STATISTICAL ANALYSIS OF THE CREEP CRACK GROWTH DATA IN TYPE 316LN STAINLESS STEEL

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ABSTRACT

The creep crack growth rate (CCGR) behavior of type 316LN stainless steel (SS) is analyzed statistically. The CCGR data is obtained from the CCGR tests, which are conducted with various applied loads of 5500N to 7000N at 600°C. The CCGR is characterized as a function of the \( C^* \) fracture parameter of \( \frac{da}{dt} = B(C^*)^q \). In order to logically obtain the \( B \) and \( q \) values, the three methods of the least square fitting method (LSFM), a mean value method (MVM) and a probabilistic distribution method (PDM) are applied. All of the CCGR lines of the three methods are in good accord with the experimental data. The PDM is most useful in predicting the CCGR equation because the CCGR line locates at medium between the other two lines and can be treated with a probabilistic analysis. Both the \( B \) and \( q \) coefficients follow a lognormal distribution, even though the \( B \) values are located in a broad range. The probability variables, \( P(B, q) \) are discussed in a case of the standard deviation of 1σ. Fracture morphologies of the intergranular crack with microvoids are examined to verify the creep crack.

Keywords: Creep crack growth rate, Type 316LN SS, \( C^* \), lognormal distribution, Probability.

1. INTRODUCTION

Austenitic stainless steel of type 316LN, containing both low carbon (0.03wt. %) and an appropriate amount of nitrogen (0.1wt. %), has been widely used as the structural material for liquid metal reactor (LMR) components, as a consequence of its good high temperature mechanical properties, compatibility with liquid sodium coolant, and adequate weldability (Kim\(^a\), et al., 2001; Kim\(^b\), et al., 2002; Kim\(^b\), et al., 2001; Jang, et al., 2002). Their components are often subjected to a non-uniform stress and temperature during service. These conditions generate localized creep damage and propagate the creep cracks to ultimately cause a fracture. A significant portion of the components’ life is spent in a stage of creep crack propagation. Most of the GEN-IV reactors will also be operated at the high temperature creep range above 500°C. To evaluate the creep crack growth rate (CCGR) is, therefore, very important from a design concern and in predicting the residual life of the components during the high temperature service (Nikbin, et al., 1986; Yagi, et al., 1997). In addition, to evaluate the design and remaining life for the components probabilistically, the creep crack behavior has to be verified experimentally and analyzed by a statistical method.
In this paper, the CCGR data was dealt with from probabilistic viewpoints in order to logically evaluate the creep crack in type 316LN SS. The CCGR data was obtained from several experimental tests, and characterized as a function of the $C^*$ parameter. The CCGR equations were compared with the least square fitting method (LSFM), a mean value method (MVM), and a probability distribution method (PDM). For an application of the PDM, the CCGR lines were suggested probabilistically and discussed in a case of the standard deviation of $1\sigma$ for the probability variables, $P(B, q)$. Also, fracture morphologies near the crack tip were observed to confirm the creep damage.

2. EXPERIMENTAL

Laboratory ingots of type 316LN SS were prepared by vacuum induction melting (VIM) and their chemical compositions are given in Table 1. The ingots were homogenized at 1150°C for 2 hr in an argon atmosphere and shaped to 15 mm plates by the hot rolling processes. The type 316LN plates were solution annealed for 1 hr at 1100°C and water quenched. Creep testing specimens were machined to be cylindrical with a 30 mm gage length and 6 mm diameter. All the specimens were taken along the rolling direction. The gage sections of the creep specimens were polished using #1000 grit sand papers with strokes along the specimen axis. In order to obtain the material properties of the type 316LN SS, tension and creep tests were conducted at 600°C. Creep tests were carried out using dead weight machines with a lever ratio of 20/1. The experimental procedures for the creep tests were carried out according to the recommendations of the ASTM standard E139. Creep data was automatically collected through a personal computer. The mechanical properties of $D_1$, $m$, $A$, and $n$ which are obtained from the tensile and creep tests at 600°C are listed in Table 2.

Creep crack growth tests were carried out at a constant load with applied load ranges of 5500N to 7000N at 600°C. Compact tension (CT) specimens were a width ($W$) of 25.4mm and a thickness ($B$) of 12.7mm with side grooves of 10% depth. Initial crack ratio ($a/W$) was about 0.5. Load-line deflection was measured using a linear gauge assembly attached to the specimen and crack length was determined by the direct current potential drop (DCPD) method. Crack extension data was continuously collected using a data acquisition system. The test temperature was constantly maintained at 600°C within 2°C, and the specimens were held at the test temperature for 2 hr before starting the test. The test was continued until a sufficient crack growth occurred. After the test, the specimens were cooled down in a liquid nitrogen solution and fractured to measure the final crack length. The crack length was calculated using the Johnson’s formula from the results of the DCPD. All the experimental procedures followed the ASTM standard E1457. The results of the crack size measurement are listed in Table 3. The results between the predicted and measured crack sizes are well within 5% of the requirement of the ASTM E1457.

