Influences of Stress Cycle Frequency and Stress Ratio
on Corrosion Product-induced Wedge Effects

by Kenjiro Komai** and Sei Nagano***

The corrosion fatigue crack growth rate of a high tensile strength steel HT55 has been measured in 1% NaCl solution at various stress cycle frequencies and stress ratios to elucidate the corrosion product-induced wedge effect and dominating mechanical parameters for crack growth. The wedge effect is greatest at $R = 0.1$, whereas it is less great in the order of $R = -1$ and $R = 0.5$. At $R = -3$, however, the wedge effect disappears, and the growth rate is higher in 1% NaCl solution than in $50 \text{ Hz}$ and $R = 0.1$ and 0.5 in 1% NaCl solution, the load-strain hysteresis loop traces different paths during loading and unloading periods, resulting from viscosity of the corrosive solution remaining within cracks, but the load sharing capacity of the viscosity is negligibly small. Regions I and II in the hysteresis loop must be taken into consideration to explain uniquely the corrosion fatigue crack growth characteristics under various conditions, and a contributory stress intensity factor range $\Delta K_{\text{cont}}$ is proposed as a difference between $\Delta K$ and $\Delta K_{\text{ref}}$, deduced from the load range shared by regions I and II.

Key Words: Corrosion Fatigue, Crack Growth, Corrosion Products, Wedge Effect, Cycle Frequency, Stress Ratio

1. Introduction

Corrosion fatigue crack growth is affected by the wedge effect of corrosion products, broadening of crack width by dissolution, and blunting of crack tips. The corrosion products-induced wedge effect is considered to raise the stress to close the crack, thereby reducing the effective stress amplitude at crack tips. Though the influences of viscoelastic or viscous properties of corrosion products on the wedge effect have been investigated by the shape of load-strain hysteresis loops, further investigation is required about the shape of the loops under various loading conditions and its effect on crack growth behavior.

In the present study, the influences of stress ratio and stress cycle frequency on the corrosion fatigue crack growth and the wedge effect of a high-tensile strength steel HT55 are discussed. A contributory stress intensity factor $\Delta K_{\text{cont}}$ is proposed from the hysteresis loops to explain uniquely the corrosion fatigue crack growth characteristics under various conditions.

2. Experimental Procedure

Material tested was a high-tensile strength steel HT55 as received whose chemical compositions and mechanical properties are shown in Tables 1 and 2 respectively. The shape and dimensions of WOL specimens are shown in Fig. 1, where crack plane ori-

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Table 1 Chemical compositions of test materials (mass %).

<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>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>0.31</td>
<td>1.13</td>
<td>0.020</td>
<td>0.025</td>
<td>-</td>
<td>-</td>
<td>R</td>
</tr>
</tbody>
</table>

Table 2 Mechanical properties of test materials.

<table>
<thead>
<tr>
<th>$\sigma_y$ (MPa)</th>
<th>$\sigma_b$ (MPa)</th>
<th>$\delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>420</td>
<td>580</td>
<td>29</td>
</tr>
</tbody>
</table>

Fig. 1 Shape and dimensions of test specimens.

presentation was T-L. In a corrosive solution the area for observing crack growth was coated with transparent silicon to prevent corrosion. A strain gage (gage length = 1 mm) was stuck to the back surface of the specimen as shown in Fig. 1 to measure compliance and load-strain hysteresis loops.
Dry air (dew point = -70°C, water content < 2 ppm) as a reference environment and 1% NaCl solution by weight in deionized water (specific electric resistance > 1 MΩ·cm) were used as testing environments. The temperature of the solution was kept at 25°C.

Fatigue tests were carried out by a 49 kN SHIMADZU closed-loop electrohydraulic servocontrolled fatigue testing machine. The stress wave form was sinusoidal, stress ratio (R = Min/MMax) being 0.5, 0.1, -1, and -3, and stress cycle frequencies (f) 5 and 50 Hz. In case of R < 0, the limit of crack length to be measured was 15 mm, and ∆K was put at KMax. Crack length was measured by a travelling microscope whose minimum scale was 10 μm and by a compliance method. Hysteresis loops by an unloading elastic compliance method and compliance were measured with a minicomputer system (MELCOM 70/10)²⁷.

