A BEHAVIOR OF ELASTIC AND PLASTIC STRAIN FOR 
(\(\alpha+\gamma\)) DUAL PHASE STAINLESS STEELS IN ROTATING BENDING TEST

1Hajime Hirose, 2Masahide Gotoh, 2Tomonori Yano and 3Toshihiko Sasaki

1Research center, Kinjo University, Matto, Japan
2Graduate school, Kanazawa University, Kanazawa, Japan
3Department of Materials Science and Engineering, Kanazawa University, Kanazawa, Japan

ABSTRACT

JIS-SUS329 is duplex steel that consists of two-phase (\(\alpha+\gamma\))-Fe materials. It has good resistance to corrosion and oxidation. Therefore, this material should be use for the shaft of a car, the screws holding a ship together, and so on. In this study, the effect of residual stress and plastic deformation on fatigue strength of SUS329 was examined. Residual stress measurement was applied to new X-ray stress measurement method, which contains the parameters of residual stress \(\sigma\) and misfit of plastic strain \(\Delta\varepsilon^p\) by micromechanics. As a result, interesting behaviors of elastic strain and plastic strain in rotating bending fatigue test were recorded.

INTRODUCTION

A new method for determining plastic strain in composite materials using X-ray diffraction was developed by the authors in recent years[1]. The present method was derived by using both Eshelby’s approach[2] and the Mori-Tanaka theory[3] to express the stress state in composite materials. JIS-SUS329 is dual phase stainless steel that consists of ferrite \(\alpha\)Fe and austenite \(\gamma\)Fe. Because dual phase stainless steel is greater than other single phase stainless steels in mechanical strength, it is expected to be used for structures such as the chemical plants, heat exchangers, and so on. However, the structures mentioned above are generally loaded repeatedly in the long run. And it is reported that fractures in the structures are almost caused by fatigue failure in metals. Therefore, it is important that mechanical strength and physical property of the material is evaluated in fatigue state. In fatigue process, crystalline structures in a material are caused not only elastic strain but also by plastic deformation related to dislocation mechanism. In this study, the effect of residual stress and plastic deformation on fatigue strength of SUS329 was examined using X-ray diffraction methodology.
THE RELATIONSHIP BETWEEN ELASTIC STRAIN/STRESSES MEASURED BY X-RAYS AND THE PLASTIC STRAIN DISTRIBUTION

Outline of the misfit of plastic strain measurement has been described by Sasaki et al.[1]. In X-ray stress measurement, the stress in each phase of a composite material can be measured separately. The stress in each phase is called 'phase stress', it can be measure by the X-ray diffraction profile from each phase. Macro stress can also be measured using following equation;

\[
(\sigma_{11}^0 - \sigma_{33}^0) = (1 - f) (\sigma_{11}^M - \sigma_{33}^M) + f (\sigma_{11}^I - \sigma_{33}^I),
\]

where \( \sigma^0 \) is the macro residual stress, \( \sigma^M \) is the residual stress of matrix, \( \sigma^I \) is the residual stress of inclusion and \( f \) is the volume fraction of inclusion. In this study, the \( \alpha \)Fe phase is determined as matrix and \( \gamma \)Fe phase is determined as inclusion. Otherwise, phase stress is described by micromechanics, which is contained Eshelby's approach and the Mori-Tanaka theory.

\[
\sigma_{11}^M - \sigma_{33}^M = 3U(\sigma_{11}^0 - \sigma_{33}^0) - 3B_i f (\Delta \epsilon_{11}^p - \Delta \epsilon_{33}^p), \quad \sigma_{11}^I - \sigma_{33}^I = 3U^* (\sigma_{11}^0 - \sigma_{33}^0) - 3B_i (1 - f) (\Delta \epsilon_{11}^p - \Delta \epsilon_{33}^p),
\]

where \( \Delta \epsilon^p = \epsilon_{11}^p - \epsilon_{33}^p \) is determined as the misfit of plastic strain by

\[
\Delta \epsilon^p \equiv \epsilon_{11}^p - \epsilon_{33}^p.
\]

