Measurement of Macro- and Microstresses of Composite Materials by X-Ray Diffraction Method Using Imaging Plate

Toshihiko Sasaki, Shoichi Yasukawa, Shigeki Takago and Yukio Hirose
Department of Materials Science and Engineering, Kanazawa University
Kakuma-machi, Kanazawa 920-1192, Japan

Abstract

A single x-ray incidence method for determining stress using the whole Debye-Scherrer ring was studied. An imaging plate (IP) was used in this study as an area detector. The method was also applied to the measurement of macro- and microstresses in composite materials. For composite materials, there is a possibility to analyze each Debye-Scherrer ring which correspond to each constituent simultaneously by exposing them on one imaging plate, as the radii of the diffraction rings are usually different from each other. This enables us to obtain phase stresses, macro- and microstresses in the material from a single x-ray exposure. It is also expected that this method will be quicker for x-ray stress measurements than the conventional $\sin^2\psi$ method. In this paper, an experiment was performed to investigate the above idea using dual phase stainless steel. In the case of the use of chromium K\alpha radiation on dual phase stainless steel, the $\alpha$Fe211 diffraction peak occurs at $2\theta=153.5\ \text{deg.}$, and the $\gamma$Fe311 diffraction peak at $2\theta=146.6\ \text{deg.}$ is also available if chromium K\beta radiation is used. Through these diffraction experiments, the stress measurements mentioned above were made. First, the phase stresses were measured in a four-point bending test. The results were compared to those obtained by the diffractometer method using parallel beam optics and also to the theoretical value which was calculated based on Eshelby’s method. It was confirmed that the accuracy of the present method is almost equivalent to the conventional one.

Introduction

The method of x-ray stress measurement is useful for determining residual stresses. It uses the x-ray diffraction technique and so is applicable to crystalline materials. Since the depth of the volume sampled by the x-ray beams is often limited to less than about 0.1 mm due to the absorption of x-rays by the material, the plane stress condition is often adopted in the principle as standard. As a result of many researches in this decade, the method allows the determination of triaxial stress state, depth profiles of the stress, macro- and microstresses in a dual phase material, and stress in a textured material.

It is, however, unavoidable to need a lot of diffraction data to calculate the stress when complicated stress states are built up in a sample. This leads to a long measurement time in general. The 1-D detectors such as PSPC or PSD are then adopted for the shortening of the measurement time. Though 1-D detectors allow a shorter time for measuring each diffraction profile, they are not adequate to decrease the number of diffraction data which are needed for the stress calculation as long as the conventional $\psi$-method is adopted as the principle. For this reason, the usefulness of the 1-D detectors seems to be almost at the limit.

The use of both a 2-D detector and the $\alpha$-angle based principle for stress determination allows us to shorten the measurement, where $\alpha$ is the circumference angle of the diffraction ring.
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and an imaging plate (IP) enables us to obtain and to analyze whole diffraction rings easier and quicker. The size of an IP can make this type of x-ray stress measurement realistic.

The \( \alpha \)-angle based principle for stress determination, which is called the \( \cos \alpha \) method, was first developed by Taira et al. in 1978. Yoshioka et al. first applied the IP to the \( \cos \alpha \) method in 1989 and reported the usefulness of the method. This kind of research has also been tried by Schubert and Hu.

In this study, the method using both the IP and the \( \alpha \)-angle based principle was applied to the measurement of macro- and microstresses in a composite material. Since the x-ray beams which diffract from each constituent in the composite are usually divided into different directions, one can carry out the stress analysis for each constituent. Through this procedure, the phase stresses in each constituent can be found. By applying the equilibrium condition for the second kind stresses (microstresses) in each constituent, these microstresses as well as the mean stress in the volume sampled by the x-ray beam (macrostress) can also be found. This microscopic information is very useful for research on the deformation behavior of the composite. In order to carry out this measurement using the conventional \( \psi \)-method, a lot of diffraction data are needed, for example, those for \( \psi \) and \( \phi \) angles for each constituent. It is, however, possible to obtain each diffraction ring which emerges from each constituent on the same IP under some special conditions. Analyzing the whole of each diffraction ring under the \( \alpha \)-angle based method, macro- and microstresses can be calculated in such cases.