3. Experimental Results and Considerations

3.1 da/dN-∆K relation

Figure 2 illustrates the relation between da/dN and ∆K in air. At ∆K = 12 MPa·m²/3, da/dN was the fastest at R = 0.5, and decreased in the order of R = 0.1, -3, and -1. Meanwhile the threshold value ∆Kth was the greatest at R = -3, and decreased in the order of R = -1, 0.1, and 0.5.

Figure 3 illustrates the relation between da/dN and ∆K in 1% NaCl solution. da/dN in 1% NaCl solution was always smaller than that in air due to the corrosion product-induced wedge effect especially at R = 0.1 with a higher threshold value. The wedge effect was proved to be the greatest at R = 0.1. No influence of stress cycle frequency was observed irrespective of the stress ratios. At R = -3, however, there was observed no wedge effect of corrosion products, with a higher da/dN in 1% NaCl solution than that in air at a smaller ∆K region. The corrosion products layer on crack walls was heavily compressed by strong compressive stresses, thereby reducing the wedge effect.

3.2 Load-strain hysteresis loop and change of KP and Kp2

Examples of the hysteresis loops at ∆K = 10 MPa·m²/3 in dry air and in 1% NaCl solution are shown in Fig. 4. Figure 5 illustrates the hysteresis loops at R = 0.1 and f = 50 Hz, where different paths during loading and unloading periods became conspicuous with an increase in ∆K owing to the viscosity of corrosive solution. The different paths during loading and unloading periods at f = 50 Hz appeared only in case of R = 0.5 and 0.1.

Solid-like corrosion products-induced wedge effect became dominant at R = -1 or at f = 5 Hz, since corrosion products were strongly adhered to crack walls in the former, or a large quantity of corrosion products was generated and a crack closing rate was small compared to that at f = 50 Hz in the latter²⁷. On of the authors has already reported that the viscosity effect of corrosive solution was observed at f = 10 Hz and R = 0.1 in a martensitic stainless steel²⁷.

In the figure, the hysteresis loops indicate the relation between (ε-ε') and load (P) where elastic deformation (ε') has been subtracted from strain (ε) so as to parallel an unloading elastic line during crack opening portion to loading axis. The hysteresis loops are divided into three regions of I, II, and III with the boundaries fixed by the loads KP1 and KP2. The difference between KP1 and KP2 gives region...
III where cracks are perfectly opened. Region III corresponds to the ∆K = J_f hitherto defined. On the other hand, region I where cracks are perfectly closed is given by the difference between $P_{opt}$ and $P_{min}$. $P_{opt}$ is the load where the hysteresis loop deviates from a straight line exhibiting the compliance $\lambda$ without fatigue cracks at notch root. Region II is a transition between regions I and III.

The relations between $K_{max}$ and the perfect crack opening $K_e$ $K_{opt}$ deduced from $P_{opt}$ in 1% NaCl solution are shown in Fig. 6. The relations between $K_{max}$ and $K_{opt}$ in air are also shown in the figure by solid lines. At $f = 50$ Hz and $R = 0.5$ and 0.1 the perfect crack opening $K_e$ during an unloading period ($K_{opt}$ in Fig. 5) was accepted since $K_{opt}$ was sensitive to the viscosity induced-wedge effect of solution.

$K_{opt}$ in 1% NaCl solution exceeded that in air at $f = 50$ Hz and 50 Hz irrespective of stress ratios. And $K_{opt}$ at $f = 5$ Hz exceeded that at $f = 50$ Hz since more corrosion products were generated in the former than in the latter resulting in a more pronounced wedge effect of corrosion products. The increase of $K_{opt}$ at $f = 5$ Hz in 1% NaCl solution from that in air was the highest at $R = 0.1$ and smaller in the order of $R = -1$, 0.5 and -3. The increase of $K_{opt}$ at $f = 50$ Hz in 1% NaCl solution from that in air was almost identical irrespective of stress ratios.

