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A study on thermo mechanical fatigue life prediction of Ni-base superalloy

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ABSTRACT

Gas turbine blades are exposed to high-temperature degradation environments due to flames and mechanical loads as a results of high-speed rotation during operation. In addition, blades are exposed to thermo-mechanical fatigue due to frequent start and shutdown. Therefore, it is necessary to evaluate the lifetime of blade materials.

In this study, the TMF life of a Ni-base superalloy applied to gas turbine blade was predicted based on LCF and TMF test results. The LCF tests were conducted under various strain ranges based on gas turbine operating conditions. In addition, IP (in-phase) and OP (out of-phase) TMF tests were conducted under various strain ranges.

Finally, a fatigue life prediction model was drawn from the LCF and TMF test results. The correlation between the LCF and TMF test results was also evaluated with respect to fatigue life.

1. Introduction

In general, gas turbine blades rotate at high speeds in a high-temperature flame, in a degradation environment under mechanical loading. The blades are also exposed to thermo-mechanical fatigue due to frequent starts and shutdowns [1,2]. These conditions shorten the life of the gas turbine and reduce the reliability of the equipment.

Since the partial failure of a blade by such causes can lead to the breakdown of the entire blade set, the mechanical characteristics of the superalloys used in gas turbine blades need to be studied in order to improve the reliability of gas turbines [3,4].

In the past, the low-cycle fatigue (LCF) test and the Manson–Coffin equation were widely used to evaluate the reliability of the substrates of gas turbine blades. However, the LCF test, which only can simulate fatigue conditions under high isothermal temperatures, cannot model actual operating conditions. For that reason, thermo-mechanical fatigue (TMF) tests, which can simulate both mechanical fatigue and thermal fatigue simultaneously, are preferred.

TMF tests are the most appropriate for simulating actual combined loading conditions during service. In particular, the leading edge (LE) of the airfoil in a blade is under out-of-phase (OP) thermo-mechanical fatigue. Therefore, it is very important to evaluate the TMF characteristics [5].

However, there are many obstacles to TMF testing, such as the requirements of complex equipment and difficult test conditions. For that reason, certain researchers have attempted to build a TMF life prediction method for superalloys such as M963 using LCF data [6]. However, in the case of GTD-111, which is used for gas turbine blades, these effort are lacking. For this reason, the development of a TMF life prediction model for GTD-111 is highly necessary.

In this study, LCF and TMF tests for the life prediction of Ni-base superalloy were carried out using the furnace. In particular, in the thermo-mechanical fatigue tests, both IP (in-phase) and OP (out of-phase) TMF tests were conducted. Finally, the correlation between the LCF and TMF test results was evaluated with respect to fatigue life. In addition, the possibility of TMF life prediction using the LCF test results and the Ostergren model [7] and Zamrik models [8] was reviewed.

2. Test equipment and methods

2.1. Specimen

In this study, tensile tests, LCF tests, and TMF tests were conducted to evaluate the mechanical characteristics of Ni-base superalloys. The specimens used in this study were made from the nickel base superalloy GTD-111, which is widely used in commercial gas turbine blades. Table 1 shows the chemical components of GTD-111.

The specimens used in this study were cylindrical, and the TMF specimens were hollow in order to minimize the temperature

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Table 1
Nominal compositions of GTD-111 (wt%).

Component	Ni	Co	Cr	W	Mo
wt(%)	Bal.	9.5	14	3.8	4.5
Component	Ti	Al	C	B	Ta
wt(%)	4.9	3	0.1	0.01	2.8

gradient, in accordance with ASTM E2368 [9]. Fig. 1 shows the shapes of the specimens used in the tests.

2.2. Test equipment and method

In this study, tensile, LCF, and TMF tests were performed using an electric furnace. Tensile tests were conducted at room temperature and at 850 °C. A hydraulic test machine was used to apply a strain rate of 1 mm/min in accordance with ASTM E8-M [10]. In the high-temperature tensile test, the specimen was maintained at 850 °C for 1 h to prevent the formation of a temperature gradient. By using the mechanical properties obtained from the tensile tests, the amplitude of the total strain to be used as input for LCF tests, TMF tests were determined. The time at which the specimen completely separates was considered to be the time of fracture.

LCF tests were performed under strain control conditions at 850 °C. The test frequency was set to 0.1 Hz and the strain ratio was −1 ($R = -1$) for a strain of constant amplitude as based on ASTM E-606 [11]. Strain was measured by a longitudinal extensometer with rods spanning a gauge length of 25 mm. Temperature was controlled by an N-type thermocouple located at the mid-length of the specimen. Total strain amplitudes (Total strain amplitude and mechanical strain amplitude is same at LCF test) of 0.7%, 0.8% and 1.0% were applied.

