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A comparative study on thermomechanical and low cycle fatigue failures of a single crystal nickel-based superalloy

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ABSTRACT

The cyclic deformation and lifetime behaviors of a single crystal nickel-based superalloy CMSX-4 have been investigated under out-of-phase thermomechanical fatigue (OP TMF) and isothermal low cycle fatigue (LCF) conditions. OP TMF life exhibited less than a half of LCF life although smaller inelastic strain range and lower mean stress level during OP TMF were observed compared to those during LCF. During OP TMF cycling, the maximum tensile strain at the minimum temperature was found to accelerate the surface crack initiation and propagation. Additionally, the multiple groups of parallel twin plates near crack provided a preferential path for crack propagation.

1. Introduction

Single crystal nickel-based superalloys have been used as turbine blade and vane materials in gas turbines and aeroengines due to their excellent creep strength at high temperatures. Since these hot section components are subjected to cyclic thermal stresses resulting from start-up and shut-down, low-cycle fatigue (LCF) at high isothermal temperatures has been an area of ever-growing interest for the past several decades [1–7]. Most studies dealing with the LCF of nickel-based superalloys focused on the macroscopic properties under a strain ratio of $R = -1$. In order to simulate more closely the operating condition of gas turbines, repeated LCF tests with $R = 0$ has been recently investigated [4–7]. However, various components experience periods of fluctuating mechanical and thermal stresses due to the complex changes in stress and temperature during service. Hence, more recently, much intention has been focused on thermomechanical fatigue (TMF) to understand more realistic material behaviors [8–14]. TMF can lead to a limited lifetime compared with isothermal LCF due to additional deformation and damage mechanisms under varying temperature conditions [9,12]. Thus, some cases can occur where LCF tests may not capture the important damage mechanisms under TMF conditions [9]. Nevertheless, LCF tests are frequently used to predict the deformation behavior and the lifetime of components exposed to TMF since TMF tests are difficult to control variables precisely [15,16]. Accordingly, before the estimation of the TMF life from an empirical correlation with the LCF life, further research work has to be conducted to understand the different mechanisms of TMF and LCF. There have been many attempts to make comparisons between LCF and TMF for various materials [12,15,16], however, little literature has been found on the comparisons of deformation mechanisms in single crystal nickel-based superalloys, especially CMSX-4.

In the present study, both LCF and TMF tests which are representative of fatigue tests used frequently to simulate the cyclic thermal stresses for the hot section components during service, were carried out with a single crystal nickel-based superalloy CMSX-4. The cyclic deformation and lifetime behaviors were investigated for both LCF and TMF with a consideration of the damage and fracture mechanisms.

2. Experimental procedures

The material tested in the present work is a second generation single crystal superalloy, CMSX-4. All castings were made using master ingots (made by Cannon-Muskegon) from a single heat with a nominal composition of Ni–6.5Cr–9Co–0.6Mo–6W–1.0Ti–6.5Ta–3Re–0.1Hf–5.6Al (in weight percent). Single crystals were cast with rods of 13 mm diameter in a vacuum furnace (ALD model ISP 0.5) by Bridgman method. For this material, the heat treatments were given as follows: the solution treatment at 1320 °C for 2 h, and then the two step aging treatments at 1140 °C for 2 h and at 871 °C for 20 h in vacuum status of 1×10^{-5} torr. The X-ray back scattering Laue method showed that the specimens were oriented near [0 0 1] direction with a maximum deviation of 9°.

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The microstructure of the CMSX-4 consists of cuboidal ordered $L1_2$-structured γ' precipitates embedded coherently in the γ matrix of fcc structure, as shown in Fig. 1. The volume fraction and the size of cuboidal γ' precipitates was 60% and about 400–500 nm, respectively. Fig. 1b displays the γ' cuboids aligned regularly along crystallographic directions, and very low dislocation density. According to earlier studies [17,18], the constrained lattice misfit of γ/γ' interface is negative and in the order of -10^{-3} at room temperature.