Figure 7 illustrates the relations between $K_{max}$ and $K_{opt}$ in 1% NaCl solution. $K_{opt}$ at $f = 5$ Hz was higher than that at $f = 50$ Hz irrespective of stress ratios since more corrosion products were generated in the former than in the latter as was $K_{opt}$. $K_{opt}$ at $R = -1$ and -3 became negative, which showed crack width broadening by dissolution (Figs. 4 and 7). At $R = -3$ the lowering of $K_{opt}$ was remarkable since the heavy
3.3 Relation between $da/dN$ and $\Delta K_{eff}$

Figure 8 illustrates the relation between $da/dN$ and $\Delta K_{eff}$ in air. The influence of stress ratios observed in Fig. 2 was eliminated except at $R = -3$, and a single curve was obtained at $da/dN > 10^{-10}$ m/cycle. At $R = -3$, however, $da/dN$ was smaller than the curves. The threshold value was the highest at $R = -3$, and smaller in the order of $R = 0.1$, $-1$, and 0.5. The reason the influence of stress ratios on $da/dN$ in terms of $\Delta K_{eff}$ was observed was that the influence of compressive stress component 51 and/or the contribution of regions I and II to crack growth existed.

Figure 9 illustrates the relation between $da/dN$ and $\Delta K_{eff}$ in 1% NaCl solution. In the figure the experimental points with arrows to the left indicate the case where $\Delta K_{eff}$ became extremely small, and the measured values are shown in parentheses. When there was observed a difference between $\Delta K_{eff}$ deduced from a loading period and the value from an unloading one, the value from the former was shown by the experimental points with asterisks. Though at $\Delta K_{eff} > 10$ MPa-m$^{1/2}$ $da/dN$ approached the air values, a large scattering of the experimental points was observed at $\Delta K_{eff} \leq 10$ MPa-m$^{1/2}$. The acceleration of $da/dN$ from the air values was the highest at $R = 0.1$ and $f = 5$ Hz, and the lowest at $R = 0.5$ at a smaller $\Delta K_{eff}$. Regions I and II as well as region III ($\Delta K_{eff}$) must be taken into consideration in the crack growth.

3.4 Arrangement of $da/dN$ in terms of $\Delta K_{cont}$ considering contribution of regions I and II

A schematic hysteresis loop deduced from Fig. 4 is shown in Fig. 10 to consider the contribution of regions I and II to crack growth. The loop in air is approximated by curves A-B-C-D-C-B-A, and A-B, B-C, and C-D corresponding to regions I, II, and III respectively.

The loop in NaCl solution is approximated by a curve E-F-G-D-G-F-E. The crack is perfectly closed in region I (E-F), and reduction of strain by the perfect crack closure at $F_{min}$ is given as HE, the load shared by the strain reduction being HN.
The load at the point N is P_{max}. Thus the effective stress amplitude at crack tips is given as DH + MH = DM.

In region II the hysteresis loop is given by a trace of F-N-G due to the viscoelasticity of corrosion products. The strain reduction by region II is shown by the difference between the traces of F-N-G and F-M-G. Here the strain reduction by region II is supposed to be given as the maximum width of MM, and the load shared by the strain MN, which is given by MN, is considered to be the load sharing capacity of region II. Consequently the total load sharing capacity of regions I and II equals MH + OM = OH, the effective stress range considering both ranges being DH = OH - DO.

In air only the load sharing capacity of region I is subtracted from DH, since the strain reduction by region II (B-C) is small.

Finally da/dN is replotted in terms of contributory stress intensity factor range \( \Delta \mathbf{K}_{\text{cont}} \) deduced from DO or DL.

The relation between da/dN and \( \Delta \mathbf{K}_{\text{cont}} \) in air is shown in Fig. 11. In the figure a unique relation was obtained at any \( \Delta K \) including threshold values irrespective of stress ratios, though \( \Delta \mathbf{K}_{\text{sh}} \) at \( R = -3 \) was a little higher.

