Notch Root Biaxial Cyclic Strain Behavior of Type 304 Stainless Steel at Elevated Temperature Using Laser Speckle Strain/Displacement Gauge*

Hiroyuki WAKI**, Keiji OGURA**
and Izuru NISHIKAWA**

A laser speckle biaxial strain gauge was developed to measure local strains, $\varepsilon_y$, $\varepsilon_z$, at notch roots. Measurements were made on single edge-notched type 304 stainless specimens under fully reversed cyclic loading at both 673 K and room temperature. The strain ranges, $\Delta\varepsilon_y$, $\Delta\varepsilon_z$, and a ratio of those, $\phi = \Delta\varepsilon_y / \Delta\varepsilon_z$, were discussed in terms of a proposed notch root deformation constraint parameter which consisted of a notch root radius, a thickness of the plate and a nominal stress level. It was found that the biaxial strain ratio, $\phi$, was uniquely correlated with the proposed parameter for all the tested notches. It was also found that no change in the notch root strain range during the whole fatigue life was observed for the limited condition in which the constraint parameter took a sufficiently large value. Furthermore, the verification of Neuber's rule in terms of the measured strain was discussed.

Key Words: Notch, Fatigue, Stress Concentration, Laser Speckle, Biaxial Notch Root Strain, Notch Root Deformation Constraint, Neuber's Rule, Type 304 Stainless Steel

1. Introduction

A study of high temperature fatigue has been an increasing demand for a machine design under severe conditions, such as higher temperature and excessive loading. Generally, a crack which governs the life of a structure frequently generates at a stress concentration region. Accurate evaluation in nonlinear stresses and strains at the notch roots is an essential problem for the fatigue life assessment of notched components. It is, however, hard to evaluate the local elastic-plastic stress-strain response accurately at elevated temperatures. Several studies using a foil strain gauge technique were reported in a literature only under less severe conditions, such as mild temperature, small plastic strain, blunt notches and so on. A new experimental technique, which is known as the “Interferometric Strain Displacement Gauge (ISDG)”, developed by Sharpe, Jr. et al. has been successfully adapted to biaxial cyclic strain measurement at a notch root. Unfortunately, they only discussed the strain concentration under monotonous loading, and didn’t examine the strain behavior during cyclic loading. An accurate assessment of cyclic strain behavior at a notch root has been still in unsolved problem.

This paper describes the local biaxial strain behavior at a notch root during cyclic loading. Fatigue tests were conducted for three types of single edge-notched specimens with root radii of $\rho=1.0, 2.5$ and $5.0$ mm. The notch root biaxial elastic-plastic strain was measured using a laser speckle strain/displacement gauge (SSDG) which had been developed by the present authors. Measurement results are discussed in terms of notch root deformation constraint. The verification of Neuber’s rule in terms of the measured strain is also made under a wide stress range including general yielding.
2. Fatigue Test of Notched Specimen

2.1 Specimen and fatigue test procedures

The material used in this study was AISI type 304 stainless steel. Table 1 shows the chemical composition of the material. Three types of single edge-notched specimens shown in Fig. 1 were machined from rods with a diameter of 25 mm. These specimens were heat treated (heating for 0.5 hr. at 1323 K followed by rapid air cooling) before fatigue tests. Stress concentration factors, \( K_t \), of these notches were calculated as 4.1, 2.16 and 1.9 by an elastic FEM analysis.

The fatigue tests were carried out at both room temperature and 673 K at a frequency of 10 Hz with a stress ratio of \( R = -1 \) with a constant nominal stress range, \( \Delta \sigma_n \), using an electro-hydraulic servo fatigue machine. The specimens were heated by induction heating in the fatigue tests at elevated temperature. Table 2 shows the details on the test condition. The root of a notch was carefully observed to detect the crack initiation during the fatigue tests using a microscope with a magnification of 75. A crack initiation life was defined as a number of cycles at which a crack of 0.4 mm in length was detected. The notch root biaxial strain until the crack initiation was measured using the SSDG.

