DEVELOPMENT OF MEASURING SYSTEM FOR STRESS BY MEANS OF IMAGE PLATE FOR LABORATORY X-RAY EXPERIMENT

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ABSTRACT

A single exposure X-ray incidence method for determining stress using the whole part of the Debye-Scherrer ring was studied. An image plate (IP) was used in this study as an area detector. A stress measuring system using an X-ray two-dimensional detector was developed. This was designed in order to be used in the authors’ X-ray laboratory. The background and the purpose of this study is to point out that it is possible to carry out the stress measurement using a two-dimensional X-ray detector, and that this method has advantages such as it is less time-consuming and its effective use of the diffraction data from the material. However, a sufficient amount of studies on the measuring systems for this kind of X-ray stress measurement have not been made, so that both the accuracy and the reliability of the final results obtained are not satisfactory at the present stage. In particular, the accuracy of the determination of the exact center of the diffraction ring, flatness of the measuring plane of IP at a microscopic level, and exact distance between the specimen and the detector (IP) is required in order to determine stress as correctly as the ordinary X-ray goniometer method (the sin^2ψ method). In this study, the authors attempted to develop a measuring system that satisfies the above requirements. The validity of the authors’ new equipment was confirmed by experiment, in which the specimen was loaded under the bending stress during the X-ray stress measurement, and the stresses obtained were compared to the applied ones.

INTRODUCTION

A diffraction ring induces deformation and its radius varies depending on the central angle when stress is applied to the material which was irradiated by X-ray beams. Using this phenomenon, it becomes possible to perform an X-ray stress measurement from a diffraction ring detected by an X-ray area detector[1-3]. This method does not require a precise and complicated instrument for measuring diffraction angle accurately such as a diffractometer. Instead, only a holder for an area detector is needed. Thus, the method becomes much simpler than the ordinary X-ray stress measurement. Since the single-exposure method can also be used, less time-consuming and effective use of diffraction data are expected.

On the other hand, it is necessary in the present method to develop an analytical program for precise image processing of diffraction data, as well as to use a precise X-ray camera for measuring diffraction rings as accurately as a diffractometer. These problems have not been considered before.
In this study, we developed a new X-ray stress measuring system in which an image plate was used as an area detector, and above mentioned matters are considered. An experiment was made for the purpose of examining the validity of our measuring system. In the experiment, the X-ray stress measurement was performed with our new system while the steel specimen was loaded with a four-point-bending device.

**DESIGN AND MANUFACTURE OF X-RAY STRESS MEASUREMENT DEVICE WITH IMAGE PLATE**

An X-ray stress measurement device with an image plate is very simple compared with an conventional instrument consisting of a gonoimeter. This is confirmed by our previous experiment in which we performed an X-ray stress measurement using our laboratory-made device and obtained similar measurement accuracy as that obtained using an ordinary X-ray stress measurement method[1,4-5].

![Figure 1. Schematic of the present X-ray device.](https://example.com/figure1.png)

It is also important to accomplish a close setting of the distance between the specimen and the image plate, as well as to obtain the exact position of the center of the diffraction ring (that is the center of the incident beam) from diffraction image data.

Thus, we designed the device as follows: (1) An image plate sheet was adhered to the exact plane which was machined precisely by an absorbing vacuum pump through small holes on the image plate holder; (2) An image plate holder was designed to have high stiffness; (3) Aluminum spacers were used for maintaining the distance between the image plate and the specimen; (4) A diffraction ring of iron powder was double-exposed on the image plate in order to determine the center of the diffraction ring, and analytical programming was developed for this purpose. Figure
shows a schematic of the present device.

THE PRINCIPLE OF Є-ANGLE-BASED X-RAY STRESS MEASUREMENT FOR DETERMINING STRESS

Consider a diffraction ring which emerged from the material when orientation of the incidence X-ray beam is expressed in terms of Є_0 and Є_0 as shown in Figure 2. Direction cosines, n_3i (i=1,2,3), are defined to express the normal at lattice plane of crystals (L_3 axis) from which diffraction beams arrive to a point on the diffraction ring on IP where central angle is defined as Є, as shown in Figure 3. We then have[5]

\[
\begin{align*}
    n_{31} &= \cos \eta \sin \psi_0 - \sin \eta \cos \psi_0 \cos \alpha \\
    n_{32} &= \sin \eta \sin \alpha \\
    n_{33} &= \cos \eta \sin \psi_0 + \sin \eta \sin \psi_0 \cos \alpha
\end{align*}
\]  

(1)