The load sharing capacity of regions I and II in 1% NaCl solution (\( \Delta \mathbf{K}_{\text{net}} \)), which was deduced from LO in Fig. 10, was equal to the contribution of the corrosion products-induced wedge effect. The relation between \( \Delta \mathbf{K}_{\text{net}} \) and \( K_{\text{max}} \Delta \mathbf{K}_{\text{net}} \) is shown in Fig. 12. \( \Delta \mathbf{K}_{\text{net}} \) at \( f = 5 \) Hz was always higher than the one at \( f = 50 \) Hz at any stress ratio, and the wedge effect appeared to be greater at \( f = 5 \) Hz. Meanwhile the negative value of \( \Delta \mathbf{K}_{\text{net}} \) at \( R = -3 \) showed that the wedge effect could cause no narrowing of effective stress range.

The relation between da/dN and \( \Delta \mathbf{K}_{\text{cont}} \) in 1% NaCl solution is shown in Fig. 13.
was exceedingly scattered at $\Delta K_{eff} \leq 10 \text{ MPa}^{0.5}$, and no consistent tendencies could be recognized when considered in terms of $\Delta K_{cont}$. In Fig. 13 $da/dN$ at $f = 5 \text{ Hz}$ exceeded the one at $f = 50 \text{ Hz}$ and the air value at $\Delta K_{eff} \geq 6 \text{ MPa}^{0.5}$, which showed that the crack growth that proceeded by stress-assisted dissolution was more advanced at $f = 5 \text{ Hz}$. $\Delta K_{cont}$ deduced from a loading period is shown by experimental points with asterisks at $f = 50 \text{ Hz}$ and $R = 0.1$ and $0.5$ in Figs. 12 and 13. There is observed little viscosity effect on crack growth rates$^{71}$.

The threshold value in NaCl solution depended upon stress ratios even when considered in terms of $\Delta K_{cont}$, and it was the lowest at $R = 0.5$ and became higher in the order of $R = 0.1, -1$, and $-3$. Though the stress-assisted dissolution disappeared in region I, it was enhanced in regions II and III. At $R = 0.5$ almost all of stress cycles were occupied by regions II and III, and the enhanced dissolution brought the lowest threshold value. Meanwhile $K_{op1}$ more exceeded $K_{th}$ with a decrease in $R$ as shown in Fig. 7, and the suppressed dissolution brought higher threshold values since a fraction of regions II and III in a single cycle was shortened.

One of the authors reported that $\gamma$ was deduced as $0.35 - 0.54$ at $R = 0.1$ and $f = 5 \text{ Hz}$ from the experimental growth rate in the relation of $\Delta K_{cont} = \Delta K_{eff} + \gamma (K_{op1} - K_{op1})$. In the present paper the authors suggested that $\Delta K_{cont}$ could be deduced by the method shown in Fig. 10, and the $\gamma$ value was known to be $0.40 - 0.47$. The contributory stress intensity factor range $\Delta K_{cont}$ thus deduced was known to be a more dominating mechanical parameter for crack growth than $\Delta K_{eff}$.

4. Conclusions

The corrosion fatigue crack growth rate and the crack opening and closing behavior of a high tensile strength steel HT55 have been measured in 1\% NaCl solution at various stress cycle frequencies and stress ratios to elucidate the corrosion product-induced wedge effect and dominating mechanical parameters for crack growth.

(1) The decrease of $da/dN$ in terms of $\Delta K$ due to the wedge effect is the greatest at $R = 0.1$, whereas it becomes smaller in the order of $R = -1$, and $R = 0.5$. At $R = -3$, however, the wedge effect disappears, and the growth rate in NaCl solution exceeds that in air.

(2) The increase of region I and the decrease of region III in a load-strain hysteresis loop occurs in NaCl solution compared to that in air. At a negative stress ratio the perfect crack opening $K_{op1}$ is negative owing to crack width broadening by dissolution.

(3) Regions I and II in the hysteresis loop must be taken into consideration to explain uniquely the corrosion fatigue crack growth characteristics under various loading conditions, and a contributory stress intensity factor range $\Delta K_{cont}$ is proposed as a difference between $\Delta K$ and the load sharing capacity of regions I and II.

(4) At $f = 50 \text{ Hz}$ and $R = 0.1$ and 0.5 in 1\% NaCl solution, the load-strain hysteresis loop traces different paths during loading and unloading periods, resulting from viscosity of corrosive solution remaining within cracks, but the load sharing capacity of the viscosity is negligibly small.

References