2.2 Notch root strain measurement using SSDG

2.2.1 Principle of strain measurement

A laser speckle can be obtained on a screen as a result of the interference of the diffused reflection when a laser light is applied to an optically rough solid surface. An example of such a speckle is shown in Fig. 2. As speckle displaces on a screen, with a change in the sample surface strain, the strain can be obtained from the speckle displacement.

The coordinate system is taken as shown in Fig. 3. A laser is applied to a sample along the \( x \)-axis. Two observation screens are set at an angle \( \theta_1 \) in the \( y \)-plane at a distance \( L_1 \) and at \( \theta_2 \) in the \( x \)-plane with a distance \( L_2 \). Denoting translations and rotations of a sample as \( \eta_x, \eta_y, \eta_z \), and \( \Omega_x, \Omega_y, \Omega_z \), respectively, the speckle displacement in \( y \)-direction on the observation screen 1, \( A_{1y}(\theta_1) \), and that in \( Z \)-direction on the screen 2, \( A_{2z}(\theta_2) \), are given in Eqs. (1) and (2), respectively.

\[
A_{1y}(\theta_1) = -\eta_x \cos \theta_1 + \Omega_z L_1 (1 + 1/\cos \theta_1)
+ \varepsilon_y L_1 \tan \theta_1
\]

\[
A_{2z}(\theta_2) = \eta_z \cos \theta_2 + \Omega_x L_2 (1 + 1/\cos \theta_2)
- \varepsilon_z L_2 \tan \theta_2
\]

Where, \( \varepsilon_x \) and \( \varepsilon_y \) are nominal strains in \( x \)-direction and \( y \)-direction, respectively. Four screens are used

Table 1 Chemical composition of the material used in this study (wt. %)

<table>
<thead>
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<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
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<th>Cr</th>
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<td>0.45</td>
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<td>0.023</td>
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<td>18.27</td>
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</table>

Fig. 1 Shapes and dimensions of the specimens used in this study

![Shapes and dimensions of the specimens used in this study](image)

Table 2 Experimental conditions

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>( K_t )</th>
<th>( t ) (mm)</th>
<th>( \Delta \sigma_n ) (MPa)</th>
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<tr>
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<td>10</td>
<td>150,200,220, 250,300</td>
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<tr>
<td>2.16</td>
<td>10</td>
<td>6</td>
<td>380,440,410, 430,440,450</td>
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<tr>
<td>1.9</td>
<td>8</td>
<td>400,500</td>
<td></td>
</tr>
<tr>
<td>673K</td>
<td>4.1</td>
<td>10</td>
<td>150,200,250</td>
</tr>
<tr>
<td>2.16</td>
<td>10</td>
<td>6</td>
<td>330</td>
</tr>
<tr>
<td>1.9</td>
<td>8</td>
<td>285</td>
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</tbody>
</table>

![Speckle pattern](image)
to measure the strain without an influence of rigid translations and rotations of a sample surface. Normal strains, $\varepsilon_x$ and $\varepsilon_z$, can be obtained by Eqs. (3) and (4), respectively.

$$\varepsilon_x = \frac{[A_{11}(\theta_1) - A_{11}(-\theta_1)]}{2L_1 \tan \theta_1}$$  \hspace{1cm} (3)

$$\varepsilon_z = \frac{[A_{zz}(\theta_2) - A_{zz}(-\theta_2)]}{2L_2 \tan \theta_2}$$  \hspace{1cm} (4)

### 2.2.2 Biaxial strain measurement system

A He-Ne Laser (wave length $\lambda=632.8 \text{ nm}$, power=5 mW, spot size diameter=1.0 mm) was used in this study. Notch roots of specimen were polished like a mirror surface. An area of 1 mm square at the center of the notch root was coated by MgO. Measured strain is an average of this area, since a laser beam reflect diffusely only on the MgO coated area. The gauge length for the strain measurement was experimentally confirmed to be less than 0.4 mm, because the intensity distribution of a laser spot was the Gaussian distribution whose intensity was max at the center of the laser spot.