From this point of view, a fundamental study was conducted on the method mentioned above using both the IP and the \( \alpha \)-angle based method. A ferritic and austenitic dual phase stainless steel was used in the experiment. The residual stress in the surface layer of a sample which was ground is discussed.

The principle of \( \alpha \)-angle based X-ray stress measurement for determining macro- and microstresses

A method for determining phase stress from diffraction ring

Consider a diffraction ring which emerged from the material when the orientation of the incident x-ray beam is expressed in terms of \( \phi_0 \) and \( \psi_0 \) respectively as shown in Fig. 1. Direction cosines, \( n_{3i} \) (i=1,2,3), are defined so as to express the normal of the lattice planes of crystals (L3 axis) from which diffraction beams arrive at a point on the diffraction ring on the IP for which the central angle is defined as \( \alpha \) as shown in Fig. 2. We then have:

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

We write \( S_i \) for the specimen coordinate system, and \( L_i \) for the laboratory coordinate system which can be obtained by rotating \( S_i \) system so as to make \( S_3 \) coincide with \( L_3 \). \( \eta \) is defined by the diffraction angle(2\( \eta \)=180-20). Denoting the normal strain in the direction \( L_3 \) by \( \varepsilon_{33}^L \), we have:
\[ \varepsilon_i^s = \frac{n_3}{n_1} \varepsilon_i^s \]

\[ \varepsilon_i^s \] indicate the strains with respect to the \( L_4 \) system and have the relation to the stress \( \sigma_{ij}^s \) in the \( L_4 \) system as follows:

\[ \varepsilon_i^s = \left( \frac{s_1}{2} \right) \sigma_{ij}^s + \delta_{ij} \left( \varepsilon_1^s + \varepsilon_2^s + \delta_{33}^s \right) \]

where \( s_1 \) and \( s_2 \) are the x-ray elastic constants and are given by the following equations respectively:

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

Consider four strains which can be obtained from diffracted beams having central angles: \( \alpha, -\alpha, \pi + \alpha \) and \( \pi - \alpha \) as shown in Fig. 2, and denote them as \( \varepsilon_\alpha, \varepsilon_{-\alpha}, \varepsilon_{\pi+\alpha} \) and \( \varepsilon_{\pi-\alpha} \) respectively. And then define the following parameter, \( a_1 \), from these strains

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

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

\[ a_1 = \frac{1}{2} \left( \sigma_{11} - \sigma_{33} \right) \sin 2\psi_0 + 2\sigma_{13} \cos 2\psi_0 \] \[ \sin 2\eta \cos \alpha \]

where the symbol \( S \), which expresses the coordinate system, was omitted here. As it is reasonable to assume that \( \sigma_{13} = \sigma_{23} = 0 \), the subsequent argument will be made under this assumption. Consequently, we have from eq(6)

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

We can see that using eq(7) one can obtain stress \( \left( \sigma_{11} - \sigma_{33} \right) \) 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 suitable conditions of x-ray diffraction, one would be able to record both the diffraction rings which emerged from the matrix and the second phase on a single IP at the same time. In such a case, we can obtain phase stresses at the same time in each constituent in the material. Moreover, it is known that macro- and microstresses can be obtained from all the phase stresses in the
constituents (3)–(7), which will be explained briefly in the following section.