We write \( S_i \) for the sample coordinate system, and \( L_i \) for the laboratory coordinate system which can be obtained by rotating the \( S_i \) system to coincide \( S_3 \) to \( L_3 \). By denoting the normal strain in the direction of \( L_3 \) by \( \varepsilon_3 \), we have

\[
\varepsilon_\alpha = \varepsilon_{33} = n_{3i}n_{3j}\varepsilon_{ij}^S,
\]  

(2)

where \( \varepsilon_{ij}^S \) indicate the strains with respect to the \( L_i \) system, their relation to the stress \( \sigma_{ij} \) in the \( L_i \) system is expressed

\[
\varepsilon_{ij}^S = \left( \frac{s_i}{2} \right) \sigma_{ij}^S + \delta_{ij}(s_1)\left( \sigma_{11}^S + \sigma_{22}^S + \sigma_{33}^S \right),
\]  

(3)

where \( s_1 \) and \( s_2 \) are X-ray elastic constants and have the following equations using Young’s modulus \( E \) and Poisson’s ratio \( \nu \), respectively.

\[
s_1 = -\frac{\nu}{E}, \quad \frac{s_2}{2} = \frac{1+\nu}{E}
\]  

(4)

Considering four strains, which can be obtained from diffraction beams having central angles, as \( \alpha, -\alpha, \pi+\alpha \) and \( \pi-\alpha \), as shown in Figure 2, and denoting them as \( \varepsilon_{\alpha}, \varepsilon_{-\alpha}, \varepsilon_{\pi+\alpha} \) and \( \varepsilon_{\pi-\alpha} \), respectively, the new parameter \( a_1 \) is defined from these strains[2].

\[
a_1 \equiv \frac{1}{2}\left( (\varepsilon_{\alpha} - \varepsilon_{\pi+\alpha}) + (\varepsilon_{-\alpha} - \varepsilon_{\pi-\alpha}) \right)
\]  

(5)
Expressing eq.(5) in terms of stress using eqs.(1)〜(3), we have

$$a_1 = -\left(-\frac{s_2}{2}\right) = \left[\left(\sigma_{11} - \sigma_{33}\right)\sin 2\psi_0 + 2\sigma_{13}\cos 2\psi_0\right]\sin 2\eta\cos\alpha,$$

(6)

where S denotes the sample coordinate system. As it is reasonable to assume that $\sigma_{13} = \sigma_{23} = 0$, the following argument will be made. Consequently, we have the next equation from eq.(6)

$$\sigma_{11} - \sigma_{33} = -\left(\frac{2}{s_2}\right)\frac{1}{\sin 2\eta}\frac{1}{\sin 2\psi_0}\left(\frac{\partial a_1}{\partial \cos\alpha}\right).$$

(7)

We can see that using eq(7) one can obtain stress $(\sigma_{11} - \sigma_{33})$ from the slope in the relation between $a_1$ vs. $\cos\alpha$, which can be derived from a single diffraction ring recorded on IP. Selecting an adequate condition of X-ray diffraction, one would be able to record both diffraction rings emerged from the matrix and the second phase on a single IP at the same time. In such a case, we can obtain each phase stress at the same time for each constituent in the material. Moreover, it is known that macro- and microstresses can be obtained from all phase stresses in the constituents. The principle mentioned above was first proposed by Taira and Tanaka for the plane stress analysis, and was modified to the triaxial analysis by Sasaki and Hirose[2, 5].

**EXPERIMENTAL**
Material and Specimen

Ferritic(α) and austenitic(γ) dual-phase stainless steel (JIS-SUS329J4L), which was manufactured by a continuous casting process, was used in the experiment. Specimens used in the experiments were fabricated through the process of cutting, milling, and grinding from a rolled plate (length of 1524 mm, thickness of 6 mm and width of 300 mm) to the final configuration having a length of 60 mm, a thickness of 5 mm, and a width of 10 mm. The longitudinal direction of the specimen coincided with the rolling direction. The specimen was then quenched in water after keeping it at 1373 K for 60 min. A single-edge notch, which has 3mm length, 1mm width and 0.5mm notch tip curvature, was introduced at the center using a fine cutter. Figure 3 shows a microstructure of the specimen and figure 4 shows the overall specimen shape and the measuring area.

