The effects of overload on the $\Delta K_{th}$ of SUS316 were studied in this study. Tensile overload was applied to a compact tension (CT) specimen. Then, fatigue tests were carried out to determine the resultant $\Delta K_{th}$. It was found that the value of $\Delta K_{th}$ increases as increasing the overload. The results were discussed from the viewpoint of fracture mechanics. The size of compressive residual stress is the key factor controlling the value of $\Delta K_{th}$. Fractographic observation of fracture surface after fatigue tests were also carried out.

Key Words: Overload, Fatigue, Stainless steel, Threshold stress intensity factor range

1. はじめに

Stainless steel is extensively applied to many energy-related components such as nuclear power plants. Component reliability could be decreased if any damage caused by fatigue cracking or stress corrosion cracking (SCC) occurs during service.

In addition, replacement and/or repair of damaged component cost is expensive and result in large amount of economic loss during outage. Applying residual compressive stress to material surface by various type of peening or heat treatment is effective and used by various types of energy plants.

As one of measures taken to prevent SCC failures in stainless steel materials, the resistance to sensitization is improved by decreasing the carbon content. In addition, plant owners have introduced other workable methods against SCC, such as peening, Induction Heat-
ing Stress Improvement (IHSI), heat-sink welding, and narrow gap welding. The IHSI process uses induction heating outside the pipe and a flow of cooling water inside the pipe to create a sufficient temperature differential across the wall so as to leave the desired residual compression stresses at the inside wall.

This is based on the following principle. Thermal expansion of the outer surface by heating produces compressive yield at outside and tensile yield at inside. After that expansion returns to initial by stop of heating, then the tensile stress at outside transfers to residual compressive stress and the compressive stress at inside to residual tensile stress.

Typically, the IHSI technique is used on the non-defective material in order to minimize initiation of SCC. However, recent studies proposed the feasibility of applying the IHSI to the material where SCC occurred, assuming that compressive overload could have an inhibitive effect on crack tips.

The studies have not demonstrated the effectiveness theoretically. Thus, the effect of overload on fatigue crack of SUS 316 was evaluated so as to ensure reliability and safety of the IHSI technique as a means to inhibit the SCC propagation of stainless steel.

When overload is applied to a cracked material, compressive residual stress field is generated in the vicinity of the crack tip and delays crack growth\(^1,2\). Also, Ogawa et al., demonstrated the effect of load history on threshold stress intensity factor range \(\Delta K_{th}\) of carbon steel \(^3\), and Mizukami et al., clarified that overload has an effect on threshold stress intensity factor range \(\Delta K_{th}\) of high tensile steel HT 540\(^h\). As \(\Delta K_{th}\) of stainless steel could improve by overloading, fatigue strength of members will increase, and in turn reliability and safety of nuclear power plant will be also improved.

Since there is no evidence that overloading will improve \(\Delta K_{th}\) of stainless steel, this study is aimed to elucidate the effect of overload on \(\Delta K_{th}\) through fatigue tests conducted using CT specimen (SUS 316) to which a single tensile overload was applied.

2. 1 ヒートシンク障害改善適用

Stainless steel, SUS 316 was selected as test material. Tables 1 and 2 show the chemical component and mechanical properties of the test material, respectively. Figs. 1 and 2 show shape and dimension of 1/2tCT and 1tCT, respectively. One surface of the test material was mirror-polished to observe the propagation of fatigue crack in an easily visible way. In addition, a slit (4-mm length, 0.1-mm width) was machined by electric spark forming.

| Table 1 Chemical component SUS316 (mass%) |
|---|---|---|---|---|---|---|---|---|
| C | Si | Mn | P | S | Ni | Cr | Mo |
| % | 0.06 | 0.43 | 0.84 | 0.028 | 0.001 | 10.07 | 16.14 | 2.1 |

| Table 2 Mechanical properties of test material |
|---|---|---|
| Young's modulus \(E(GPa)\) | Yield stress \(\sigma_y(MPa)\) | Tensile strength \(\sigma_u(MPa)\) |
| SUS316 | 197 | 286 | 571 |

![Fig.1 Shape and dimension of 1/2tCT specimen unit: mm](image-url)
The fatigue test was conducted with hydraulic servo fatigue test machine at room temperature in air. The load condition is as follows: stress ratio $R = 0.1$, frequency $20\text{Hz}$, stress wave form is sine wave. Fig. 3 shows a frame format of single overload history during the test.

