Creep-Fatigue Crack Propagation Behavior in Surface Cracked Plate

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ABSTRACT

A series of experiments were performed in order to clarify the surface crack growth behavior under creep-fatigue condition. 304 stainless steel were tested at 550°C and 650°C. Specimens were plate with surface notch. Loading patterns were axial fatigue, bending fatigue, axial creep-fatigue and bending creep-fatigue. As a result, (1) Beach mark method was available to measure the changes of crack front shape after test (2) Electrical potential method was available to measure the changes of crack front shape in real time (3) The crack front shape was affected by the loading mode (4) ΔJ and ΔJc calculated from the proposed simplified method could characterize the surface crack growth rates were obtained.

1. INTRODUCTION

To assess the structural integrity of the FBR components, the creep-fatigue crack behavior must be clarified. "Fundamental Research on Structural Integrity Assessment of Fast Breeder Reactor" has been conducted by FCC II Subcommittee of Nuclear Engineering Research Committee, the Japan Welding Engineering Society under the contract with Power Reactor and Nuclear Fuel Development Corporation. The main purpose of this project is to clarify the creep-fatigue crack behavior in surface cracked plate and pipe, and to evaluate J and J' integrals which can characterize the crack propagation rate. This paper describes a part of the results of this project which is about the creep-fatigue crack propagation test in surface cracked plate.

2. EXPERIMENTAL PROGRAM AND PROCEDURE

Test program is shown in Table 1. At the first step, the fatigue tests were performed at 550°C and 650°C under axial stress and bending stress. At the second step, the creep-fatigue tests with short-hold time were performed at 650°C under axial stress and bending stress. At the last step, the creep-fatigue tests with long-hold time were performed at 550°C under bending stress.

The conditions is shown in Table 1. Test materials was 304 stainless steel. As shown in Fig. 1, specimens were plate with semi-elliptical surface notch. Temperatures were 550°C and 650°C. Loading patterns were axial fatigue, bending fatigue, axial creep-fatigue and bending creep-fatigue. Bending test
apparatus is shown in Fig. 2. Crack front shape was measured by the beach mark method and the electrical potential method. Also the crack opening displacement was measured to calculate the fracture mechanics parameter experimentally. Measurement methods of electrical potential and crack opening displacement are shown in Fig. 3.

3. RESULTS AND DISCUSSION

3.1 Beach mark measurement

Through the conducted test program, following loading condition was adopted for beach mark formation.

a) stress ratio; R = -1 (or 0)
b) load range; a half of cyclic load range of test condition
c) number of cycles; cycles to be of 0.2mm beach mark width. By these loading conditions, the clear beach marks were obtained. The typical beach mark patterns are shown in Fig. 4. It was confirmed that the beach mark method was available to measure the changes of crack front shape after test.

In the creep fatigue tests, the characteristic phenomenon was observed in crack propagation behavior by forming beach mark. That is, crack propagation rate decreased just after forming beach marks in both load and stroke controlled tests. This phenomenon is explained as follows. The damage accumulation at crack front just after beach marks were not enough compared with the steady damage in other area by objective crack propagation tests and therefore, crack propagation rate became lower.

3.2 Electrical potential measurement

To measure the changes of crack front shape in real time, the electrical potential method was applied. Compared the potential value with the real crack front shape measured by the beach mark method, the calibration curve of electrical potential method was prepared.

Fig. 3 shows the procedure of potential measurement. Ni or Pt wire was spotwelded on the surface of the specimens as a potential lead. Crack potential $E$ was measured between two points on both sides of the crack surface with a distance of $2y$. Reference potential $E_{\infty}$ was also measured between another two points away from the crack. Smaller $2y$ produce higher sensitivity to measure the crack growth, so $2y = 2mm$ was adopted in this study. In the case of DC-electrical potential method, input current to the specimen was constant 20~30A.

From the potential analysis of Roe and Coffin for an infinite width plate with surface crack, $E/E_{\infty}$ is predicted to be a function of the parameter $Vac/y$. Fig. 5 shows the relation between potential ratio $E/E_{\infty}$ and crack size parameter $Vac/y$, which shows a good correlation with little scattering, though these data was obtained from tests under various temperature, loading modes and initial aspect ratio of the crack. Here there appears to be a unified calibration for the various shapes of specimens with surface cracks. The crack depth can be estimated using this calibration by the measurement of potential value and crack length on the surface.

3.3 Shape of crack front

Fig. 6 shows the change of aspect ratio ($a/c$) of crack in axial or bending fatigue crack propagation test. In the axial load-controlled test, it was found that the aspect ratio monotonously increased from the initial value toward the constant
value of about \( a/c = 0.8 \) with the increase of crack depth. In the bending fatigue crack propagation test, on the other hand, the aspect ratio monotonously decreased to about 0.4 at the crack depth ratio \( a/t \) of 0.6 and this value was irrespective of control mode, load-control or displacement-control. Although Fig. 6 shows examples for a initial aspect ratio for each loading condition, it was found by other experiments that the final aspect ratio did not depend on the initial crack shape. These features were also observed in the creep-fatigue test with the hold time of 10 to 300 minutes.