**A brief summary of the Noyan method for determining macro- and microstresses from phase stresses**

When external stress is applied to a composite material, microscopic state of stress, as shown in Fig. 3, is usually built up due to the misfit of physical and mechanical properties between the constituents in the material. The following equations can be deduced from the equilibrium conditions for microstresses by defining \( \sigma^m \), \( \sigma^\Omega \) as microstresses in matrix and in the second phase, \( \sigma^M \), \( \sigma^I \) as phase stresses (i.e. total stresses) in matrix and in the second phase,

\[
\begin{align*}
\sigma^M_{11} - \sigma^M_{33} &= \left( \sigma^M_{11} - \sigma^M_{33} \right) + \left( \sigma^M_{11} - \sigma^M_{33} \right) \\
\sigma^I_{11} - \sigma^I_{33} &= \left( \sigma^I_{11} - \sigma^I_{33} \right) + \left( \sigma^I_{11} - \sigma^I_{33} \right) \\
\sigma^0_{11} - \sigma^0_{33} &= (1 - f) \left( \sigma^M_{11} - \sigma^M_{33} \right) + f \left( \sigma^I_{11} - \sigma^I_{33} \right)
\end{align*}
\]

(8)

where \( f \) denotes the volume fraction of the second phase. From these equations we have

\[
\begin{align*}
\sigma^m_{11} - \sigma^m_{33} &= f \left[ \left( \sigma^M_{11} - \sigma^M_{33} \right) - \left( \sigma^I_{11} - \sigma^I_{33} \right) \right] \\
\sigma^I_{11} - \sigma^I_{33} &= (f - 1) \left[ \left( \sigma^M_{11} - \sigma^M_{33} \right) - \left( \sigma^I_{11} - \sigma^I_{33} \right) \right]
\end{align*}
\]

(9)

which enables us to obtain microstresses in the both constituents if the phase stresses in all constituents are determined.

**A method for determining plastic strain**

For dual phase composites, which consist of both isotropic spherical inclusions and an isotropic matrix, the following equations are obtained from the Eshelby approach and the Mori-Tanaka method:

\[
\begin{align*}
\sigma^M_{11} - \sigma^M_{33} &= 3B \left( \sigma^0_{11} - \sigma^0_{33} \right) - 3B_f \left( \Delta \varepsilon^M_{11} - \Delta \varepsilon^M_{33} \right) \\
\sigma^I_{11} - \sigma^I_{33} &= 3B' \left( \sigma^0_{11} - \sigma^0_{33} \right) + 3B_f (1 - f) \left( \Delta \varepsilon^I_{11} - \Delta \varepsilon^I_{33} \right)
\end{align*}
\]

(10)
where $\Delta \varepsilon^p_{ij}$ is the difference of the plastic strain between the matrix and the inclusions. Other parameters in eq(10) can be obtained from Young’s modulus of the matrix ($E$), that of the inclusion ($E^*$), Poisson’s ratio of the matrix ($\nu$) and that of the inclusion ($\nu^*$) respectively using the following equations,

$$B = \frac{\mu - \beta (\mu - \mu^*)}{3R}, \quad B^* = \frac{\mu^*}{3R}, \quad B_1 = \frac{2(\beta - 1)\mu^*}{R}, \quad \beta = \frac{2(4 - 5\nu)}{15(1 - \nu)}$$

From eqs (10) and (11) we have

$$\Delta \varepsilon^p_{ij} - \Delta \varepsilon^p_{kk} = \frac{B}{B_1} \left( \sigma^M_{ij} - \sigma^M_{kk} \right) - \frac{B^*}{B_1} \left( \sigma^M_{ij} - \sigma^M_{kk} \right)$$

Eq(12) shows that if material constants ($E$, $E^*$, $\nu$ and $\nu^*$) and the volume fraction of the inclusions ($f$) are known, the plastic strain $\Delta \varepsilon^p_{ij} - \Delta \varepsilon^p_{kk}$ can be obtained using phase stresses ($\sigma^M_{ij}$, $\sigma^M_{kk}$).