<table>
<thead>
<tr>
<th>Table 1 Chemical composition of type 316LN SS</th>
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<tbody>
<tr>
<td>Fe</td>
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<tr>
<td>Bal.</td>
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<th>Table 2 Mechanical properties at 600°C of type 316LN SS</th>
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<tbody>
<tr>
<td>E (GPa)</td>
</tr>
<tr>
<td>---</td>
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<tr>
<td>149</td>
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</tbody>
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Table 3 CCGR test conditions and crack size measurement at 600°C of type 316LN SS

<table>
<thead>
<tr>
<th>S.P –I.D.</th>
<th>Test conditions &amp; transition time</th>
<th>Results of crack size measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load (N)</td>
<td>Applied K (MPa√m)</td>
</tr>
<tr>
<td>K1</td>
<td>7000</td>
<td>34.9</td>
</tr>
<tr>
<td>K2</td>
<td>6500</td>
<td>32.7</td>
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<td>K3</td>
<td>6000</td>
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<td>K5</td>
<td>5500</td>
<td>28.5</td>
</tr>
<tr>
<td>K6</td>
<td>6000</td>
<td>29.8</td>
</tr>
<tr>
<td>K7</td>
<td>6000</td>
<td>29.9</td>
</tr>
<tr>
<td>KR</td>
<td>6500</td>
<td>31.9</td>
</tr>
</tbody>
</table>

- a : initial crack size (at sharp notch), a0 : pre-cracked size by fatigue
- apf : predicted final crack size, amf : measured final crack size
- tT : Transition time

3. RESULTS AND DISCUSSION

3.1 Calculation of the $C^*$ values

The $C^*$ fracture parameter is defined by replacing the strains with the strain rates, and the displacements with the displacement rate in the $J$ contour integral equation. It has been widely used to characterize the creep crack growth rate in materials undergoing a steady state creep. The general form between the CCGR ($da/dt$) and the $C^*$ can be expressed as the following equations and determined from the test data (Ryu, et al., 2003):

$$\frac{da}{dt} = B[C^*]^q,$$  \hspace{2cm} (1)

$$C^* = \frac{P V_c}{B W} \eta\left(\frac{a}{W}, n\right)$$ \hspace{2cm} (2)

where,

$$\eta\left(\frac{a}{W}, n\right) = \frac{1}{(1-a/W)} \frac{n}{n+1} \left(\gamma - \delta\right)$$ \hspace{2cm} (3)

$$V_c = \dot{V} - \frac{\partial B}{P} \left(\frac{2K^2}{E}\right).$$ \hspace{2cm} (4)

$\dot{V}_c$ is calculated from the measured value of the load-line displacement $\dot{V}$, $\dot{a}$ is the crack growth rate, $B$ and $q$ are the material constants. In many materials, $q \approx n/(n+1)$. The $n$ is an exponent of the power law creep (or Norton’s rule) of $\dot{\varepsilon}_\sigma = A\sigma^n$ (Saxena, 1997; Anderson, 1995; Nikbin et al, 1986). For calculating the $da/dt$ in Eq. 1, the material constants, $D_0$, $m$, $A$, and $n$ were obtained from the tension and creep tests at 600°C, as described in section 2. Material properties of Table 2 were used to calculate the $C^*$ values. All the calculating procedures followed the ASTM E1457.

3.2 CCGR comparison with various data regression methods

The $B$ and $q$ coefficients in Eq. 1 are very important because the CCGR depends on them. Thus, in order to logically obtain the CCGR line of the type 316LN SS, the three methods of the least square fitting (LSFM) method, a mean value method (MVM) and a probabilistic distribution method (PDM) are applied. Fig. 1 shows the results of the CCGR lines obtained by the LSFM, the MVM and the PDM, respectively. They show some differences in the CCGR lines.

At First, the CCGR equation for the LSFM was obtained as
It is shown that the slope, $q$, of a regression line was the lowest. Although the LSFM has been generally used for obtaining the best fitting line of the CCGR data so far, it produces only the best fitting line of the $y$-axis for all the data points, regardless of the $C^*$ ranges of the $x$-axis for each applied condition. In reality, each range of the $C^*$ values in the CCGR lines are different with the applied load conditions. The numbers of data points are also different with the $C^*$ values. Due to this reason, the $q$ value in the LSFM is low, at 0.89.

