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On the low cycle fatigue behavior of a Ni-base superalloy containing high Co and Ti contents

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ABSTRACT

Low cycle fatigue behavior was studied at 400, 650 and 725 °C in the total strain ranges of 0.79–1.22% for a recently developed Ni-base superalloy containing high Co and Ti contents. Detailed examinations were conducted on cyclic hardening/softening behavior, deformation substructure, fatigue life, as well as crack initiation and subsequent propagation. Continuous cyclic hardening at 400 °C was observed whereas cyclic softening at 650 and 725 °C was examined, except at 650 °C and low strain range (0.8%) where alloy exhibited relative stable stress response until crack initiation. Transmission electron microscopy analysis suggests that cyclic hardening is caused by the inhomogeneous dislocation activity and interactions of dislocations, and cyclic softening is related to shearing of gamma prime precipitates by stacking faults and coupled dislocation pairs combining with thermal activation process. The relation between fatigue life and plastic strain followed the Coffin–Manson law. Fatigue cracks often initiated on or near the surfaces of specimen during cycling, while subsurface carbide clusters initiation was also observed. Oxidation accelerated crack propagation at 650 and 725 °C.

1. Introduction

Many Ni-base superalloys have been developed for wide use in critical components, e.g. disk, of turbine engines because of their excellent mechanical properties and environmental resistance at elevated temperatures. The operating temperatures of high-pressure turbine disks and commercial pressures have continued to challenge materials and design engineers as temperatures now approach 700 °C or even higher for military applications and ever-growing cost down requirement. Generally, commercially available cast and wrought (C&W) superalloys such as U720Li for turbine disks applications are confined to use below 680 °C due to the degradation of their mechanical properties [1]. Hence, a disk superalloy capable of operation at greater than 700 °C is highly desired for advanced gas turbine engines.

The mechanical properties of Ni-base superalloys can be optimized by tailoring alloy chemical composition and controlling the material processing and heat treatment. It is known that the major changes in microstructure and properties can be caused by relatively small changes in compositions. A typical Ni-base disk alloy usually contains 5–20 wt% Co and 2–5 wt% Ti. It is reported that addition of Co as an alloying element in Ni-based superalloys generally reduces the creep rate of Ni-base disk superalloys [2–6]. On the other hand, addition of Ti as a strong γ' precipitates formation element and a substitute for Al in γ' phase increases the strength of Ni-base superalloys by increasing the Ti/Al ratio (concentrations in at%) [7,8]. Therefore, it can be expected that achieving improved mechanical properties in C&W disk alloys by increasing the contents of both Co and Ti is possible. Based on this concept, the authors have recently developed new C&W Ni-base superalloys, named TMW® alloys [9–12]. In these TMW® alloys, the contents of Co and Ti are higher than in current commercial C&W disk alloys, i.e., Co content varies from 22 wt% to 31 wt% and Ti content varies from 5.1 wt% to 7.4 wt% [12]. TMW® alloys exhibit higher tensile strength at temperatures up to 750 °C and superior creep resistances up to 725 °C as compared to those of U720Li alloy [9–12], and are promising for turbine disk applications at 700 °C or more.

The main role of turbine disk is to hold the turbine blade with high rotational speeds/temperatures and to transmit the power to the high pressure turbine shaft. Thus, the disk is subjected to repeated thermal and mechanical stresses during start-up, steady-state, and shut-down operations. Although precipitation strengthened superalloys keep excellent monotonic strength levels up to high fractions of their melting point ($\sim$0.6 T_m), the lives of superalloys are often shortened during service due to fatigue, especially when the cyclic loading is applied at low frequency and in an oxidizing environment [13,14]. Therefore, the resistance to fatigue at elevated temperatures is an essential property for disk alloy and

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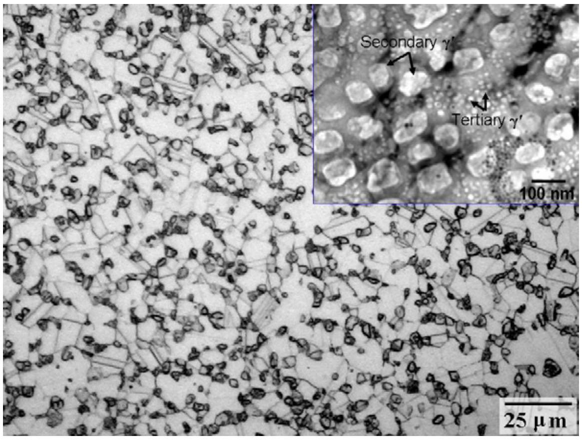

Fig. 1. The microstructure of TMW-4M3 alloy. The inset image shows the fine secondary and tertiary γ′ precipitates.

must be considered in engineering design. The cyclic deformation behavior of C&W Ni-base superalloys has been studied for several different viewpoints, e.g. mechanical response, slip band formation on surfaces of fatigued specimens and cracking, as well as the dislocation structures that develop during fatigue. It is often reported that at lower temperatures many alloys exhibit an initial period of cyclic hardening followed by either cyclic saturation or cyclic softening, while at higher temperatures cyclic softening typically follows a brief period of hardening [14–23]. However, some alloys showed immediate softening instead of hardening [24]. Material response also influenced by other factors, such as imposed strain range. Planar slip was the major deformation mode for the Ni-base superalloys because of their low stacking fault energy (SFE) [14,25–27]. Cracks often were found to be initiated on the surface of specimens and at the subsurface non-mental inclusions [15,28,29].