In the confirmed absence of crack development at $2.0 \times 10^6$ cycles, the cycle criteria checking for fatigue crack, the maximum stress intensity factor range ($\Delta K$) at this cycle is defined as the threshold stress intensity factor range ($\Delta K_{th}$). Also, the stress intensity factor was calculated in accordance with ASTM E 399.$^9$

During the fatigue test to confirm overload effect, fatigue test with non-overload was conducted and the base $\Delta K_{th}$ has been measured at first.

Next, fatigue test with overload was conducted and it was confirmed whether crack is initiated or not, and the relationship between stress intensity factor ($K_{ov}$) and threshold stress intensity factor range ($\Delta K_{th}$) has been clarified. After one time fatigue test with overload and without load was performed, normal fatigue test was conducted. The stress intensity factor during adding overload was $K_{ov} = 15.3 \sim 100 \text{MPam}^{1/2}$. At above 60 MPam$^{1/2}$, the quasi 1 tCT specimen was used, which had the same thickness with $1/2\text{tCT}$ specimen and the same surface area with $1\text{tCT}$ specimen, because large scale yield was occurred when overload was added to $1/2\text{tCT}$ specimen.

The test material without fatigue failure was heat tinted and then forcibly fractured using hydraulic servo fatigue test machine. The scanning electronic microscope (SEM) was used to observe the fractured surface.

To evaluate the effect of overload on delay in fatigue crack growth, the CT specimen was first installed in the hydraulic servo fatigue test machine and was then fatigue-precracked ($0.5 \text{mm}$) in air at the room temperature. The load condition is as follows: stress ratio $R = 0.1$, frequency $20\text{Hz}$, stress wave form is sine wave. The fatigue crack grew to $0.5 \text{mm}$ at the stress intensity factor ($\Delta K$) of $15 \text{MPam}^{1/2}$. Then, fatigue test was conducted after a single overload was applied so that the correlation between the number of cycles and crack length could be clarified. The overload stress intensity factor ($K_{ov}$) was $0, 20, 28, 30$ and $41 \text{MPam}^{1/2}$, while $\Delta K$ was $15\sim17 \text{MPam}^{1/2}$ at the start of the test.
3. Results of Fatigue Test

3.1 Improvement of ΔK_{th} by Overload

Fig. 4 is results of the fatigue test that shows the relationship between the number of cycles to failure (N_f) and stress intensity factor (ΔK). N_f is defined as the number of cycles when fracture occurred. ΔK_{th} improves as K_{ov} increases. Fig. 5 also depicts the correlation of K_{ov} and K_{th}.

The above equation almost agrees with the equation in studies of Ogawa and Mizukami, et al., showing ΔK_{th} slants upward at a slope of 0.28. The relation of ΔK_{th} and crack delay or non-propagation is discussed in Section 3.3.

Table 3 shows the test results of ΔK_{th} at K_{ov} of 15.3 - 97.6 MPam^{1/2} (In addition, above K_{ov} of 80 MPam^{1/2}, it is general - yield.), showing K_{ov} increases proportionally as K_{th} increases. For example, ΔK_{th} increases about 5.1 times at K_{ov} of 97.6 MPam^{1/2} compared to 0 MPam^{1/2}. Thus, this study was conducted with a focus on stress distribution near the tip of crack after overload was applied.

Fig. 6 shows stress distributions at overload (full line) and those at unload (dot line). The equations (2) and (3) express overload plastic zone size(ω_{ov}) and unload plastic zone size(ω_r) of the crack-tip fields in full elastic-plastic material under plane strain condition, respectively. Fig. 6 suggests that overloading and compressive residual stress field has the same effects on fatigue crack growth by blunting the crack tips.

\[
\Delta K_{th} = 0.28K_{ov} + 3.15
\]

