ICM11

A study on life prediction of low cycle fatigue in superalloy for gas turbine blades

Jae-Hoon Kim*, Ho-Young Yang and Keun-Bong Yoo

*Dept. of Mechanical Design Engineering, Chungnam National University, 99 Daehak-ro(S), Yuseong-gu, Daejeon, 305-764, Korea

bPower Generation Laboratory, Korea Electric Power Research Institute, 65 Munji-ro, Yuseong-gu, Daejeon, 305-380, Korea

Abstract

A more accurate life prediction for gas turbine blade takes into account the material behaviour under the Low Cycle Fatigue cycles normally encountered in turbine operation. In this study, low cycle fatigue tests are performed as the variables of total strain range and temperatures. The relations between plastic and total strain energy densities and number of cycles to failure are examined in order to predict the low cycle fatigue life of superalloy at different temperatures. The fatigue lives that are predicted by Coffin-Manson method and strain energy methods are compared with the measured fatigue lives at different temperatures.

Keywords: Low Cycle Fatigue; Ni-based Superalloy; Coffin-Manson Method; Strain Energy Method; Elevated Temperature;

1. Introduction

It is important to design for as high temperatures gas as possible in order to attain a high thermal efficiency in gas turbines. In the case of power generating gas turbines, the increase of temperature leads to lower fuel consumption, reduced pollution and thus lower costs [1]. Ni-based super alloys are widely used for high performance applications such as disks and blades of either aircraft engines or land-based gas turbines [2]. Gas turbine blades used for power generation are mostly made of nickel based superalloys such as GTD-111 alloy. Low cycle fatigue behavior is formulated the well known Coffin-Manson law [3]. Since the fatigue damage is generally caused by the cyclic plastic strain, the plastic strain energy plays an important role in the damage process. Therefore, the idea of relating fatigue life to the plastic work during a load cycle has been proposed. Morrow [4] studied plastic strain energy and the

* Corresponding author: Tel:+82-42-821-6645; fax:+82-42-821-8894
E-mail Address: kimjhoon@cnu.ac.kr

© 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of ICM11

Table 1 Chemical compositions of GTD-111 (wt%)

<table>
<thead>
<tr>
<th></th>
<th>Cr</th>
<th>Co</th>
<th>Ni</th>
<th>Mo</th>
<th>W</th>
<th>Al</th>
<th>Ti</th>
<th>Ta</th>
<th>C</th>
<th>Hf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14.3</td>
<td>10.0</td>
<td>58.1</td>
<td>1.56</td>
<td>3.88</td>
<td>3.36</td>
<td>5.13</td>
<td>3.29</td>
<td>0.10</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 2 Mechanical properties for GTD-111 at RT

<table>
<thead>
<tr>
<th></th>
<th>E (GPa)</th>
<th>σ_p (MPa)</th>
<th>σ_τ (MPa)</th>
<th>E.L. (%)</th>
<th>R.A. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>213</td>
<td>983</td>
<td>1061</td>
<td>40.2</td>
<td>3.90</td>
</tr>
</tbody>
</table>

Fig. 1 LCF specimen  
Fig. 2 Wave form of low cycle fatigue test  
Fig. 3 Plastic and elastic density definition

researches on the relation of fatigue life to the plastic work during a load cycle have been proposed. Ellyin [5-8] proposed a fatigue failure criterion based on the strain energy density damage law. In this study, low cycle fatigue tests are performed on GTD-111 superalloy. This material is used for gas turbine blades. Therefore it is under periodic low cycle fatigue loads such as operation and shutdown. The relations between absorbed strain energy density and number of cycle to failure are examined in order to predict the low cycle fatigue life using total and plastic strain energy density methods. The fatigue life is evaluated Coffin-Manson equation, also the predicted lives by plastic and total strain energy density are compared with experimental results.

2. Material and Experimental Procedures

The material used in this test was GTD-111. Its chemical composition is detailed in Table 1. Table 2 shows the mechanical property at room temperature.

Low cycle fatigue specimens are manufactured to uniform gauge type according to ASTM E 606 [9] shown in Fig.1. The low cycle fatigue tests are performed with electro hydraulic servo-controlled fatigue testing machine (INSTRON 8861) under strain control. The strain is controlled by the 12.5 mm extensometer in the gage length, the wave form is chosen in a trapezoidal shape shown in Fig.2, and frequency is 0.25 Hz. Hysteresis loops were recorded periodically and the values of elastic and plastic deformations were determined from the stabilized hysteresis loops. Stress ratio is held reversals. The total strain range is 0.6-1.6%. fatigue life was determined at the stress drop of 25% from the initial stress.

