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Effect of microstructural characteristics on the low cycle fatigue behaviors of cast Ni-base superalloys

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ABSTRACT

Low cycle fatigue behaviors of two cast Ni-base superalloys have been investigated. Effects of microstructure of a solution hardened alloy and a precipitation strengthened alloy on cyclic stress responses were studied at various temperatures and strain ranges. In the case of a solution hardened alloy, Hastelloy X, fatigue lives at lower temperatures are longer than those at higher temperatures regardless of total strain range. IN738LC which is strengthened by γ' particles is founded to have longer fatigue life at low temperature than high temperature when total strain range is low. However, the alloy has longer fatigue life at high temperature than low temperature when the total strain range is high. Because γ' particles are cut by coupled dislocation and slip band forms, deformation is inhomogeneous, and strain is concentrated to local region during low temperature fatigue test, while thermally assisted dislocation movements result in less stress concentration at high temperature. Therefore, fatigue life of the alloy at high temperature is longer than that of low temperature under high strain range condition. When strain range is low, oxidation plays important role in the fatigue behavior. Oxidation decreases fatigue life by means of affecting crack initiation and growth behavior at high temperature.

1. Introduction

Ni-base superalloys are widely used for gas turbine hot section due to their excellent high temperature strength and creep properties. Because these components are operated at high temperature, superior creep properties are primarily demanded. Low cycle fatigue (LCF) at high temperature has been an area of ever-growing interest for the past several decades since the hot section components of gas turbine are also subject to variation of mechanical and thermal loads [1–6]. Many studies have been carried out in order to understand fatigue behaviors of superalloys under the variation of several parameters such as temperature [7,8], dwell time [9,10], crystal orientation [11], and environment [12,13]. Cyclic deformation behavior of superalloy depends on not only LCF conditions such as temperature and strain range but also microstructure of the superalloy. However, limited research has been conducted to explain the relationship between fatigue deformation and microstructure of superalloys [14].

In the present investigation, the LCF behaviors of two cast Ni-base superalloys, a precipitation strengthened alloy IN738LC and a solid solution hardened alloy Hastelloy X, have been studied to understand the effect of deformation mechanism on the fatigue life under the variation of temperature and strain range. Different fatigue behaviors of the superalloys which were attributed to different microstructures have been also discussed.

2. Experimental procedures

Two equi-axed polycrystalline Ni-base superalloy IN738LC and Hastelloy X specimens of 13 mm in diameter were investment cast under vacuum. Chemical compositions of the alloys are listed in Table 1. Grain sizes of both specimens were about 1 mm and uniform. The standard heat treatment for the cast specimens of IN738CL was performed, i.e. solution treatment at 1120 °C for 2 h and aging at 843 °C for 24 h. Hastelloy X specimens were subjected to solution heat treatment at 1175 °C for 1 h.

Cylindrical specimens of 5 mm gauge diameter and 16 mm gauge length were machined for LCF tests. The gauge sections of specimens were mechanically polished before tests to prevent premature crack initiation at machined traces on specimen surface. Fatigue tests were carried out in air under axial total strain control using a servo-hydraulic testing machine (Instron 8501) with a capacity of 100 kN load cell. Loading was push–pull type triangle with a cyclic frequency of 0.25 Hz. The specimens were tested at 650–927 °C with a total strain range of 0.6–1.2%, and R ratio ($\varepsilon_{min}/\varepsilon_{max}$) was −1.

For observation of the fractured surface and microstructures, optical microscope (OM), scanning electron microscope (SEM) and transmission electron microscope (TEM) examinations were conducted. The polished samples for SEM observation were etched in a solution with 2–3 g $CuCl_2$, 70 ml ethanol, 30 ml HCl. To prepare thin foil for TEM observation, thin sheets were cut parallel to the stress axis of the tested specimens. Three-millimeter-diameter disks were punched out from the mechanically polished thin foils, and electropolished to perforation

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Table 1
Chemical compositions of superalloys (wt.%).

Alloy	C	B	Zr	Al	Ti	Cr	Fe	Co	Mo	Ta	W	Nb	Ni
IN738LC	0.099	0.011	0.03	3.53	3.33	15.91	-	8.32	1.76	1.91	2.60	0.90	Bal.
Hastelloy X	0.083	0.002	–	–	–	22.57	18.3	1.55	9.10	–	0.58	–	Bal.

with an 80% methanol and 20% perchloric acid electrolyte at −25 °C and 20 V, using a twin-jet electropolisher.

3. Results and discussions

3.1. Microstructures of the superalloys

Microstructures of heat treated IN738LC and Hastelloy X are shown in Fig. 1. Two Ni-base superalloys have different microstructural features. IN738LC is a precipitation hardened superalloy whose strength is primarily derived from precipitation of coherent γ′ particles in the matrix. On the other hand, Hastelloy X is a solid solution strengthened superalloy. Segregation of alloying elements in IN738LC is not completely eliminated after solution and aging heat treatment as shown in optical micrograph (Fig. 1(a)). Fig. 1(b) shows bimodal distribution of primary and secondary γ′ particles after aging heat treatment. Coarse primary γ′ particles with cuboidal shape have a cube edge of about 0.4–0.5 μm, and spherical secondary γ′ particles form with 0.05–0.1 μm in diameter. Hastelloy X also shows segregation of alloying elements after solution heat treatment, and some parts of grain boundaries are indistinctive as shown in Fig. 1(c). Partial dissolution of $M_{23}C_6$ carbides on grain boundaries occurs during solution heat treatment as shown in Fig. 1(d).