The examples of the fracture surfaces of bending load test specimen are shown in Fig. 7. In the bending fatigue test, the crack initiation and growth with the linkage on the back-side surface was observed. On the other hand, in the creep-fatigue test with long hold time, the back-side surface crack was hardly observed. The creep-fatigue crack propagation rate was accelerated by 2 to 10 times at crack deepest point compared with fatigue crack propagation rate, and especially, the growth rate along the direction about 30 degrees from the surface seemed higher than those of the other directions. Fig. 8 shows the examples of the scanning electron microscope photographs of the fracture surface. The clear striations were observed in the fatigue specimen, and the creep-fatigue test specimen showed the typical intergranular fracture mode.

3.4 Simplified method to calculate \( \Delta J \) and \( \Delta J_c \)

The simplified experimental methods were proposed to calculate fatigue \( J \)-integral range (\( \Delta J \)) and creep-\( J \)-integral range (\( \Delta J_c \)) which can characterize the fatigue crack growth rate and creep-fatigue crack growth rate in the surface cracked plate. These fracture mechanics parameters are the modification of the fracture mechanics parameters which are available to the thorough crack.

In the case of axial fatigue, \( \Delta J \) was proposed as follows:

\[
\Delta J = \Delta k^E/E + 2Sp/(2WB - nac/2)
\]

where, \( \Delta k \): Stress intensity factor (Newman & Raju), \( E \): Young’s modulus, \( S_p \): Energy calculated from load-COD hysteresis loop. As shown in Fig. 9, the surface crack growth rate could be characterized by the proposed \( \Delta J \).

In the case of bending creep fatigue, \( \Delta J_c \) was proposed as follows:

\[
\Delta J_c = \left( \frac{a - 1}{(a + 1)} \right) \Delta \sigma \Delta \delta_c
\]

where, \( a \): stress exponent in Norton law, \( \sigma_c \): bending stress at the evaluation point, \( \Delta \delta_c \): increment of COD during load hold. As shown in Fig. 10, the surface crack growth rate could be characterized by the proposed \( \Delta J_c \).

4. CONCLUSIONS

The results obtained were summarized as follows.

1. The clear beach mark was obtained when the controlled stress range was half of main stress range and the stress ratio was -1. It was confirmed that the beach mark method was available to measure the changes of crack front shape after test.
2. The simplified method for the prediction of crack size in real time was proposed on the basis of the electrical potential measurement. The crack depth can be predicted by the measured potential value and crack length on the surface.
3. The crack front shape was approximately semi-ellipse under any kinds of loading conditions. Aspect ratio of the ellipse approached to the value of about 0.8 under axial load and approached to the value of about 0.2 under bending load. In the bending fatigue test, the crack initiation and growth with the linkage on the back-side surface was observed.
4. The simplified method to determine the fatigue \( J \)-integral and the creep \( J \)-integral for surface crack was proposed. The proposed \( J \)-integrals was proved to be useful to characterize the fatigue and the crack growth behaviors.
Table 1. Test program and test condition.

<table>
<thead>
<tr>
<th>Hold time (min)</th>
<th>Loading mode</th>
<th>Control mode</th>
<th>Temp. (°C)</th>
<th>Specimen size (mm)</th>
<th>Initial notch size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue</td>
<td>Axial Load</td>
<td>550</td>
<td>8° x 25°</td>
<td>a₀=0.5,2</td>
<td>2c₀=5</td>
</tr>
<tr>
<td></td>
<td>Bending</td>
<td>550, 850</td>
<td>10° x 50°</td>
<td>a₀=1.4,1.3</td>
<td>2c₀=4,6</td>
</tr>
<tr>
<td>Creep-fatigue</td>
<td>Axial Load</td>
<td>650</td>
<td>8° x 25°</td>
<td>a₀=0.5</td>
<td>2c₀=5</td>
</tr>
<tr>
<td></td>
<td>Bending Load stroke</td>
<td>12° x 60°</td>
<td>10° x 80°</td>
<td>a₀=1.3</td>
<td>2c₀=4,6</td>
</tr>
<tr>
<td>Creep-fatigue 60</td>
<td>Bending Load stroke</td>
<td>550</td>
<td>8° x 60°</td>
<td>a₀=1</td>
<td>2c₀=2</td>
</tr>
</tbody>
</table>

Fig. 1 Test specimen.

Fig. 2 Bending test apparatus.

Fig. 3 Procedure for potential measurement and COD measurement.
Fig. 4 Fracture surface showing the beach marks.

Fig. 5 Relation between $\sqrt{a/c}$ and $E/E$.

Fig. 6 Relation between aspect ratio and crack depth.
Fig. 7 Examples of fracture surface (stroke control).

Fig. 8 Examples of SEM photographs of fracture surface (stroke control).

Fig. 9 Relation between axial fatigue crack growth rate and $\Delta J$.

Fig. 10 Relation between bending creep-fatigue crack growth rate and $\Delta J_c$. 

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