Table 3 Relationship K_{OV} between ΔK_{th}

<table>
<thead>
<tr>
<th>K_{ov} [MPam^{1/2}]</th>
<th>0</th>
<th>15.3</th>
<th>30.6</th>
<th>45.9</th>
<th>61.3</th>
<th>80.0</th>
<th>97.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔK_{th} [MPam^{1/2}]</td>
<td>6.0</td>
<td>7.0</td>
<td>11.0</td>
<td>16.0</td>
<td>20.0</td>
<td>26.0</td>
<td>31.0</td>
</tr>
</tbody>
</table>
In short, the crack tip is arrested in the compressive residual stress field so that crack may delay or may not propagate as the relevant $\Delta K$ decreases. When the crack tip grows up beyond the field, crack may propagate. As shown in Fig. 5, $\Delta K_{th}$ improves as $K_{ov}$ increases.

3.2 有限要素法による応力分布解析

Fig. 7 and 8 show SEM images of fractured surfaces of the test material under the conditions of $K_{ov} = 30$ MPam$^{1/2}$ and $45$ MPam$^{1/2}$, $\Delta K_{th} = 11.0$ MPam$^{1/2}$ and 16.0 MPam$^{1/2}$, respectively. In Figs. 7, (a) is non-propagating crack while (b) is compulsive destruction zone. Fig. 9 shows $K_{ov}$ and $\omega_r$ as well as measured values of non-propagating crack length. These figures clarified that crack on non-fracture specimen was arrested in compressive residual stress field.

3.3 有限要素法による応力分布解析

Fig. 10 shows the relationship between crack length and the number of cycles. The number of cycles ($N$) is 0 when a single overload is applied after 0.5-mm precrack is machined artificially. Crack delayed slightly under the conditions of $K_{ov} = 20$ MPam$^{1/2}$ and 28 MPam$^{1/2}$, and then fractured. When $K_{ow}$ is 30 MPam$^{1/2}$, crack delayed substantially and then fractured. These phenomena support an as-
assumption that crack growth rate decelerates when the crack tip is arrested in compressive residual stress field induced by overload, and crack growth rate accelerates when the crack tip propagates beyond the field. Crack does not propagate when \(K_{ov}\) is 41 MPam\(^{1/2}\). This is partly because crack growth rate decreased very close to zero as the crack tip was arrested in compressive residual stress field.

Fig. 11 shows relationship between \(K_{ov}\) and \(\Delta K_{th}\) or applied \(\Delta K\). As shown in the figure, cracks delay and fracture in the upper threshold zone, behaving against cracks in the lower threshold side to the contrary.

\[
\Delta K_{th} = \Delta K_{th} + K_R \quad \text{Equation (4)}
\]

\[
K_R = K_R - K_{R_0} \quad (K_{th,max} \leq K_{ov} \leq \sigma_f \sqrt{\pi a})
\]

Where,

- \(K_R\) : stress intensity factor in overload-induced compressive residual stress field
- \(K_{R_0}\) : when \(K_{ov}\) is equal to \(K_{th,max}\), \(\Delta K_{th}\) is inclusive of \(K_{R_0}\).

Since \(K_{th,max}\) is determined as material constant,
it is reasonable to derive overload-induced compressive residual stress around the crack tip from the above equation.

These experimental results were compared with findings presented by Ogawa\(^3\), Mizukami\(^4\) and Takahashi\(^6\), and the correlation between \(\Delta K_{th, ov}\) and \(K_{ov}\) is expressed as follows. Thus, it is concluded that overload has an effect of increasing fatigue endurance limit, regardless of materials type.

\[
\frac{\Delta K_{th, ov}}{K_{ov}} \approx 0.25 - 0.31
\]

4. \(\Delta K_{th, ov}/K_{ov}\)

1) When \(K_{ov}\) was 97.6 MPam\(^{1/2}\), \(\Delta K_{th}\) was 31 MPam\(^{1/2}\), and improved by 5.1 times compared with \(K_{ov} = 0\) MPam\(^{1/2}\).

2) It is found that the crack growth rate is delayed or the crack does not propagate when crack is arrested in compressive residual stress field induced by overload.

3) The correlation between \(\Delta K_{th}\) and \(K_{ov}\) is expressed as follows.

(4) It is concluded that overload has an effect of increasing fatigue endurance limit, regardless of materials type.

(5) Effect of overload improves the fatigue limit of material with crack, which improves safety and reliability.

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