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Cyclic deformation behavior of a nickel-base superalloy under fatigue loading

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Total strain-controlled low cycle fatigue (LCF) tests of a nickel-base superalloy were performed at 650 °C. Combined with fatigue test data, cyclic deformation behaviors of the alloy were analyzed. Fatigue cycle life decreases significantly with the increasing total strain amplitude. The cyclic hardening and cyclic softening phenomena occur during the LCF process, which are associated with the total strain amplitude. Fracture morphologies and dislocation characteristics were observed through scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The combined effects of brittle fracture and ductile fracture are the main LCF fracture mechanism of the alloy.

1. Introduction

With the development of the aviation career, further improvement of the thrust–weight ratio is an important trend in engine development. The new-type of engines with high thrust–weight ratio put forward higher requirements for hot-end components. The turbine disk is one of the most important hot-end components in the aeroengines, withstanding the combined effects of mechanical and thermal stresses [1,2]. The materials of turbine disk must possess high creep resistance, persistent strength and thermal fatigue resistance, which can adapt to the reliable working requirements under harsh conditions such as high temperature and strong corrosion [3,4]. High-temperature materials possess overall performance of high temperature strength and high temperature oxidation resistance, so that they can be used as candidate materials of turbine disk using in extreme environments. Currently, high-temperature materials include superalloys, intermetallic compounds, refractory metals, metal–ceramic materials and composite materials. In practical applications, nickel-base superalloys become the key materials of high temperature components such as turbine disk due to high temperature oxidation and corrosion resistance, excellent creep resistance, good fatigue resistance at high temperatures [5–8].

The nickel-base superalloy studied in this paper is used mainly for aeroengine turbine disks in the temperature ranges from 600 °C to 750 °C. Aeroengine turbine disks withstand high temperatures and effect of alternating loading for a long time, which are easy to produce strain-controlled high temperature LCF damage. Thus, it seriously leads to the reduction of the working life of components [9,10]. The LCF behaviors of superalloys have become a research hotspot in recent decades. Extensive researches have been studied about the effects of the cyclic frequency, strain rate, strain range, predeformation, corrosive environment and testing temperature on fatigue behavior of superalloys [11–17]. Kunz et al. [11] investigated casting defects and high temperature fatigue life of IN 713LC superalloy. Shi et al. [12] carried out experiments at elevated temperature to investigate the effect of brazing itself and post-brazing heat treatment on the lifetime of directionally solidified superalloy. Shyam and Milligan [13] studied effects of deformation behavior on fatigue fracture surface morphology in a nickel-base superalloy. Rho and Nam [14] investigated the effect of applied strain range on the fatigue cracking in Nb-A286 iron-base superalloy. Lu et al. [15] studied hold time effects on low cycle fatigue behavior of HAYNES 230®superalloy at high temperatures. Bhattacharyya et al. [16] studied the origin of microtwinning at low strains during low cycle fatigue of Inconel 718 at room temperature. Marchionni et al. [17] investigated high temperature low cycle fatigue behavior of UDIMET 720 Li superalloy. The fatigue behaviors of other high-temperature materials have been also studied. Pegorin et al. [18] evaluated comparative study of the mode I and mode II delamination fatigue properties of z-pinned aircraft composites. Li et al. [19] investigated simulation of fatigue failure in composite axial compressor blades. Wu et al. [20] investigated systematically the effects of microstructure types and microstructure parameters on high cycle fatigue (HCF) properties

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through an analysis on microstructure and HCF properties of Ti–6Al–4V alloys which were selected from literature. Prasad et al. [21] studied the LCF behavior of a near α Timetal 834 titanium alloy under fast–slow and slow–fast waveforms at peak dynamic strain aging (DSA) temperature (450 °C).

The actual service temperature of aeroengine turbine disks is about 650 °C. At this temperature, the complex service environments put forward higher requirements to the performance of superalloys. The following two measures are currently used to improve the performance of superalloys: (1) changing the composition; (2) using appropriate heat treatment. In the present study, nickel-based superalloy with certain components was conducted an appropriate heat treatment. Then LCF tests were conducted so as to determine high temperature low cycle fatigue properties for this alloy under the conditions of 650 °C. Thus, based on total strain-controlled LCF tests, the effects of strain amplitudes on mechanical response and microstructure at 650 °C were studied. Combined with fatigue test data, mechanical properties of the alloy were explored. Fracture morphology and dislocation characteristic were observed through SEM and TEM so as to study the fracture mechanism of the LCF of the alloy.

2. Experimental details

The chemical composition (wt%) of the alloy is as fellows: C 0.042, Cr 14.50, Mo 3.18, Al 1.70, Ti 2.68, Fe < 0.10, Nb 2.02, Ni the rest. The procedure of heat treatment was the following: 1100 °C/8 h, AC + 1000 °C/4 h, AC + 775 °C/16 h, AC + 700 °C/16 h, AC (AC means air cooling).

