bending load obtained from strain data of γ-Fe(620) lattice plane.

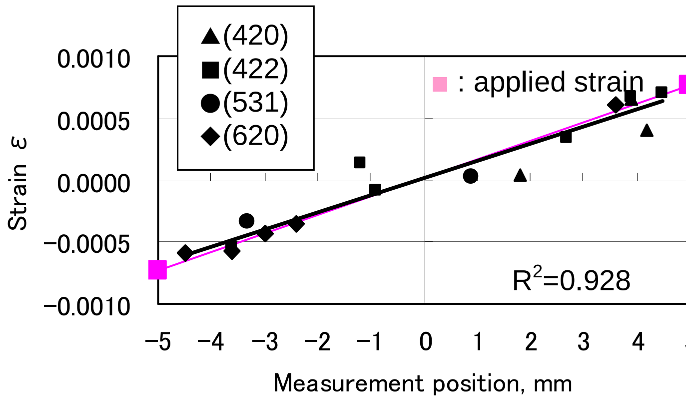

Fig. 4 Strain distribution of SUS304L under bending load obtained from strain data of four lattice planes.

Conclusion

The austenitic stainless steel specimen of 5 mm thickness was subjected to bending. The internal strain measurement of it was carried out using high energy white X-rays from a synchrotron radiation source of BL14B1 of SPring-8 in Japan. As a result, the internal strain of it could be evaluated using white X-rays which range of energy from 60 keV to 125 keV. The accuracy of the measured strain could be increased by using the strain data from several lattice planes simultaneously. The measurement error of strain was decreased by using the diffracted beam with high energy, high peak count and the profile which is close to the Gaussian distribution. It was confirmed that the high energy white X-rays is effective for the internal strain measurement in the depth of the order of millimeter of the material.

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