Speckle images were taken using a CCD camera with 410 thousand pixels. A screen angle and a screen distance were selected as $\theta_1=30$ degrees, $\theta_2=45$ degrees and $L_1=163$ mm, $L_2=200$ mm, respectively. Speckle image signals were introduced into a personal computer through an image processing board (512 pixel$\times$485 pixel$\times$8 bit). Figure 4 shows the schematic illustration of an experimental setup.

The images before and after deformation were compared to obtain the speckle displacement. Denoting the intensity of images before and after deformation as $I_0(X, Y)$ and $I_1(X, Y)$ respectively, a residual given by Eq. (5) is calculated as a function of the unknown variables $u$ and $v$. When a residual $D(u, v)$ takes a minimum value, $u$ and $v$ are determined as the speckle displacement in $X$ and $Y$-direction, respectively.

$$D(u, v) = \frac{1}{M} \sum \sum |I_0(Y, Z) - I_1(Y + u, Z + v)|$$  \hspace{1cm} (5)

Where $M$ is a total number of pixels in the image. The surface resolution in the speckle displacement corresponds to a pixel size, because $u$ and $v$ are integers. In order to obtain a higher resolution in the speckle displacement less than one pixel size, residual $D(u, v)$ was fitted to a continuous function using a least squares method. Decimal speckle displacement was determined, when the continuous $D(u, v)$ took a minimum value. It is noted that the strain increment must be limited in a certain small value, because an excessive strain increment may cause a change in the speckle pattern. And so the strain measurement was made incrementally, and the total strain could be obtained by summation of the incremental strain. The software for the speckle displacement analysis was programmed by the C language. When the surface resolution in Eqs. (3) and (4) is assumed to be one pixel size which is 5.7 $\mu$m, the strain resolution can be calculated as $61 \times 10^{-5}$ for longitudinal strains and $29 \times 10^{-5}$ for lateral strains in the measurement system used in this study.

Air turbulence causes the error in the strain measurement at elevated temperature. In order to reduce the convection of hot air, the specimen was put into a small box. The air turbulence error decreased by more than fifty percent by the introduction of this box. Figure 5 shows the error induced by the air turbulence plotted against time. The error is less than $100 \times 10^{-6}$ in both $\varepsilon_x$ and $\varepsilon_z$ at 673 K.

### 3. Test results and Discussion

#### 3.1 Notch root biaxial strain behavior

Tension compression fatigue tests were conducted under load control at both room temperature and 673 K. Notch root strains were measured during the fatigue tests until crack initiation. Figure 6(a) and
An effect of air turbulence in strain dimension at 673 K

Fig. 5

(b) show typical examples of the relation between the nominal stress and the local strain at the notch root at room temperature and 673 K, respectively. The symbols $\varepsilon_x$ and $\varepsilon_y$ in this figure present a longitudinal strain and a lateral strain, respectively. As shown in Fig. 6(a), the width in a hysteresis curve gradually increases with increasing the number of stress cycles, $N$, at room temperature. Thus type 304 stainless steel shows cyclic softening behavior at room temperature. The width in a hysteresis curve, on the other hand, gradually decreases with increasing $N$ at 673 K, as illustrated in Fig. 6(b). This material

Fig. 6 Hysteresis loops between nominal stress and notch root strain at several numbers of stress cycles

(a) R.T. $K_t=4.1$

(b) R.T. $K_t=2.16$

Fig. 7 Biaxial strain range at the notch root plotted against number of cycles

(a) R.T., $K_t=4.1$

(c) R.T., $K_t=1.9$

(d) 673 K
shows cyclic hardening behavior at 673 K.

Figure 7(a)–(d) show the strain range at the notch root as a function of cycles, N, for all the notched specimens. Figure 7(a), (b) and (c) show the results at room temperature with stress concentration factors, \( K_t = 4.1, 2.16 \) and 1.9, respectively. Figure 7(d) shows the result at 673 K for all the tested notches. A significant change in the cyclic strain range is observed for \( K_t = 1.9 \), while a little change is observed for \( K_t = 4.1 \). For the specimens with the same stress concentration factor, a significant change in the cyclic strain range is observed when a specimen subjected to a higher applied stress range, \( \Delta \sigma_n \). The reason that \( K_t \) and \( \Delta \sigma_n \) play an important role on such a cyclic strain behavior is considered as both \( K_t \) and \( \Delta \sigma_n \) control the notch root deformation constraint which is caused by the difference in the stress and strain gradients. There is a similar result that \( \Delta \sigma_n \) play an important role on such a change in the cyclic strain on a smooth specimen.(13)