The fatigue tests are referred to ISO 1099:2006 (Metallic materials-Fatigue testing-Axial-force-controlled method) [22]. Standard fatigue specimens were machined from heat-treated specimens with 6.350 mm in diameter and 90 mm in gauge length. MST NEW 810 fatigue testing machine is the LCF equipment. The fatigue tests were conducted in air. Experimental program was total axial strain-controlled LCF. The total strain amplitude varied from 0.3% to 0.8%. The strain ratio was $R = -1$. The loading frequency of 0.50 Hz was applied in a triangular waveform. The temperature of LCF tests was 650 °C. All specimens were run to failure.

The fatigue fracture specimens were placed in acetone solution for the ultrasonic cleaning after the fatigue tests. The grain morphology was observed by Olympus microscope after mechanical grinding, polishing and chemical etching of metallographic specimens. The fracture morphology was observed by SEM so as to determine the mechanism of fatigue fracture. Specimens for TEM were obtained from thin slices (500 μm in thickness) at a distance of 1 mm away from the fracture surfaces of the failed specimens. Thin slices were grounded to about 50 μm using 200 # to 1200 # sandpaper and then prepared for ion thinning. Then dislocation characteristics were observed through TEM.

3. Results and discussion

3.1. Grain morphology and precipitates

The procedure of heat treatment includes solution treatment and aging treatment. The solution treatment is to dissolve the original state of the reinforcing phase, to obtain the desired grain size and to eliminate machining stresses. The aging treatment is to precipitate γ′ phase, while to precipitate the complex carbide and boride phases on the grain boundary, and then the turbine disks possess a good overall performance. The γ′ phase melting temperature is 1050 °C. In order to obtain the desired grain size and to dissolve strengthening phase, the solution temperature should exceed the γ′ melting temperature. Thus 1100 °C is selected as the solution temperature. Original grain morphology and heat treatment grain morphology are shown in Fig. 1. It can be observed from morphology that the grain of original organization is much small and many twins exist. The size of grains significantly increases and some twins still exist after heat treatment. Fig. 2 shows the precipitates of the nickel-base superalloy after heat treatment. It can be seen that γ′ phase has no significant differences and mainly two sizes dispersed circular particle. The carbides occur at the grain boundaries.

3.2. Fatigue property and fatigue life prediction

The fatigue test results are shown in Table 1, where, $\Delta\varepsilon_t/2$ is the total strain amplitude, $\Delta\varepsilon_e/2$ is the elastic strain, $\Delta\varepsilon_p/2$ is the

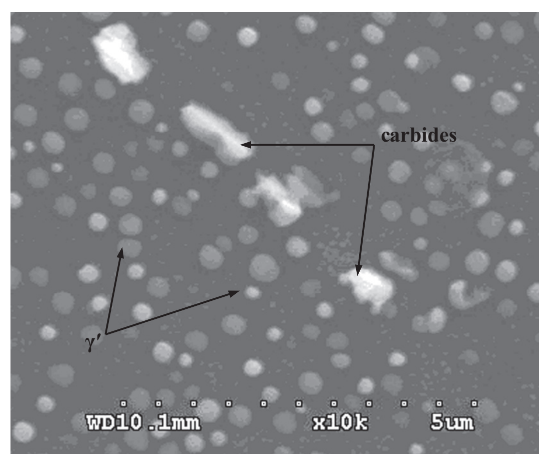

Fig. 2. The precipitates of the nickel-base superalloy after heat treatment.

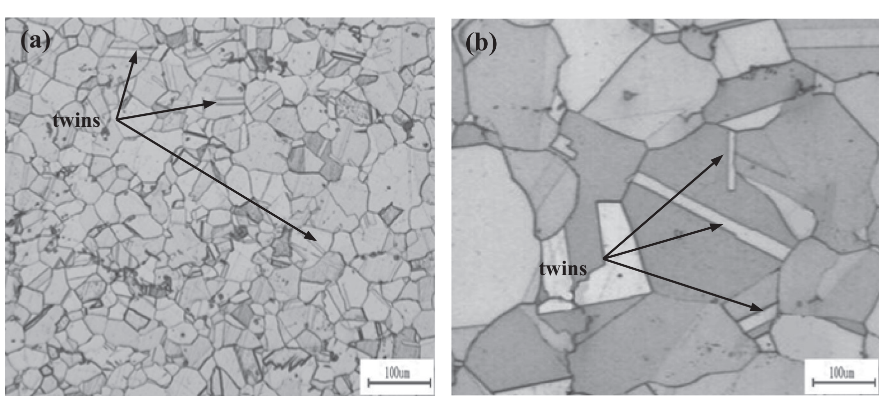

Fig. 1. Original grain morphology and heat treatment grain morphology of the alloy. (a) Original grain morphology; (b) heat treatment grain morphology.