**Experimental**

**Materials and specimens**

A ferritic($\alpha$) and austenitic($\gamma$) dual phase stainless steel(JIS-SUS329J4L), which was manufactured by a continuous casting process, was used in the experiment. The chemical components and mechanical properties are shown in Table 1 and 2 respectively. Specimens used in the experiments were fabricated by cutting from a rolled plate a specimen with a length of 1524 mm, a thickness of 6 mm and a width of 300 mm, milling and grinding to a final configuration having a length of 60 mm, a thickness of 5 mm and a width of 10 mm respectively. The longitudinal direction of the specimen coincided with the rolling direction. One of the specimens was quenched in water after holding at 1373K for 60 min. This specimen, which is named specimen-A, was used for the bending test. Another one, which is named specimen-G, was normalized by holding at 1133K for 30 min. and then cooling in the furnace. Then it was ground under the condition shown in Table 3, and was used for the experiment on the damaged layer due to the grinding process. The classifications of the specimens are shown in Table 4.

| Table 1. Chemical composition of SUS329J4L (wt. %) |
|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| C         | Si     | Mn     | P      | S      | Cr     | Ni     | Mo     | Cu     | W      | N      |
| 0.016     | 0.5    | 0.91   | 0.02   | 0.002  | 24.67  | 7.37   | 3.01   | 0.43   | 0.29   | 0.16   |

<table>
<thead>
<tr>
<th>Table 2. Mechanical properties of SUS329J4L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength, MPa</td>
</tr>
<tr>
<td>Tensile strength, MPa</td>
</tr>
<tr>
<td>Elongation, %</td>
</tr>
<tr>
<td>Reduction of area, %</td>
</tr>
<tr>
<td>$\gamma$-phase volume fraction, %</td>
</tr>
<tr>
<td>Young’s modulus, GPa</td>
</tr>
</tbody>
</table>
Table 3. Conditions of grinding.

| Diameter of grinding wheel, mm | $\phi 280 \times 32$ |
| Grinding fluid | Solution $\times 50$ |
| Grinding width, mm/pass | 10 |
| Grinding direction | Up-cut |
| Number of passes | 1 |
| Table speed, m/min. | 20.36 |
| Spindle speed, r.p.m. | 1552 |

Table 4. Classification of specimens used in the present study.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Heat treatment ((^1))</th>
<th>Surface treatment</th>
<th>X-ray for $\gamma$ phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>H1</td>
<td>none</td>
<td>Cr-K$^*$</td>
</tr>
<tr>
<td>G</td>
<td>H2</td>
<td>grinding</td>
<td>V-K$^*$</td>
</tr>
</tbody>
</table>

(*1) H1 : 60 min. at 1373K, water quench.
H2 : 30 min. at 1133K, furnace cooling.

Fig. 4. Experimental device used for two-point-bending.

**Conditions for X-ray diffraction**

Each of the phase stresses in $\alpha$ and $\gamma$ phases of specimen-A were measured using the method of x-ray stress measurement under applied stress, by means of a two-point-bending device shown in Fig. 4. The conditions used for the x-ray diffraction experiment are summarized in Table 5 (Cr-K$\alpha$ radiation was used for the measurement of the $\gamma$ phase). The applied stress
Fig. 5. Diffraction patterns obtained from specimen used for two-point-bending test.

Table 5. Conditions of x-ray diffraction experiment for dual phase stainless steel.