Although previous study on the effects of Co and Ti on the fatigue properties of Ni-base superalloys is limited in open literatures, from earlier studies on the influence of Co on tensile and creep properties of Ni-base superalloys [3,4], it can be expected that these elements might play key roles in the fatigue behavior of superalloys. The observed excellent creep resistance and high tensile strength in TMW® alloys [30–32] may also imply that these alloys possess excellent fatigue properties at elevated temperatures. The objective of this paper is to investigate the cyclic stress–strain relations, cracking, and the low cycle fatigue (LCF) behavior of a Ni-base superalloy containing high contents of Co and Ti and to relate this to the substructural development with respect to dislocation configurations. The material studied, TMW-4M3, has higher contents of Co (25 wt%) and Ti (6.2 wt%) than the conventional Ni-base superalloys together with higher Ti/Al ratio. This may both alter the SFE, anti-phase boundary (APB) energy and the volume fraction of γ′ precipitates, which in turn may change the cyclic deformation behavior.

2. Material and experimental procedures

TMW-4M3 alloy used in this work was developed by National Institute for Materials Science, Japan. The chemical composition of TMW-4M3 is listed in Table 1. For comparison, the compositions of U720Li were also included. As can be seen, these two alloys have similar chemical compositions, except the higher levels of Co and Ti in TMW-4M3. The detailed fabrication process for TMW-4M3 is described in elsewhere [12]. The microstructure of TMW-4M3 alloy, as shown in Fig. 1, consists primarily of a fine mean grain size (8.7 μm) gamma (γ) grains and primary gamma prime (γ′) precipitates with a size of 0.5–2.5 μm between the γ grains or in the interior of grains. The volume fraction of primary γ′ was about 16.9%. Aging twins were also discernible within some γ grains. In addition, small quantities of $M_{23}C_6$ and MC carbides (∼0.5%) were also present at grain boundaries. Fine secondary (30–100 nm in diameter) and tertiary γ′ (5–10 nm) particles precipitated in γ grain can be seen in the inset image in Fig. 1.

The specimens for LCF testing were machined from the heat-treated pancake with a dimension of 440 mm in diameter and 65 mm in thickness. All tests were carried out on a threaded round specimen with 6.35 mm in gauge diameter and 19 mm in gauge length. Prior to testing, specimens were polished using SiC paper to a 600 grit surface finish parallel to the stress axis to remove any circumferential/radial scratches/machining marks that might act as crack initiation sites. The LCF tests were carried out in a computer-controlled MTS New810 servo-hydraulic machine. Tests were conducted in air at 400, 650, and 725 °C under longitudinal strain-controlled conditions with total strain range ($\Delta\varepsilon_t$) varied from 0.79% to 1.22%. The strain ratio (R_ε) of minimum to maximum strain was zero. An identical frequency of 0.5 Hz, applied in symmetric triangular waveform was used for each test. All the tests were started after the temperature reached the designated values for 10 min, and the temperature over the gauge length was maintained within ±5 °C. The fatigue tests were continued until specimen fractured.

The fracture surfaces of fatigued samples were examined by scanning electron microscopy (SEM) to determine the crack initiation and propagation modes. Deformation-induced substructures were studied by transmission electron microscopy (TEM). Samples for TEM examination were obtained from thin foils sliced from adjacent to the fracture surface. Discs of 3 mm in diameter were punched out from the foils after which were mechanically thinned down to about 50 μm, and followed by twin-jet electrolytic thinning in a chemical solution (10 vol% perchloric acid, 20 vol% ethanol, and 60 vol% *n*-butoxyethanol) at about 0 °C and 20 mA. TEM observation was performed on TECNAI-20 operated at 200 kV.

3. Results

3.1. Evolution of cyclic stress

During the course of the fatigue tests the changes in load were recorded. The cyclic tensile stress responses at various strain levels for different test temperatures are shown in Fig. 2. It can be seen that, the cyclic stress response of TMW-4M3 is closely related with both strain range and test temperature. At 400 °C, continuous increase of the peak tensile stress (hardening) was observed prior to the onset of the microcrack initiation stage at all the strain ranges. At 650 and 725 °C, however, the evolution of the stress with the number of cycles was found to be different from that observed at 400 °C. Under all the strain ranges, the period of hardening was absent (Fig. 2(b) and (c)) and the specimens soften from the first cycle, except the specimen tested at 650 °C and $\Delta\varepsilon_t = 0.8\%$, which shows relatively stable stress response with data fluctuation until failure initiation.

3.2. Degree of cyclic hardening/softening

To quantify the degree of cyclic hardening/softening, the hardening parameter, *D*, is calculated using the following equation:

$$D(\%) = \left[\frac{\sigma_{\text{mid-life}} - \sigma_1}{\sigma_1}\right] \times 100 \tag{1}$$

where $\sigma_{\text{mid-life}}$ is the peak tensile stress exhibited at mid-life, and σ_1 is the peak tensile stress at the first cycle. The variation of *D* with temperature at each $\Delta\varepsilon_t$ is shown in Fig. 3. It is evident that, at 400 °C, the magnitude of hardening of TMW-4M3 increased with