Secondly, the conception of a mean value was adopted for obtaining the CCGR line. The MVM line showed a good agreement with the experimental data, as shown in Fig. 1. Because the MVM line takes a mean value for each $B$ and $q$ of all the CCGR lines, this method equally reflects the individual characters of each experimental line. The $q$ value in the MVM was high, at 0.93 and the CCGR equation in the MVM was obtained as

$$da/dt = 5.32 \times 10^{-2}[C^*]^{0.93}.$$  (6)

Finally, the conception of a statistical distribution was applied to obtain the CCGR line from a probabilistic viewpoint. For using this method, it was necessary to investigate the distribution functions of the $B$ and $q$ coefficients. Figs. 2 and 3 show the results of the $B$ and $q$ distributions obtained from seven experimental CCGR data. Probability distribution on a paper of the lognormal distribution follows a linear relationship well. Thus, the $B$ and $q$ data are identified to follow the lognormal distribution. Standard deviation, $\sigma_{L10}$ (subscript L means log) and mean value, $\mu_{L10}$ for the $B$ and $q$ distributions can be obtained using Figs. 2 and 3. The standard deviation of $q$ is low, while the one for the $B$ is a little bit high. The CCGR equation in the PDM was obtained as

$$da/dt = 4.64 \times 10^{-2}[C^*]^{0.92}.$$  (7)

As shown in Fig. 1, the PDM line is located at middle between the other lines of the MVM and the LSFM. Thus, the PDM can be used as a reasonable method for estimating the CCGR of high temperature materials. Especially, this PDM method enables to predict the CCGR with a probabilistic possibility.

$$da/dt = 3.84 \times 10^{-2}[C^*]^{0.89}.$$  (5)
3.3 Probabilistic prediction of CCGR line

If the \( B \) and \( q \) distributions are determined, it is possible to predict probabilistically the CCGR of materials. It was shown that the \( B \) and \( q \) followed a lognormal distribution. Thus, the reliability of the \( B \) and \( q \) values can be calculated from Figs. 2 and 3. As an example for an application, Figs. 4 and 5 were plotted in the case of 1\( \sigma \) in which the probability variable, \( P(B, q) \), is \([15.87\% \leq F(B, q) \leq 84.13\%]\).

Fig. 4 shows the results of the CCGR lines with the \( B \) parameter at a fixed \( q \) value of 50%. All the data points are included in the 1\( \sigma \) range of \( B = 84.13\% \) and 15.87%. But in the lower values of \( C^* \), the data points have a possibility to be out of the boundaries. So the parameter of the \( q \) value should be considered to predict the probability. Fig. 5 shows the results of the CCGR lines which are considered for all the eight cases: the \( B \) and \( q \) values are freely changed with 15.87%, 50% and 84.13%. In this case, the prediction band is wider than that of Fig. 4. The upper prediction line with both \( B \) and \( q \) of 84.13% will be the most conservative prediction, because the fastest CCGR is predicted in the upper line. On the contrary, the lower prediction line in 15.87% will be the most non-conservative prediction because the lowest CCGR is predicted in the lower line. It indicates that knowing the probability distribution for the \( B \) and \( q \) can be utilized usefully for predicting a design life and a remaining life of cracked components under a high temperature creep condition.

3.4 Fracture morphology

Fig. 6 shows the typical SEM photographs of the fracture surface under the applied load of 5500N. In Fig. 6,
the fractograph in front of the precrack shows the brittle surface due to creep damage. It shows the typical intergranular fracture mode with some second cracks (Mathew, et al., 1991; Sasikala, et al., 2000).

Fig. 7 shows the morphologies of the precipitates on the grain boundary, growth of the microvoids at the precipitates, and growth at crack tip under CCG condition. The sample was fractured under the load condition of 5500N at 600°C. It is obvious that the precipitates are created and grown along the grain boundary as shown in (a), and the microvoids are formed at the precipitates as shown in (b). Then, the microvoids are coupled by interconnecting, and the main sharp crack propagates in front of crack tip as shown in (c). Finally the crack is extended by the creep damage, and some branches are divided along grain boundaries.

![Fig. 6 Intergranular fracture micrographs near crack tip](image1)

![Fig. 7 Morphologies showing precipitates, microvoids and crack propagation](image2)
4. Conclusions

In order to probabilistically predict the CCGR of the type 316LN SS, three methods of the least square fitting (LSFM) method, a mean value method (MVM), and a probabilistic distribution method (PDM) were applied to calculate the CCGR parameters. Each range of the \( C^* \) values in the CCGR lines were different with the applied load conditions, and the numbers of data points were also different with the \( C^* \) values. The PDM was used as the most reasonable method for estimating the CCGR of high temperature materials. The PDM line was located between the other two lines of the MVM and the LSFM. In addition, the PDM method enabled to predict the CCGR with a probabilistic possibility. The \( B \) and \( q \) coefficients of the CCGR equation, \( \frac{da}{dt} = B[C^*]^q \), followed a lognormal distribution. The CCGR line of the MVM was in good accord with the experimental data but showed the highest \( q \) value, because the MVM reflects equally the individual behavior of each CCGR line. The LSFM which has been generally used for obtaining the best fitting line of the CCGR data made only the best fitting line showing the lowest \( q \) value. Fracture morphologies showed the typical intergranular creep fracture mode.

Acknowledgements

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References