<table>
<thead>
<tr>
<th></th>
<th>Ferrite</th>
<th>Austenite</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Characteristic X-ray</strong></td>
<td>Cr-Kα</td>
<td></td>
</tr>
<tr>
<td><strong>Diffraction plane, hkl</strong></td>
<td>211</td>
<td>220</td>
</tr>
<tr>
<td><strong>Kβ-Filter</strong></td>
<td>V</td>
<td></td>
</tr>
<tr>
<td><strong>Tube voltage, kV</strong></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td><strong>Tube current, mA</strong></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td><strong>Exposure time, sec.</strong></td>
<td>180</td>
<td></td>
</tr>
<tr>
<td><strong>Incidence angle, deg</strong></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td><strong>Camera length(specimen), mm</strong></td>
<td>35</td>
<td></td>
</tr>
<tr>
<td><strong>Diffraction angle, deg</strong></td>
<td>153.5</td>
<td>128.9</td>
</tr>
<tr>
<td><strong>Peak position</strong></td>
<td>Half value breadth method</td>
<td>Half value breadth method</td>
</tr>
<tr>
<td><strong>Mechanical Young’s modulus, GPa</strong></td>
<td>206</td>
<td>193</td>
</tr>
<tr>
<td><strong>Mechanical Poisson’s ratio</strong></td>
<td>0.28</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>X-ray elastic constant, GPa</strong></td>
<td>175</td>
<td>149</td>
</tr>
</tbody>
</table>

was monitored by means of a strain gauge bonded to the specimen on the face opposite to the x-ray irradiated one. The applied strain ranged from 0 to 1000×10⁻⁶ with an interval of 250×10⁻⁶. Similar x-ray conditions were used for specimen-G except V-Kα radiation was used 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-Kα radiation was used at a tube voltage of 30 kV and a tube current of 10 mA. The diameter of the collimator used was 1 mm. The incidence angle of the x-ray beam was ψ₀=30°. An IP sheet 5 in × 5 in, set in an x-ray camera based on the Laue method, was used. The read-out system, which is on the market (Rigaku), was used in order to store digital image data of diffraction images in 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 illumination from the IP. The resolution for the read-out process was 100 μm. Thus, a diffraction pattern consisted of 1150×1140 pixels.

The location of the incident x-ray beam on the IP image was roughly determined from the
CRT of the computer. The location was used as an initial one for a more precise determination as explained in ref(16). Diffraction profiles were obtained as distributions of diffraction intensity of the diffraction ring along radial directions from the location of the incident beam determined above. These profiles were obtained from $\alpha=0$ to $\alpha=359$ deg., with an interval of 1 deg. and used for stress analysis.

Results and discussion

Debye-Scherrer ring and diffraction profile

Fig. 5(a) shows an example of the diffraction ring obtained from specimen-A using Cr-K$\alpha$ radiation. Three kinds of diffraction ring, coming from the $\alpha$ and $\gamma$ phases of the specimen and also from the powder, can be seen in Fig. 5(a). The inner ring is the 211 reflection of the $\alpha$ phase of the specimen and the outer one is the 220 reflection of its $\gamma$ phase. The middle ring is the 211 reflection from the powder. The distribution of the intensity for the rings from the specimen is continuous and uniform, which means that the grain size in the specimen is relatively small and there is a large enough number of grains to carry out the x-ray stress measurement successfully. Fig. 6 shows the diffraction profiles for four different angles $\alpha$ obtained from the diffraction rings shown in Fig. 5 using the image process developed in this study. As shown from the figures, we can see that it is possible to measure both peaks for $\alpha$ and $\gamma$ phases on a single IP at the same time. The reason why the peaks at $\phi=270$ deg are weak is thought to be caused by the increase of the x-ray absorption, as well as the decrease of the number of grains diffracting due to the existence of the weak rolling texture. It is found from Fig. 6 that the maximum intensities of the diffraction profiles from the powder are similar for each angle $\alpha$ whereas those from the specimen are changed markedly. So a smoothing treatment for the image data was conducted before determining the peak positions. The treatment is the same as that reported in ref(20).

Determination of location of incident X-ray beam in IP

Since the precise determination of the location of the incident x-ray beam is needed for the $\alpha$ angle based method, the diffraction ring of the powder exposed in the same IP was used in this study. The iron powder was used with a shorter camera length than that for the specimen in order to avoid piling superposition. The location was determined using the fact that the diffraction ring of the powder is a circle and its center is the location to be obtained. The centers for 180 diameters of the specimen's diffraction ring were calculated with respect to the rough center that was determined from the computer display. The new center, which is the mean of these 180 centers, was used to correct the coordinates of all the old peak positions. This process was repeated till the change of the new center was less than 0.1 $\mu$m. The location of the last center was assumed to be the location of the incident x-ray beam.
Fig. 6. Diffraction profiles obtained from Imaging Plate method after image processing.