Cylindrical solid specimens, of which gauge section has 5 mm in diameter and 16 mm in length, were machined for the LCF and TMF tests. The specimens were mechanically polished before fatigue tests to prevent premature crack initiation at surface-machined scratches. The strain-controlled LCF and TMF tests were carried out according to the test program summarized in Table 1. These LCF and TMF test conditions were determined as representative of fatigue tests used frequently to simulate the cyclic thermal stresses for the hot section components during service. In order to simulate more closely the operating condition of gas turbines, many LCF tests have been carried out with a frequency of 1/4 Hz under a strain ratio of $R = 0$ while most TMF tests have been conducted with a frequency lower than 1/180 Hz under a strain ratio of $R = -1$ [4–6,9–16,19,20]. In the present study, LCF tests were carried out with a frequency of 1/4 Hz under a strain ratio of $R = 0$ while TMF tests with a frequency of 1/180 Hz under a strain ratio of $R = -1$, as shown in Table 1. An extensometer with a detection resolution of 1 μm was used to measure the strain on the gauge section of specimen for both LCF and TMF tests. TMF tests were performed by induction heating in air to failure on a mechanically-driven servoelectric fatigue machine (Instron 8861) with a capacity of ±35 kN. The TMF specimens were heated by a high frequency microprocessor-controlled generator rated at 10 kW with a frequency range of 150–400 kHz. In the present study, it is deemed that heating/cooling rate is sufficiently slow (6.1 °C/s), and the frequency range of 150–300 kHz measured during heating does not cause heat to be limited to near the surface of the specimen. Thus, it can be expected that there is no temperature gradient across the specimen section. For the TMF tests, the temperature was measured and controlled with a R-type thermocouple spot-welded in the middle of the gauge length. Special care was taken when the thermocouple was spot-welded to the specimen in order to avoid crack initiation at welded region. The TMF tests were conducted in the temperature range of 400–950 °C under mechanical strain control. A simple triangular push–pull strain cycle with a mechanical strain range ($\Delta\varepsilon_{mech}$) of ±0.3–±0.5% was imposed out-of-phase (OP) with the temperature cycle: the maximum mechanical strain was attained at the minimum temperature. The life of both TMF and LCF was defined as the number of cycles at which the specimen broke.

For the observation on the fractured surfaces and deformed microstructures, scanning electron microscopy (SEM) was performed on a JEOL JSM-5800 microscope with a tungsten filament operating at 20 keV. To prepare thin foils for transmission electron microscope (TEM) examination, the fatigued specimens were cut perpendicular to the stress axis using a low-speed diamond saw to obtain thin sheets. Then, they were mechanically ground down to about 30–50 μm in thickness using a SiC and diamond-embedded polishing media. Three-millimeter-diameter disks were punched out from the thin sheets, and electropolished to perforation with an 80% methanol and 20% perchloric acid electrolyte at −25 °C and 20 V, using a double-jet electropolisher. The TEM characterization was performed on a field emission type JEOL JEM-2100F operating at 200 keV. Some of the TEM observations have been done with the foils prepared by a focused ion beam (FIB) system to investigate deformed microstructures near fatigue crack tips.

Table 1
Summary of LCF and TMF test conditions.

Test	Waveform	Temperature		Frequency	R ratio	Total strain range ($\Delta\varepsilon_{mech}$)
		Max.	Min.			
LCF	Trapezoidal (1 −1 −1 −1)	950 °C (isothermal)		1/4 Hz	0	0.6–1.0%
TMF	Triangular (out-of-phase)	950 °C	400 °C	1/180 Hz	−1	0.6–1.0%

3. Results and discussion

3.1. Cyclic stress–strain comparison

Fig. 2 shows the typical hysteresis loops in the LCF and the OP TMF tests at mechanical strain ranges of 0.6% and 1.0%. The loops are given by those at the first cycle ($N = 1$) and at the mid-life ($N = N_f/2$, where N_f is the number of cycles to failure). With increasing the number of cycles, the loop shifted upwards slightly during OP TMF cycling while downwards during LCF cycling. The downward shift of hysteresis loop is characteristics of the LCF test with $R = 0$, where the decrease in the maximum tensile stress is frequently observed [12]. In the case of OP TMF test, the compressive stress decreased in the high temperature half cycle (maximum compressive strain ~ 0) while the tensile stress increased in the low temperature half cycle ($0 \sim$ maximum tensile strain). The decrease in the maximum stress at 950 °C (the maximum tensile stress during LCF while the maximum compressive stress during OP TMF) results from stress relaxation at each cycle. The stress relaxation at elevated temperatures could be caused by the weakened γ/γ' coherency (the formation of interfacial dislocations

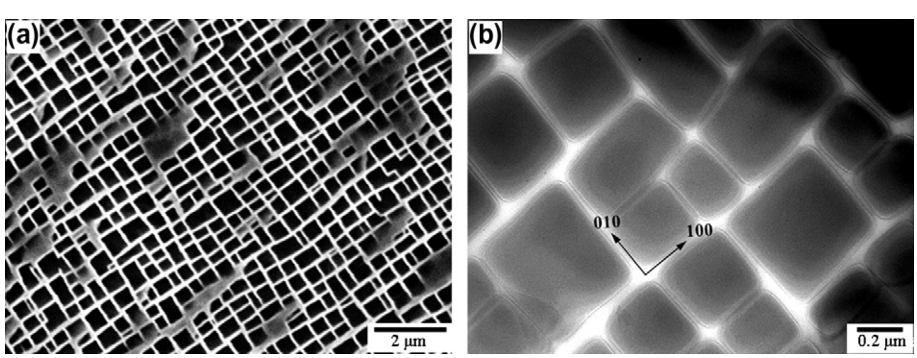

Fig. 1. Initial microstructure of CMSX-4: (a) SEM and (b) TEM micrographs.