3.2 Biaxial strain ratio

A biaxial strain ratio, \( \psi \), is defined as a ratio of a lateral strain range to a longitudinal strain range, that is \( \psi = \frac{\Delta \varepsilon_y}{\Delta \varepsilon_x} \), and the change in the biaxial strain ratio during cyclic loading is examined. Figure 8(a) and (b) show the biaxial strain ratio, \( \psi \), as a function of the number of cycles, \( N \), for all the notched specimens at both room and elevated temperatures. As shown in Fig. 8, little change in \( \psi \) during cyclic loading is observed at both room and elevated temperatures, though the material shows either cyclic softening or hardening. This indicates that the change in the strain ranges of \( \Delta \varepsilon_y \) and \( \Delta \varepsilon_x \) during cyclic loading behave almost the same in the cyclic hardening or softening.

Next, the absolute value of \( \psi \) is discussed. The value, \( \psi \), increases up to 0.5 when the blunter notched specimens subjected to a higher applied stress range, while it decreases to 0 when the sharper notched specimens subjected to a lower applied stress range. The value, \( \psi \), also increases up to 0.5 when thickness of a specimen, \( t \), increases. These results may be caused by a difference in notch root deformation constraint. In this study, a new parameter \( \chi / \Delta \sigma^* \), which is a measure of the notch root deformation constraint, is introduced, and the relation between this parameter and the biaxial strain ratio is examined. \( \chi \) is a notch root stress gradient in an elastic deformation which is given by \( 2/\rho \) in the present notches, where \( \rho \) is a notch root radius. \( \Delta \sigma^* \) is a dimensionless nominal stress range, \( \Delta \sigma_n / \Delta \sigma \), where \( \Delta \sigma_n \) is a cyclic yielding stress range whose values are 430 MPa at room temperature, 250 MPa at 673 K. Calculating an average value of \( \psi \) over the total fatigue life in the Fig. 8(a) (b), the average value, \( \bar{\psi} \), for all the tested notches are plotted against the parameter, \( \chi / \Delta \sigma^* \) in Fig. 9. The value, \( \bar{\psi} \), is found to be uniquely governed by the parameter for all the notches at both room and elevated temperatures. The value, \( \bar{\psi} \), is also found to decreases to 0 with increasing this parameter. In other words, the stress state at the notch root approaches plane strain condition with increasing this parameter. In summary, the biaxial strain ratio, \( \psi \), is found to be strongly governed by the proposed
parameter which consists of a notch root radius and a stress level.

3.3 Cyclic strain behavior

The change in the cyclic strain range during the fatigue test is examined. Only the longitudinal strain range, $\Delta \varepsilon_{x}$, is discussed, because the change in $\Delta \varepsilon_{x}$ is similar in trend to that in $\Delta \varepsilon_{z}$. The cyclic strain range is also thought to be controlled by the notch root deformation constraint as it is the case in the biaxial strain ratio, $\phi$. An another ratio of a cyclic strain range ratio, $R_{\phi}=(\Delta \varepsilon_{x}^{\text{max}}/\Delta \varepsilon_{y}^{\text{max}})$, is introduced to examine the change in the cyclic strain range during the fatigue test, where $\Delta \varepsilon_{y}^{\text{max}}$ is a final strain range just before crack initiation, $\Delta \varepsilon_{y}^{\text{init}}$ is an initial strain range. Figure 10 shows $R_{\phi}$ plotted against the proposed parameter, $\Delta \varepsilon_{x}/\Delta \sigma^{*}$. The value, $R_{\phi}$, increases over 1 if the material shows cyclic softening, while the value decreases below 1 if it shows cyclic hardening. The value keeps the constant value, 1, if it shows neither cyclic softening nor hardening. At room temperature, $R_{\phi}$ takes a large value close to 1.8 if $\Delta \varepsilon_{x}/\Delta \sigma^{*}$ takes a small value, while $R_{\phi}$ approaches 1 if the value of $\Delta \varepsilon_{x}/\Delta \sigma^{*}$ exceeds 10, as shown in Fig. 10. At elevated temperature, $R_{\phi}$ takes a small value close to 0.78 if $\Delta \varepsilon_{x}/\Delta \sigma^{*}$ takes a small value, while $R_{\phi}$ approaches 1 if the value of $\Delta \varepsilon_{x}/\Delta \sigma^{*}$ exceeds 10, as illustrated again in Fig. 10. $R_{\phi}$ is found to be correlated with the constraint parameter, $\Delta \varepsilon_{x}/\Delta \sigma^{*}$, in both case of cyclic softening and hardening. It is noted that no change in the notch root strain is observed during whole fatigue life up to crack initiation when the constraint parameter takes a sufficiently large value.

