INFLUENCE OF IMAGE PROCESSING CONDITIONS OF DEBYE SCHERRER RING IMAGES IN X-RAY STRESS MEASUREMENT USING AN IMAGING PLATE

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ABSTRACT
This paper describes the study of the possibility of x-ray stress measurement in which stresses are obtained by analyzing the whole of one diffraction ring detected with a two-dimensional x-ray detector called an imaging plate (IP). The theory of the stress determination proposed by Taira et al (1978) was shown and advanced to make measurable all plane stress components. The experiment showed good agreement with stresses applied mechanically.

INTRODUCTION
X-ray stress measurement is usually performed with the well known \( \sin^2 \psi \) method (1). It is, however, also possible with a method which uses the whole of one diffraction ring obtained with a single incident x-ray beam (2). The principle of this method was first developed by Taira et al (1978) (2). Recently Yoshioka et al (3,4,5) carried out this kind of stress measurement using a newly developed two-dimensional x-ray detector called an Imaging Plate (IP) (6,7,8) based on Taira's method. Schubert et al also reported the use of IP for determining stress from the whole diffraction ring (9-12). In this study, we developed a measuring system for this unique method of x-ray stress measurement and examined its possibilities.

The measuring system used in this study consists of a UNIX workstation for control and digital image data processing, machine read-out of image data from the IP, a back-reflection Laue camera with stress loading device, and an x-ray generator of rotating target type. A method for determination of the center of x-ray incidence beam using a stress-free powder material was developed and used in this study. The accuracy of the present method was evaluated experimentally by comparing the results to stresses applied mechanically.
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THEORY OF STRESS DETERMINATION

The coordinate system shown in Fig. 1 is used. We suppose that a diffraction ring can be
detected on the IP with incidence angles of $\psi_0$ from the z axis and $\phi_0$ from the x axis. The strain $\varepsilon_\alpha$, which
is in the direction of angle $\alpha$ from $-\eta$ as illustrated in Fig. 1, is expressed using strains in the
sample system, $\varepsilon_{xx}, \varepsilon_{yy}, \tau_{xy}, \cdots$, as follows:

$\varepsilon_\alpha = n_1^2 \varepsilon_x + n_2^2 \varepsilon_y + n_3^2 \varepsilon_z + n_1 n_3 \gamma_{xy} + n_2 n_3 \gamma_{yz} + n_1 n_2 \gamma_{zx}$

(1)

where $n_i (i=1,2,3)$ are direction cosines of the normal of the diffraction plane with respect to the axes
in the sample system. They are expressed as:

$n_1 = \cos \eta \sin \phi_0 \cos \phi_0 - \sin \eta \cos \phi_0 \cos \alpha - \sin \eta \sin \phi_0 \sin \alpha$
$n_2 = \cos \eta \sin \phi_0 \sin \phi_0 - \sin \eta \cos \phi_0 \sin \alpha + \sin \eta \cos \phi_0 \sin \alpha$
$n_3 = \cos \eta \cos \phi_0 + \sin \eta \sin \phi_0 \cos \alpha$

(2)

Assuming a plane stress state in the diffraction volume in the sample, the following constitutive
relations are used.

$\varepsilon_x = \frac{1}{E} \left( \sigma_x - \nu \sigma_y \right)$
$\varepsilon_y = \frac{1}{E} \left( \sigma_y - \nu \sigma_x \right)$
$\varepsilon_z = -\frac{\nu}{E} (\sigma_x + \sigma_y)$
$\gamma_{xy} = \frac{2(1+\nu)}{E} \tau_{xy}$
$\gamma_{yx} = \gamma_{zx} = 0$

(3)