By the equation (2) and (3), \( \Delta \epsilon^p \) has following form;

\[
\Delta \epsilon_{11}^p - \Delta \epsilon_{33}^p = \frac{U}{Q} \left( \sigma_{11}^I - \sigma_{33}^I \right) - \frac{U^*}{Q} \left( \sigma_{11}^M - \sigma_{33}^M \right),
\]

where \( U \), \( U^* \) and \( Q \) are determined by

\[
U = \frac{\mu - \beta (\mu - \mu^*)}{3B}, \quad U^* = \frac{\mu^*}{3B}, \quad Q = B_i \{3U(1 - f) + 3U^* f\}, \quad B_i = \frac{2(\beta - 1)\mu \mu^*}{3B},
\]

\[
\mu = \frac{E}{2(1 + \nu)}, \quad \mu^* = \frac{E^*}{2(1 + \nu^*)}, \quad B = \mu - \{\beta - f(\beta - 1)\}(\mu - \mu^*), \quad \beta = \frac{2(4 - 5\nu)}{15(1 - \nu)}.
\]
where $E$, $E^*$ is Young’s modulus of matrix and inclusion, respectively. And $\nu$, $\nu^*$ is also Poisson’s ratio of matrix and inclusion, respectively. The misfit of plastic strain $\Delta \varepsilon^p$ can be calculated using the equation (5) with the phase stress measurement of each phase.

**EXPERIMENTAL**

**Table 1. Chemical composition. (wt.%)**

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.33</td>
<td>0.88</td>
<td>0.024</td>
<td>0.001</td>
<td>6.79</td>
<td>25.6</td>
<td>2.96</td>
<td>0.14</td>
</tr>
</tbody>
</table>

**Figure 1. A shape of specimen. (unit:mm)**

**Table 2. Mechanical properties of SUS329.**

<table>
<thead>
<tr>
<th>Yield strength, MPa</th>
<th>553</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, MPa</td>
<td>777</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>40</td>
</tr>
<tr>
<td>Reduction area, %</td>
<td>71</td>
</tr>
</tbody>
</table>

**Specimen**

Figure 1 shows the shape of specimen. Diameter of a part of giving highest load is 12mm. Chemical composition of the specimen are shown in Table 1. In addition, Table 2 shows mechanical properties of SUS329. Figure 2 shows the micrograph of specimen. Volume fraction of each phase was measured with the point count method using pictures of grains. As a result, $f_{\alpha\text{Fe}} : f_{\gamma\text{Fe}} = 0.54 : 0.46$ was obtained, and the flat dispersion of inclusions $\gamma\text{Fe}$ were in matrix $\alpha\text{Fe}$.

**Rotating bending test and X-ray stress measurement**

A schematic illustration of experiment is shown in Figure 3. The machine of rotating bending test was simply supported by a beam type called ‘Ono-shiki’, with rotation speed of 1800 r.p.m., stress ratio of $1 = R$. Figure 4 shows a $S$-$N$ curves measured in this test. Fatigue limit was obtained as 350MPa. Therefore, the stress amplitude was set for $\sigma_a = 325$, $\phi=0$, $\sigma_3$, $\varepsilon_3$, $\sigma_2$, $\psi$, and the irradiated area.
350 and 400MPa because of investigation of stress behavior in X-ray stress measurement. Stress measurements were executed at the eight cycles, which is indicated as experimentation point in Figure 3. X-ray tube voltage was 30kV, and tube current was 10mA. Cr-Kα radiation was used for α-Fe phase, and also Cr-Kβ was used for γ-Fe phase. Measured plane was α-Fe211 and γ-Fe311 for each phase. Bending stress is generated on the surface perpendicular to axial direction of a specimen by the weight. Bending stress on the surface of a specimen is different from internal stress at the center. In other words, the stress gradient is generated to radius direction of a specimen. Therefore, bending stress on the surface of a specimen become maximal tensile and minimal compress on reverse side. The mean stress in irradiated area of X-ray can be measured with X-ray stress measurement. Information obtained by the X-ray residual stress measurement is almost from the surface of a specimen, because the penetration depth of X-ray is about a few micrometers.