3.4 Crack initiation life

Figure 11 shows the fatigue crack initiation life plotted against the nominal stress range at both room temperature and 673 K. For the specimens with the same $K_T$, the fatigue life at elevated temperature is shorter than that of at room temperature. For the specimens under the same temperature, the fatigue life of the specimens with $K_T=4.1$ is shorter than that with both $K_T=1.9$ and $K_T=2.16$, and the fatigue life of the specimens with $K_T=1.9$ is almost the same as that with $K_T=2.16$.

Figure 12 shows an average value in the equivalent strain range during the fatigue life plotted against the fatigue crack initiation life at both room temperature and 673 K. The average equivalent strain range, $\Delta \varepsilon_{eq}$ was calculated by the following Eqs. (6) and (7).

$$\Delta \varepsilon_{eq} = \frac{1}{N_i} \int_{0}^{N_i} \Delta \varepsilon_{eq}dN \tag{6}$$

$$\Delta \varepsilon_{eq} = \sqrt{\frac{2}{3}} \left[ (\Delta \varepsilon_{x} - \Delta \varepsilon_{y})^2 + (\Delta \varepsilon_{y} - \Delta \varepsilon_{z})^2 + (\Delta \varepsilon_{z} - \Delta \varepsilon_{x})^2 \right]^{1/2} \tag{7}$$

Where $\Delta \varepsilon_{x}$ and $\Delta \varepsilon_{z}$ were measured values, $\Delta \varepsilon_{y}$ was calculated using a volume constant low, $\Delta \varepsilon_{y} = -(\Delta \varepsilon_{x} + \Delta \varepsilon_{z})$. In case that only $\Delta \varepsilon_{y}$ was measured, assuming the notch root stress state as plane stress or plane strain, the equivalent strain could roughly be estimated only from the measured value, $\Delta \varepsilon_{y}$, using the $\Delta \varepsilon_{y}$ versus $\Delta \varepsilon_{x}/\Delta \sigma^{*}$ relation in Fig. 9. It is found from Fig. 12 that the fatigue crack initiation life is successfully
correlated with the average equivalent strain range at the notch root with no dependence on the notch shapes. It is also found that the fatigue life becomes shorter at 673 K than that at room temperature for any level of $\Delta \varepsilon_{\text{eq}}$. A similar trend in fatigue life was obtained in the relation between the longitudinal strain range and the crack initiation life. These results give a good agreement with literatures\textsuperscript{39,40,41}.

3.5 Verification of Neuber’s rule

3.5.1 Notch root strain estimation using Neuber’s rule

A common expression for estimating the elastic plastic stress and strain at the notch root is Neuber’s rule\textsuperscript{[19]}. There are few literatures\textsuperscript{39,40,41} that verification of Neuber’s rule in terms of the measured strain is made over wide test conditions, which cover the wide range of $K_t$ including sharply notched specimens and the wide stress range including general yielding. The verification of an estimated strain using Neuber’s rule is made by comparing the estimated strain with the measured strain using a SSDG.