Fig. 1  Explanation of the present method and definitions of symbols used in the text.
where \( E \) is Young's modulus and \( v \) is Poisson's ratio. Substituting eqs(2) and eqs(3) into eq(1) we have the following equation:

\[
\varepsilon_a = \sigma_x \left[ \frac{1}{E} \left( n_1\nabla^2 - v(n_2^2 + n_3^2) \right) \right] + \sigma_y \left[ \frac{1}{E} \left( n_2\nabla^2 - v(n_1^2 + n_3^2) \right) \right] + \tau_{xy} \frac{2(1 + v)}{E} (n_1 n_2) \tag{4}
\]

where \( n = \pi / 4 - \theta \). Substituting \( -\alpha, \pi + \alpha \) and \( \pi - \alpha \) for angle \( \alpha \) in eq(4), respectively, we will consider the following relations:

\[
\bar{\varepsilon}_a = \frac{1}{2} \left[ (\varepsilon_i - \varepsilon_{\pi + \alpha}) + (\varepsilon_{-\alpha} - \varepsilon_{\pi - \alpha}) \right] \tag{5-1}
\]

\[
\bar{\varepsilon}_a = \frac{1}{2} \left[ (\varepsilon_i - \varepsilon_{\pi + \alpha}) - (\varepsilon_{-\alpha} - \varepsilon_{\pi - \alpha}) \right] \tag{5-2}
\]

Calculating the above equations from eq(4) we have:

\[
\bar{\varepsilon}_a = \frac{1 + \nu}{E} \left[ \sin^2(\varphi_0 - \eta) - \sin^2(\varphi_0 + \eta) \right] \cos \alpha \cdot \sigma_x \tag{6-1}
\]

\[
\bar{\varepsilon}_a = -\frac{2(1 + \nu)}{E} \sin 2\eta \sin \varphi_0 \sin \alpha \cdot \tau_{xy} \tag{6-2}
\]

These equations show linear relations in \( \cos \alpha \), or \( \sin \alpha \), and we can obtain \( \sigma_x \) and \( \tau_{xy} \) from their slopes as shown by the following equations.

\[
\sigma_x = \frac{E}{(1 + \nu) \sin^2(\varphi_0 - \eta) - \sin^2(\varphi_0 + \eta)} \times \left[ \frac{\partial \bar{\varepsilon}_a}{\partial \cos \alpha} \right] \tag{7-1}
\]

\[
\tau_{xy} = \frac{E}{2(1 + \nu) \sin 2\eta \sin \varphi_0} \times \left[ \frac{\partial \bar{\varepsilon}_a}{\partial \sin \alpha} \right] \tag{7-2}
\]

The theory stated above was first proposed by Taira et al(2). Recently we advanced this method to be able to obtain the stress \( \sigma_y \) together with the other plane stress components(9,10). So this method enables us to obtain all the plane stress components from only one diffraction ring.

**EXPERIMENTAL**

Diffraction rings were detected on an IP of size 127x127 (mm) using an x-ray generator of rotating target type and a back reflection Laue camera. Diffraction intensity was read out as 1140x1150 (pixel) from the IP based on the phenomenon of luminescence by a laser beam using a Rigaku RAXIS-II. The resolution was 100 (\( \mu \)m). Diffraction profiles in the radius direction from the center of the Debye ring were obtained by processing the image data in the UNIX workstation. Diffraction angles were also determined by a similar manner based on the half value breadth method. The center of the incident x-ray beam was determined from a diffraction ring double-exposed on the IP and assuming it to be a real circle. The diffraction angles which had been determined in advance with a temporary beam center, were corrected by the accurate center of the
incidence beam and then used for the calculation of stresses.

The material used was steel of length 55(mm) x width 10(mm) x thickness 5(mm) which was annealed at 923K for 30 min. and cooled in the furnace. Diffraction conditions were: Cr-Ka radiation at 30(kV) and 50(mA), 1(mm) diameter collimator, 80(mm) distance between specimen and IP, 50(mm) distance between stress free powder and IP, 150(sec) of exposure time for the specimen, 120(sec) for the powder. The stress measurement was performed on both a non-polished surface and one polished with emery paper.

**EXPERIMENTAL RESULT**

Fig.2 shows an example of photographs of diffraction rings of the 211 reflection from both the specimen and the Fe-powder obtained in this study. The photograph was taken from a computer screen. Fig.3 shows diffraction profiles in the direction of $\alpha=0$ obtained by processing the IP image data on the workstation. The left peak is from the powder and the right one from the specimen in each figure. After determining peak locations of these profiles for the whole of the diffraction ring (one-degree-intervals of the angle $\alpha$), the results of which are shown in Fig.4, and correcting the center of the x-ray beams using powder data, we carried out stress determination based on the cos $\alpha$ method.