Fig. 7. Stress calculation using X-ray data diffraction patterns.

**Determination of phase stresses**

After correcting the coordinates of the diffraction peaks with respect to the above-converged location of the incident x-ray beam, the diffraction angles and the x-ray strains were calculated. Fig. 7 shows the relation between $a_1$ defined in eq(6) and $\cos \alpha$ for both the $\alpha$ and $\gamma$ phases. It is found that each of the results show a linear relation for all the applied stress levels, which agrees with eq(7).

The state of the stress in the both constituents under the applied stress was calculated for specimen-A, which was given only the heat-treatment. First the phase stress was calculated using eq(8), and the microstress was then calculated using eq(9). The x-ray elastic constants used were those cited in reference (31), and are listed in Table 5. The volume fraction of the $\gamma$ phase ($f$) was measured from a photograph of the cross section of the specimen using the point-count method, and resulted in $f=0.5$. Fig. 8 shows the relation between these obtained stresses and the applied stress. The applied stress was obtained by multiplying the mechanical Young’s modulus by the strain gage value. The lines in the figure indicate the theoretical values based on micromechanics. In the calculation of the theoretical values, it was assumed that
Since the uniaxial load was within the elastic range, the points of intersection for each of the longitudinal axes were determined by fitting the data, as they can not be obtained theoretically. As a result, it is found that the experimental data agree well with the theoretical ones. It can then be concluded that the present method is a valid method by which one can obtain each of the phase stresses at the same time using IP.

Residual stress and plastic strain in damaged layer of ground specimen

Fig. 9 shows the diffraction rings obtained from different depths of the specimen-G which was machined by grinding. It can be observed that the patterns of each phase become spotty as the depth increases. Fig. 10 shows the depth profiles of phase stresses and the macrostresses. The upper figure shows the phase stress in the γ phase obtained from the following three kinds of methods. Namely, A indicates the phase stresses in γ phase obtained using both IP and Cr-Kα radiation by the simultaneous measurement of the two phases. Similarly, O indicates those which were obtained using both IP and V-Kα radiation by the independent measurement of the γ phase, and 0 indicates those which were obtained using both the diffractometer and V-Kα radiation by the independent measurement of the γ phase. It is found from the left figure of Fig. 10 that both O and 0 data show a similar behavior with respect to the depth profile and the degree of data scatter, whereas A is almost similar in the depth profile but has comparatively larger data scatter. The result is thought to be related to the fact that the strain sensitivity is smaller due to the lower diffraction angle of the 220 reflection for Cr-Kα radiation, and that the range of the change of the x-ray strain on the diffraction ring is smaller than that for the case of the sin²ψ method.

The right figure in Fig. 10 shows the distribution of the phase stresses in the both constituents as well as of the macrostress under the surface. The dashed-dotted line in the figure indicates the mean of the three results shown in the left figure. The dashed line indicates the distribution in the α phase, and the solid line that of the macrostress respectively. Fig. 11 shows the distribution of the plastic strain difference, \( (\Delta \varepsilon_{11}^p - \Delta \varepsilon_{55}^p) \), which can be calculated using eq(12). Fig. 12 shows the distribution of the full width at half maximum (FWHM) for both the constituents.
Fig. 9. Diffraction patterns for ground specimen at different depths.

(a) depth: 0 μm  (b) depth: 10 μm  (c) depth: 40 μm  (d) depth: 471 μm

Fig. 10. Macro and phase stress distributions with depth from the surface. Grinding conditions: UP-CUT 10 μm, Grain size 46 mesh (Japanese Industrial Standard).