The TMF tests used a furnace, compressed air cooling units, and a control system. The interval per cycle of the TMF test was 20 min, and the specimen temperature was varied from 450 °C to 850 °C considering the real start-up and shut-down conditions of an industrial gas turbine. A triangle waveform was used for both thermal cycling and mechanical cycling [9]. In the IP-TMF test, when temperature was increased, strain was increased. However, in the OP-TMF test, when temperature was increased, strain was decreased. Fig. 2 shows schematics of the IP and OP TMF tests.

Thermal strain was measured before each TMF test. Mechanical strain was also calculated for each TMF test by Eq. (1), as suggested in ASTM-E2368 [9].

$$\varepsilon_m = \varepsilon_t - \varepsilon_{th} \quad (1)$$

where ε_m is the mechanical strain, ε_t is the total strain (as measured by extensometer), and ε_{th} is the thermal strain (as derived by 450–850 °C thermal cycles at zero load).

The IP-TMF test was conducted with mechanical strain amplitudes of 0.39%, 0.55%, and 0.59%, and the OP-TMF test was conducted using 0.68%, 0.86%, 0.92%, and 1.07%. Fig. 3 shows the configuration of the TMF tester and Table 2 shows the conditions for each test.

3. Test results and discussion

Fig. 4 shows the results of tensile tests at room temperature and 850 °C. The tensile test at room temperature was performed once and the tensile tests at 850 °C were performed twice. The tensile strength of the tested specimen was 1,140 MPa at room temperature and 1,120 MPa at 850 °C. Yielding occurred at 1020 MPa at room temperature and at 830 MPa at 850 °C. When the temperature was increased, the yielding strength decreased by about 20%, and strain increased by about 33%. These results indicate that GTD-111 became ductile. This tendency was also confirmed by the LCF and TMF tests. Table 3 shows the results of this study and the data from another study [12]. Both results show that the material is softened under high temperature conditions.

Fig. 5 shows the hysteresis loops obtained from LCF tests at room temperature and at 850 °C. GTD-111 became ductile at high temperature. In addition, the slope of the curve changes near the maximum load, meaning that material deformation reached the plastic region. In addition, the maximum point of the hysteresis loops decreases, meaning that the material was softened by fatigue. This tendency was the seen in both the IP and OP-TMF tests.

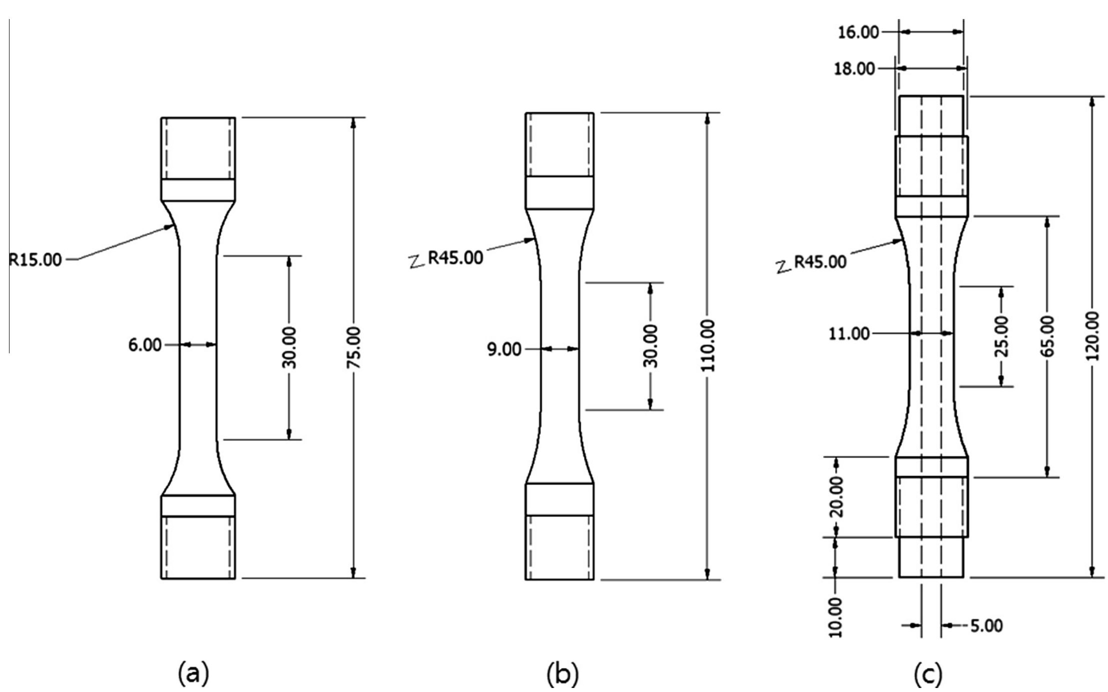

Fig. 1. The sketch of the specimens - (a) tensile specimen, (b) LCF specimen, (c) TMF specimen.