The plastic strain energy dissipated per unit volume during a loading cycle for an element with a cyclically varying stress and strain history is shown in Fig. 3. Ellyin [5] is proposed stain energy
density methods as follows:

\[ \Delta W_t = \Delta W_p + \Delta W_e = K' \frac{1}{n'} \sigma_{\max}^{1+n'} \left( \frac{1-n'}{n'} \right) \frac{\sigma_{\max}^2}{2E} \]  

(1)

Where, \( \Delta W_t, \Delta W_p \) and \( \Delta W_e \) are total strain energy, plastic strain energy and elastic strain energy respectively, \( K' \) is a cyclic strength coefficient, \( n' \) is a cyclic strength exponent, Young modulus \( E \), maximum stress \( \sigma_{\max} \), total strain \( \epsilon_t \), plastic strain \( \epsilon_p \) and elastic strain \( \epsilon_e \). A relationship between plastic strain energy density and cycles-to-failure (Nf) may be written as Eqs. are

\[ \Delta W_p = A (N_f)^m \]  

(2)

and

\[ W_t = \chi (N_f)^n \]  

(3)

respectively. Where, \( A, m, \chi \) and \( n \) are experimental constants. Therefore the fatigue lives were evaluated by using Coffin-Manson equation [3,10], plastic and total strain energy methods [5,11].

3. Results and Discussions

Fig. 4 shows hysteresis loops of \( \Delta \epsilon = 1.2\% \) for RT, 870°C, 927°C. The stress range decreases and plastic deformation area increases with increasing of temperature. Fig. 5 shows curves of \( \Delta \epsilon = 1.2\% \) at various temperatures. Fatigue life decreases as the test temperature increases, the fracture behavior at RT and 920°C occurred sharply after progressing of cyclic softening, but the fatigue specimen at 870°C is fractured after the stress decreases about 25 % of the initial stress. Fig. 6 represents relationship between strain amplitude and fatigue life obtained from Coffin-Manson equations. The transition fatigue lives are 60.73, 17.05 and 40.50 reversals. The transition fatigue life at room temperature is longest compared with
the others, the transition life at 927°C is longer than that at 870°C.

Figs. 7, 8 show results of plastic and total strain energy density versus reversals to fatigue failure for various temperatures respectively. Fatigue life at room temperature is longest compared with these of the others, the fatigue life at 927°C is similar to that at 870°C. Table 3 summarizes the experimental and predicted results by plastic and total strain energy density, Fig. 9 shows the results compared with of measured and predicted fatigue lives at various temperatures. The measured fatigue life using plastic strain energy density agree comparatively well with the predicted fatigue life, but the predicted fatigue life using total strain energy density is larger than the predicted fatigue life at all conditions. Fig. 10 shows SEM images of fracture surfaces for the total strain of 1.2%. As you can see, the fracture surfaces at room temperature appeared to be transgranular and quasi-cleavage fracture, but

Table 3 Equations of calculated results by plastic and total strain energy density

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>Plastic strain energy density</th>
<th>Total strain energy density</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.T.</td>
<td>$\Delta W_p = 451980.8(N_f)^{1.2523}$</td>
<td>$\Delta W_t = 5724.00(N_f)^{-0.3856}$</td>
</tr>
<tr>
<td>870°C</td>
<td>$\Delta W_p = 30143.94(N_f)^{-0.9567}$</td>
<td>$\Delta W_t = 5502.25(N_f)^{-0.5754}$</td>
</tr>
<tr>
<td>927°C</td>
<td>$\Delta W_p = 45033.95(N_f)^{-1.344}$</td>
<td>$\Delta W_t = 20785.48(N_f)^{-0.803}$</td>
</tr>
</tbody>
</table>
the intergranular fracture with striation was observed at the fractured surfaces of 870°C and 927°C.

4. Conclusions

(1) The stress range decreases and plastic deformation area increases with increasing of temperature, and presents cyclic hardening behavior.

(2) The transition fatigue life at room temperature is longest compared with the others, the transition life at 927°C is longer than at 870°C. The fatigue life obtained from plastic and total strain energy density at room temperature is longest compared with the other temperatures, the fatigue life at 927°C is similar to that at 870°C.

(3) The measured fatigue life by plastic strain energy density agree comparatively well with the predicted fatigue life, but the predicted fatigue life by total strain energy density is slightly larger than the predicted fatigue life at all temperatures.

(4) The fracture surfaces at room temperature appear to be transgranular and quasi-cleavage fracture, but the intergranular fracture with striation is observed at 870°C and 927°C.
Acknowledgements

This work was supported by the research fund of Korea Electric Power Research Institute.

References