![Figure 4. Optical micrograph of the material used in this study.](image1)

![Figure 5. Dimensions of the specimen having single notch and area where the X-ray measurement was made.](image2)

Conditions for X-ray Diffraction

Each phase stress in the α and γ phases of the specimen were measured using the X-ray stress measurement method under applied stress by means of a two-point-bending device. The applied stress was monitored by means of a strain gauge bonded to the specimen on the opposite face to the X-ray irradiated one. The applied strain was ranged from 0 to 1000 × 10⁻⁶ with an interval of 250 × 10⁻⁶. Similar X-ray conditions were used for another specimen except the use of V-K radiation for the measurement of the γ phase. In order to obtain the distribution of the residual stress in the damaged layer, electrochemical polishing was used.

Cr-K₂ radiation was used under a tube voltage of 30 kV and tube current of 10 mA. The diameter
of the collimator used was 1 mm. The incidence angle ($\psi_0$) of the X-ray beam was $\psi_0=30^\circ$. X-ray conditions are summarized in Table 1. An IP sheet of 5 in $\times$ 5 in, which was set in the X-ray camera based on the Laue method, was used. The read-out system, which is on the market (Rigaku R-AXIS 2), was used in order to store digital image data of diffraction images into a computer. In the system, the IP sheet is put on a drum which rotates during the read-out time, and is irradiated by a laser beam. Diffraction intensity is analyzed by means of the intensity of light illuminated from the IP. The resolution for the read-out process was 100 $\mu$m. Thus, the diffraction pattern consisted of 1150 $\times$ 1140 pixels. The location of the incidence X-ray beam on the IP image was roughly determined from the display of a computer. This location was used as an initial one for the precise determination of the exact center of the diffraction ring which is explained in references 4 and 5. Diffraction profiles were obtained as distributions of diffraction intensity along the radial direction of the diffraction ring from the location of the incidence beam determined above. These profiles were derived from $\alpha=0$ to $\alpha=359^\circ$ with an interval of 1$^\circ$ and used for stress analysis. Figure 6 shows lines on which X-ray measurement was conducted. The figure shows in the case of $\theta=90^\circ$ the projection angle $\varphi$ ranged from 0$^\circ$ to 180$^\circ$ with 15$^\circ$ intervals. The line measurement of stress was conducted at each projection angle, and the stresses obtained (projection) were reconstructed to stress distribution.

RESULTS AND DISCUSSION

Figure 7 shows the stress distribution in the vicinity of the notch tip shown in Figure 6. The plots in the figure indicate the obtained data and the curve indicate the theoretical value which was obtained. The X-ray diffraction conditions for dual phase stainless steel are shown in Table 1.

### Table 1. Conditions of X-ray diffraction experiment for dual phase stainless steel.

<table>
<thead>
<tr>
<th>Characteristic X-ray</th>
<th>Cr-K$_\alpha$</th>
<th>Cr-K$_\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffraction line,hkl</td>
<td>$\alpha$ 211</td>
<td>$\gamma$ 311</td>
</tr>
<tr>
<td>Mechanical Young’s modulus E,GPa</td>
<td>206</td>
<td>187</td>
</tr>
<tr>
<td>Mechanical Poisson’s ratio</td>
<td>0.28</td>
<td>0.30</td>
</tr>
<tr>
<td>Tube voltage , kV</td>
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<td></td>
</tr>
<tr>
<td>Tube current , mA</td>
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<td></td>
</tr>
<tr>
<td>Collimator $\phi$ , mm</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$\psi_0$ angle , deg</td>
<td>Specimen 30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe-powder 0</td>
<td></td>
</tr>
<tr>
<td>Camera length , mm</td>
<td>Specimen 75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe-powder 45</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. X-ray irradiated lines in square area in front of notch tip. The square shows the area where the stress measurement was made. Lines in the square shows locations irradiated by X-ray.
Figure 7. Distribution of normal stress perpendicular to notch direction. Plots indicate mean stress along each line. The stress shows the phase stress in ferritic phase in the material.

calculated based on the linear fracture mechanics. The difference between experimental data and the theoretical value can be explained from the difference of the sampling area. Namely, the measurement was made along the lines shown in Figure 6 in order to obtain a smooth diffraction ring from a bit coarse-grained sample, and the theory gives stresses at each point. The triangle marks (\(\triangle\)) indicate the result of the plane stress analysis using the \(\cos \alpha\) method, and the closed circles (\(\bullet\)) indicate the result of the triaxial stress analysis. We can see that the latter agrees with the theory compared with the former, and the stress concentration is steeper. This is because the triaxial stress state was built up near the notch tip.

CONCLUSIONS

A new device was designed for X-ray stress measurement using an image plate, and the device was applied to obtain the mean stress on a line near the notch tip in order to reconstruct the distribution of stress. The distribution of stress inside the area shows good agreement with the theoretical one, and the stress outside the area does not.

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REFERENCES