Discussion

From the right figure in Fig. 10, it is found that the phase stress in the α phase is larger than that in the γ phase in the range between the surface and a depth of about 100 μm, and that the relation becomes opposite after that. Fig. 13 shows the distribution of the volume fraction of the γ phase (f) as a function of depth. It is found that the value of f decreases near the surface. The result implies a phase transformation from the γ phase to the martensite phase due to the deformation by grinding. So the change in the phase stresses in Fig. 10 is thought to be affected by the change in mechanical properties due to the phase transformation, plastic strain built up by the grinding and the macrostress state. Assuming that the mechanical properties of the α phase do not change for simplicity, we have the following equations from eq(9):

$$(\sigma_{11}^M - \sigma_{33}^M) - (\sigma_{11}' - \sigma_{33}') = f_\sigma + f_\varepsilon,$$

where $f_\sigma$ is a term related to the macrostress and $f_\varepsilon$ is that to the plastic strain, which are expressed as

$$f_\sigma = 3(B - B^\gamma)(\sigma_{11}^\gamma - \sigma_{33}^\gamma)$$

$$f_\varepsilon = -3B_1(\Delta \varepsilon_{11}^\sigma - \Delta \varepsilon_{33}^\sigma)$$

(13)
Eqs (13) and (14) mean that the difference between the phase stresses in each phase depends on the state of both the macrostress and the plastic strain, and corresponds to the summation of $f_\alpha$ and $f_\gamma$, which result from them. Their values are mainly related to the elastic constants of both the phases. Fig. 14 shows the distribution of $f_\alpha$ and $f_\gamma$. It is found from the figure that $f_\alpha$, which is indicated by the closed circles $\bullet$, has small values and a small change, whereas $f_\gamma$, which is indicated by the open circles $\circ$, changes about 30 times as much as $f_\alpha$, in magnitude. This means that $f_\gamma$ governs the distribution of $(f_\alpha + f_\gamma)$. As shown in Fig. 11, $(\Delta \epsilon_1^\alpha - \Delta \epsilon_3^\alpha)$ changes its sign from plus to minus, and then a similar change occurs in $(f_\alpha + f_\gamma)$, which leads to the change of the relation between both phase stresses shown in Fig. 10. The reason why the equilibrium condition is not satisfied in Fig. 10 is that the distributions of the phase stresses are limited to only the surface region. From the distributions of other x-ray parameters shown in Fig. 10 to 13, the depth points at which they converge to be constant differ from each other. These points for the phase stress in the $\alpha$ phase and its plastic strain are similar, and that for the FWHM is $1/7$ to $1/8$ of this depth, and that for the $f$ value is $1/3$ to $1/4$ of this depth respectively. The phase stress in the $\gamma$ phase converges at a similar depth as its FWHM. Further study is necessary to solve the reason why these parameters showed different behavior for each of the phases. In the field of x-ray fractography, however, it is found that the relation between the size of the plastic zone and the x-ray parameters which are obtained from the fracture surface depend on the mechanical properties of the material, for example, the FWHM is an effective parameter for low strength materials.
whereas the residual stress is for high strength materials. There are some common trends between the results in the x-ray fractography and those in the present study.

Conclusions

An $\alpha$- angle based method of x-ray stress measurement, in which the stress is determined from two dimensional x-ray diffraction data, was applied to a dual-phase composite material for determining macro- and microstresses at the same time. A method for determining the plastic strain, in which the Eshelby/Mori-Tanaka model is used, was also shown. As an example of the application of these methods, the x-ray data, which were obtained from a ferritic and austenitic dual phase stainless steel, was analyzed. It was first confirmed that the relation between the phase stresses which were measured and the applied stress agreed well with that which was obtained theoretically using micromechanics. Through an experiment on the ground surface of a sample using present methods, the distribution of the phase stresses, macrostresses, microstresses and plastic strains were obtained, from which it was found that the behavior of the phase stresses depends on the plastic strain.

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Reference