Neuber’s rule is given by Eq. (8), where $K_t$ is an elastic stress concentration factor, $K_\sigma$ and $K_\varepsilon$ are stress and strain concentration factors in an elastic-plastic range, respectively.

\[ K_\sigma K_\varepsilon = K_t^2 \]  

$K_\sigma$ is defined as a local stress range, $\Delta \sigma$, divided by a nominal stress range, $\Delta \sigma_{\text{n}}$, $K_\varepsilon$ is defined as a local strain range, $\Delta \varepsilon$, divided by a nominal strain range, $\Delta \varepsilon_{\text{n}}$. Given constitutive equation by next Eq. (9), the solution for $\Delta \sigma$ and $\Delta \varepsilon$ at the notch root is found from Neuber’s rule in combination with the constitutive equation (9).

\[ \Delta \sigma = E \Delta \varepsilon \quad (\Delta \sigma \leq \Delta \sigma_{\text{n}}) \]  
\[ \Delta \sigma = C \Delta \varepsilon^n \quad (\Delta \sigma > \Delta \sigma_{\text{n}}) \]

Where $E$ is a Young’s modulus, $C$ is a constant, $n$ is a work-hardening exponent. These material constants were experimentally determined from a cyclic stress-strain curve on a smooth specimen, and listed in Table 3. The relation between $\Delta \sigma_{\text{n}}$ and $\Delta \varepsilon_{\text{n}}$ are given by Eq. (10).

\[ \Delta \varepsilon_{\text{n}} = \frac{\Delta \sigma_{\text{n}}}{E} \]

3.5.2 Comparison of the estimated strain with the measured strain

Figure 13 shows the dimensionless nominal stress range parameter, $K_t \Delta \sigma_{\text{n}} / \Delta \sigma_{\text{n}}$, plotted against the dimensionless notch root strain range which is defined as the longitudinal strain range divided by a yielding strain range, $\Delta \varepsilon_{\text{y}} / \Delta \varepsilon_{\text{n}}$, where $\Delta \varepsilon_{\text{y}}$ is an average value during the fatigue test until crack initiation, $\Delta \sigma_{\text{n}}$ and $\Delta \varepsilon_{\text{n}}$ were determined from a measured cyclic stress-strain curve on smooth specimen, and also listed in Table 3. Estimated strains using Neuber’s rule are also shown in Fig. 13. As shown in Fig. 13, measured strains does not solely correlated with the value of $K_t \Delta \sigma_{\text{n}} / \Delta \sigma_{\text{n}}$ unlike the estimate by Neuber’s rule in which estimation $\Delta \varepsilon_{\text{y}} / \Delta \varepsilon_{\text{n}}$ is solely determined by $K_t \Delta \sigma_{\text{n}} / \Delta \sigma_{\text{n}}$. These results give a good agreement with literatures\textsuperscript{[19,40,41]}.

Estimated strains are compared with the measured strains to examine a validity of Neuber’s rule. Figure 14 shows $\Delta \varepsilon_{\text{y}} / \Delta \varepsilon_{\text{Neuber}}$ plotted against a dimensionless plastic zone size, $\omega/W$, which is defined as a plastic zone size, $\omega$, divided by a ligament size, $W$, where $\Delta \varepsilon_{\text{Neuber}}$ is the strain estimated using Neuber’s rule. $\omega$ was estimated by an elastic analysis of Eq. (11)\textsuperscript{[19]}.

\[ \omega = \frac{\rho}{4} \left( \frac{(K_t \Delta \sigma_{\text{n}})^2}{\Delta \varepsilon_{\text{n}}} - 1 \right) \]

The measured strains are found to be larger than the estimates for all the notched specimens at both room and elevated temperatures when $\omega/W$ takes a large value under a large scale yielding condition. On the

Table 3 Material constants in cyclic stress-strain curve

<table>
<thead>
<tr>
<th>E (GPa)</th>
<th>C (GPa)</th>
<th>n</th>
<th>$\Delta \sigma_{\text{n}}$ (MPa)</th>
<th>$\Delta \varepsilon_{\text{n}}$ (%)</th>
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<td>R.T.</td>
<td>205</td>
<td>1.32</td>
<td>0.266</td>
<td>430</td>
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<td>673K</td>
<td>175</td>
<td>2.0</td>
<td>0.387</td>
<td>250</td>
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Fig. 13 $K_t \Delta \sigma_{\text{n}} / \Delta \sigma_{\text{n}}$ plotted against $\Delta \varepsilon_{\text{y}} / \Delta \varepsilon_{\text{n}}$