![Fig. 2 Diffraction rings obtained from the non-polished specimen (left), and that polished with emery paper (right).](image)

![Fig.3 Diffraction profiles for the non-polished specimen (left), and that polished with emery paper (right).](image)
Fig 5 shows the relations expressed in eq(6-1) and eq(6-2). We can see linear relations for each data set which proves the validity of the theory. As stated in the section on the theory, stress values can be calculated from the slopes of the straight lines in Fig.5. The stresses obtained are plotted against applied stresses in Fig.6. The result of the present method agree well with the applied stresses. The stresses determined similarly for the specimen polished with emery paper were also plotted against the applied stresses in the figure. Though the stress level was down because of the compressive stress due to the polishing, the correspondence to the applied stress was almost the same as for the non-polished data.

Recently, the measurement theory has been advanced by the authors to be able to obtain the component $\sigma_y$ at the same time together as the other components\(^{(13,14)}\). So all of the plane stress components can be obtained from only one diffraction ring with a single incident x-ray beam. From our recent experiment, it was shown that the stress could be measured with sufficient accuracy under the condition of an exposure time of 10(s). This seems to be due to the nature of the high sensitivity of the IP. If the present method is used, we have some advantages such as: (1) rapid plane stress analysis, (2) simple goniometer, (3) measurement in narrow places such as fillet weldment. We also investigated the influence of the assumption, in the cos $\alpha$ method, that the angle $\eta$ is constant against the angle $\alpha$\(^{(9,10)}\).

### Table I Influence of distance between powder and IP on stresses. Applied stress was 200MPa.

<table>
<thead>
<tr>
<th>Powder-IP distance (mm)</th>
<th>Authors' method (MPa)</th>
<th>Sp-Pow (Input)</th>
<th>Sp-IP (Output)</th>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
<th>$\tau_{xy}$</th>
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<td>Output</td>
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### Table II Influence of $2\theta_0$ on stresses. Applied stress was 200MPa.

<table>
<thead>
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<th>$2\theta_0$ (deg)</th>
<th>Authors' method (MPa)</th>
<th>EPS (um)</th>
<th>Distance corrected (um)</th>
<th>Authors’ method (MPa)</th>
<th>Sp-Pow (Input)</th>
<th>Sp-IP (Output)</th>
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Fig. 4 Distributions of positions of diffraction peaks obtained from diffraction rings emerging from the non-polished specimen (left), and the polished specimen (right).

Fig. 5 Experimentally obtained results of $\bar{\varepsilon}_{\alpha}$ as a function of $\cos \alpha$ (left), and $\bar{\varepsilon}_{\alpha}$ as a function of $\sin \alpha$ (right).

Fig. 6 Relation between applied stress (by strain gage) and measured stress $\sigma_x$ (left), and $\tau_{xy}$ (right) by the present method.
The result of examining the influence of each experimental condition on the measurement result is shown in Tables I - IV. As a result, the following tendencies are seen.

Table I shows the results of a calculation of the distance (L) between the surface of the IP and that of the specimen, as well as stress components, for different input values of L, assuming that $2\theta_0$ is known to be $2\theta_0 = 156.4(\text{deg})$. It is found from the table that difference in L for the initial value varying from 46.0(mm) to 50.0(mm) is lower than 0.004(mm). This means that it is possible to correct the distance L with the help of a standard powder.

Tables II and III indicate the change in stress value and distance L when each input value is changed. It is found that the change of these values does not influence $\sigma_x$ and $\tau_{xy}$, but seriously influences $\sigma_y$.

Table IV shows the change in the amount of beam position correction and the stress value when the settling judgment value (EPS) is roughly set in the calculation of the incident beam position. As a result, it is found that EPS does not cause a big change in $\sigma_x$ and $\sigma_y$ though the incident x-ray beam center position influences $\tau_{xy}$. Moreover, it is found that we can get enough stress values for EPS=10(\mu m).

CONCLUSION

The validity of the Taira et al method (the cos $\alpha$ method) was proved experimentally in the present study. A method for determining $\sigma_y$ was also proposed by the authors by advancing the Taira et al method. This means that this method enables us to obtain all plane stress components from one diffraction ring obtained by a single incident x-ray beam.

REFERENCES