RESULTS AND DISCUSSION

The behavior of residual stress for cycle number is shown in Figure 5. Figure 5 (a) shows the behavior under fatigue limit, and (b) shows over fatigue limit $\sigma_{\text{Limit}} = 350$ MPa. Under fatigue limit, residual stress before fatigue test was compressive about $-300$ MPa in α-Fe phase, and was tensile about $150$ MPa in γ-Fe phase. As the cycle number increased, value of residual stress approached about 0MPa up to $N=10^3$ cycles, and remained nearly constant over $N=10^4$ cycles in each phase. In addition, the behavior of stress on amplitude $\sigma_a=325$MPa was similar to the behavior of stress on amplitude $\sigma_a=350$MPa. On the other hand, the behavior of stress over $\sigma_{\text{Limit}} = 350$ MPa was different from the case under fatigue limit. About α-Fe phase, the tendency of stress variation was similar to the case under fatigue limit. However, only the tendency of γ-Fe phase over fatigue limit was different when it is compared to that of others. As cycle number increased, value of residual stress approached about $-100$ MPa up to $N=10^3$ cycles, and was rough around 0MPa over $N=10^4$ cycles in γ-Fe phase. Figure 6 shows the behavior of the misfit of plastic strain $\Delta \varepsilon^p$ for cycle number. As cycle number increased, value of the misfit of plastic strain approached about 0 up to $N=10^3$ cycles in all amplitude. They indicated similar tendency over $N=10^4$ cycles except for $\sigma_a=400$MPa. In other words, the misfit of plastic strain converged a constant value under fatigue limit, and it was unstable over fatigue limit. Here, the state of plastic
Figure 5. Relation between phase residual stress and cycles.

(i) $\alpha$Fe phase.

(a) Under fatigue limit.

(ii) $\gamma$Fe phase.

(b) Over fatigue limit.

Figure 6. Relation between misfit of plastic strain and cycles.

Figure 7. Behavior of elastic and plastic strain.

$e.s.$ = elastic strain
$p.s.$ = plastic strain

Figure 8. An idea of stress reduction.

Figure 9. Instability of residual stress in $\gamma$Fe.
strain for each phase is considered. Figure 7 shows the concept figure of the movement between residual stress and plastic strain. The vertical axis and the horizontal axis are determined as the residual stress and the plastic strain, respectively. In the initial state, the relationship is drawn like Figure 7(a) by Figure 5 and Figure 6. In area1 indicated in Figure 5, the residual stress of $\alpha$Fe and $\gamma$Fe approached about 0MPa, and the plastic strain will become like Figure 7(b). Stress reduction mechanism is explained using Figure 8. The forces given to crystals will induce the slip immediately after fatigue test begins. If the crystals are given compressive stress, generated stress by compression might be reduced by the slip. In area2, the work hardening should apply to the restraint of slips in case of excessive dislocation. Otherwise, the movement in area3 is indicated in Figure7(c). In area3, the misfit of plastic strain was unstable due to instability of the residual stress in $\gamma$Fe phase. This mechanism can be explained using Figure 9. If the crack is appeared in $\gamma$Fe grains, the elastic strain should be unstable by stress release due to crack opening. Figure 10 shows a micro crack of fracture surface by SEM. Judging from size of a micro crack, there may be cracks in a grain.

CONCLUSIONS

Main results in this study are summarized as following:

(1) In case up to $N=10^3$ cycles, value of residual stress approached about 0MPa as cycle number increased except for $\sigma_{\text{lim}}=400\text{MPa}$ regardless of fatigue limit $\sigma_{\text{lim}}=350\text{MPa}$. Slip mechanism could explain a cause of residual stress reduction.

(2) In case over $N=10^3$ cycles, the residual stress of $\gamma$Fe phase over fatigue limit was unstable at between 0 and $-100\text{MPa}$. It is thought that micro cracks cause these phenomena.

(3) In case over $N=10^3$ cycles, the misfit of plastic strain over fatigue limit was also unstable. Therefore, it is possible to forecast the life of dual-phase stainless steels SUS329 by X-ray methodology.

REFERENCES