Fig. 14 $\Delta \varepsilon_{\text{y}} / \Delta \varepsilon_{\text{Neuber}}$ plotted against a dimensionless plastic zone size, $\omega/W$
contrary, the measured strains are found to be smaller than the estimates when \( \omega/W \) takes a small value under a small scale yielding condition. Comparing the data with the same \( \omega/W \), Neuber’s rule is found to give a larger underestimate in the strain at room temperature than that at elevated temperature. The reason is that the work-hardening exponent, \( n \), of this material at elevated temperature is larger than that at room temperature, and the accuracy of the strain estimation using Neuber’s rule decreases for materials with a small work-hardening exponent\(^{113}\).

Ogura et al.\(^{119}\) reported that Neuber’s rule tends to give an overestimate in strain under a small scale yielding condition, and that Neuber’s rule is essentially inapplicable to the condition of large scale yielding. However, there is a case that Neuber’s rule is extensively used for large scale yielding in combination with a relation between a nominal stress and a nominal strain given by Eq. (9) instead of Eq. (10)\(^{17}\). Figure 15 shows \( \Delta \varepsilon_{\omega}/\Delta \varepsilon_{\text{Neuber}} \) plotted against \( \omega/W \), where \( \Delta \varepsilon_{\text{Neuber}} \) was estimated using Neuber’s rule in combination with Eq. (9). As shown in Fig. (15), the underestimate of the strain is improved if the value of \( \omega/W \) takes more than 0.2. Finally, \( \Delta \varepsilon_{\omega}/\Delta \varepsilon_{\text{Neuber}} \) tended to take more than 1 when the deformation constraint parameter, \( t_{\omega}/\Delta \sigma^* \), took a small value. However, a dear correlation between \( \Delta \varepsilon_{\omega}/\Delta \varepsilon_{\text{Neuber}} \) and \( t_{\omega}/\Delta \sigma^* \) was not found.

4. Conclusion

Tension compression fatigue tests under load control were carried out for three types of single edge-notched plate specimens with root radii of \( \rho = 1.0, 2.5 \) and 5.0 mm made of type 304 stainless steel. The notch root biaxial elastic-plastic strain was measured using the laser speckle strain/displacement gauge (SSDG). Measurement results were discussed in terms of notch root deformation constraint. The verification of Neuber’s rule in terms of the measured strain was also discussed. The results obtained are summarized as follows:

1. Little change in the biaxial strain ratio, \( \phi \), at the notch root during cyclic loading was observed though the cyclic strain behaves either hardening or softening. The biaxial strain ratio, \( \phi \), was found to be strongly governed by the proposed notch root deformation constraint parameter, \( t_{\omega}/\Delta \sigma^* \), which consisted of a notch root radius and a stress level. The value, \( \phi \), was also found to decrease to 0 with increasing this constraint parameter.

2. The cyclic strain range ratio, \( R_{\omega} \), was also found to be controlled by the constraint parameter, \( t_{\omega}/\Delta \sigma^* \). It is also found that no change in \( R_{\omega} \) during the whole fatigue life was observed when the constraint parameter took a sufficiently large value.

3. It was confirmed that the fatigue crack initiation life was successfully correlated with both the equivalent strain range and the longitudinal strain range at the notch root surface, and that the fatigue life became shorter at 623 K than that at room temperature for any level of the strain.

4. It was found that estimated strains using Neuber’s rule was larger than the measured ones for all the notched specimens under a small scale yielding condition, and that it, on the other hand, was smaller under a large scale yielding condition. A dear correlation between the accuracy of the estimated strain using Neuber’s rule and the proposed parameter \( t_{\omega}/\Delta \sigma^* \) was not found.

Authors acknowledged to Messrs. Y. Yamanuki and Y. Oosaki for their helps in the experiment.

References