3.2. LCF behavior

The variation in number of reversals to failure of two superalloys as a function of imposed half of total strain range at various temperatures is plotted in Fig. 2. Fatigue life of IN738LC at 650 °C is longer than that of 927 °C with small total strain amplitude of 0.4%. However, the alloy revealed longer fatigue life at 927 °C than 650 °C with the total strain amplitude of 0.6%. For Hastelloy X, fatigue lives at lower temperatures are longer than those at higher temperatures regardless of total strain amplitude. It can be noted that two superalloys exhibited different fatigue behaviors with variations of temperature and total strain range.

Based on the well-known strain vs. life relationship, low cycle fatigue behavior of the alloys can be explained by separating total strain amplitude into the elastic and plastic strain amplitudes [15].

$$\frac{\Delta\varepsilon_t}{2}=\frac{\Delta\varepsilon_p}{2}+\frac{\Delta\varepsilon_e}{2}=\varepsilon_f^{'}(2N_f)^{-c}+\frac{\sigma_f^{'}}{E}(2N_f)^{-b} \tag{1}$$

where $\Delta\varepsilon_p$ and $\Delta\varepsilon_e$ are the plastic and elastic strain ranges, respectively, $\varepsilon_f^{'}$ is the fatigue ductility coefficient, N_f is the number of cycles to failure, c is the fatigue ductility exponent, $\sigma_f^{'}$ is fatigue strength coefficient, and b is the fatigue strength exponent. The relationship between elastic, plastic strain amplitudes and the number of reversals to failure of IN738LC and Hastelloy X at various temperatures is shown in Fig. 3. The values of elastic and plastic strain amplitudes are obtained at half of fatigue lives of the alloys at each temperature. The portion of plastic strain amplitude is very small while elastic strain amplitude is almost same with total strain amplitude at 650 °C for IN738LC. Although the portion of plastic strain amplitude increased at 927 °C, elastic strain amplitude is still larger than plastic strain amplitude. Plastic strain amplitude is relatively large at low temperature of 650 °C for Hastelloy X. The portion of plastic strain amplitude exceeded the elastic strain amplitude at 871 °C. Plastic strain amplitude is small where the total strain amplitude is small, but it increases with increasing total strain amplitude for both alloys.

Generally, it is well known that high ductility materials have better fatigue resistance at the regime where plastic strain is important while high strength materials have superior fatigue resistance at the

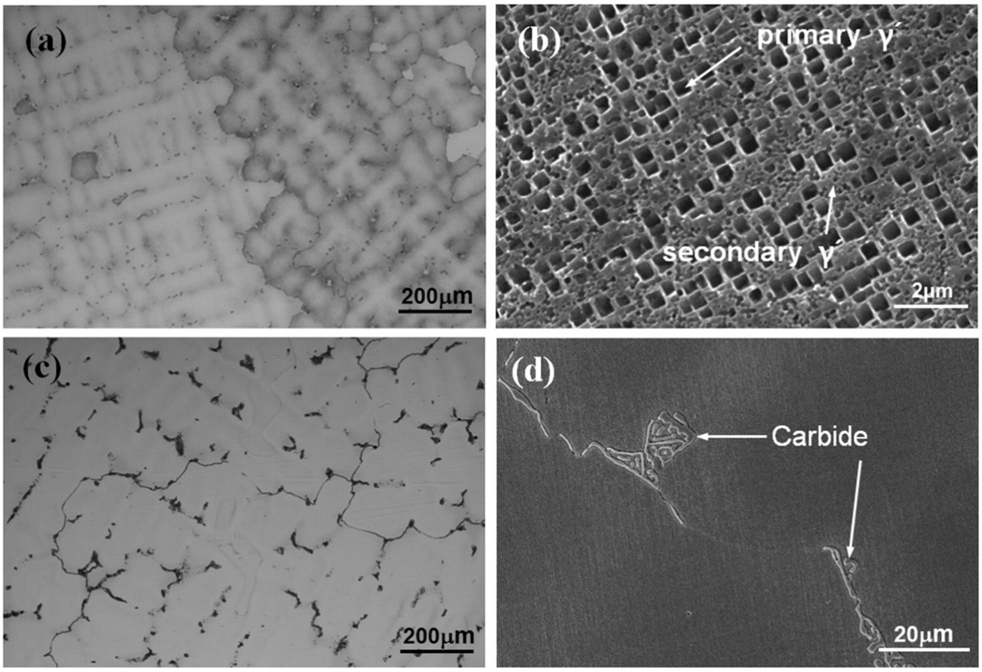

Fig. 1. Microstructures of the heat treated alloys, (a), (b) optical and SEM micrographs of IN738LC, and (c), (d) optical and SEM micrographs of Hastelloy X.