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Effect of dwell condition on fatigue behavior of a high-Nb TiAl alloy at 750 °C

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ABSTRACT

The strain-controlled low cycle fatigue (LCF) and creep-fatigue interaction (CFI) tests of a newly developed Ti-45Al-8Nb-0.2W-0.2B-0.02Y (at.%) alloy were carried out at 750 °C in air. The hysteresis loop, cyclic stress response and life modeling as well as failure mechanism of the alloy were investigated in detail. It was revealed that the tensile and compressive mean stresses would generate when the dwell condition was introduced at minimum and maximum strain, respectively. In addition, the dwell condition, especially for the compressive dwell condition, would significantly decrease the fatigue life. The typical continuum damage accumulation (CDA) and modified CDA life models proposed in the present study were employed to predict both LCF and CFI life of the alloy, which showed that the modified CDA life model had a higher accuracy than the typical CDA life one. Moreover, only single crack initiation source was observed at 92% (*i.e.* 11/12) of LCF fracture while multiple crack initiation sources at 84% (*i.e.* 31/37) of CFI fracture. Apparently different from LCF specimen showing more transgranular appearance, CFI specimen shows more intergranular appearance.

1. Introduction

TiAl alloys have been widely used in the turbine blades of advanced aeroengines because of their excellent benefits such as lower density, high specific strength, excellent high temperature property and so on [1–4]. According to statistics, more than 40,000 TiAl low pressure turbine (LPT) blades have been manufactured for GEnx 1B (Boeing 787) and GEnx 2B (Boeing 747-8) turbine engine applications [5]. In order to explore TiAl alloys bearing higher temperatures, high Nb containing TiAl alloys, which exhibited better high temperature strength and oxidation resistance than ordinary TiAl alloys, have drawn a great deal of attention in recent years [6–13]. Kim et al. [6] has reported that the developed high-Nb TiAl alloy showed excellent tensile strength at room temperature and high temperature (900 °C) as well as good oxidation resistance at 900 °C compared to the commercial TiAl alloy. Tian et al. [7,8] has studied that the creep properties of as-cast high-Nb TiAl alloys were obviously affected by the microstructure and heat treatment. Yu et al. [9] has investigated the effect of stress ratio on fatigue lifetime, crack initiation sites and fracture mode of a cast high-Nb TiAl alloy at 750 °C. Ding et al. [10] has demonstrated that the high-Nb TiAl alloy exhibited a rapid saturation of stress amplitude at low strain amplitude while the cyclic stress-strain behavior was characterized by generally cyclic softening at 850 °C. Wu et al. [11] has reported that the static tensile and fatigue fracture behavior was correlated with microstructure of the high-Nb TiAl alloy fabricated by the plasma arc melting (PAM). Kartavykh et al. [12] has proposed a high-gradient induction float zone (FZ) technique to replace HIPing or complex thermal treatments of a cast β-stabilized γ-TiAl and obtained better tensile yield strength(837 MPa), rupture strength(983 MPa) and elongation(1.45%) at room temperature. Chlupová et al. [13] has investigated the effect of the as-received microstructure and phase composition on the monotonic testing (tensile and compression) and LCF behavior of a high-Nb TiAl alloy at ambient and elevated temperatures.

Although many studies on mechanical behavior of high-Nb TiAl alloys have been carried out, some issues on their CFI behavior have not been investigated yet. The high-Nb TiAl alloy, just like Ni-based superalloys, would experience both fatigue and creep loadings in service inevitably. Therefore, it was very necessary to study CFI behavior of the alloys at high temperatures.

Firstly, both LCF and CFI tests of a newly developed high-Nb TiAl alloy were conducted at high temperature in order to investigate the effects of the dwell condition on the fatigue behavior. Secondly, a newly

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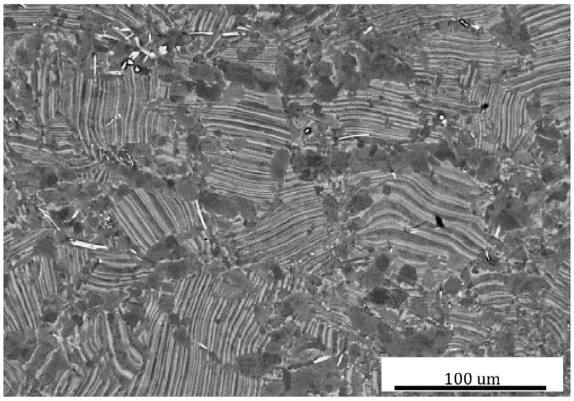

Fig. 1. Microstructure of Ti-45Al-8Nb-0.2W-0.2B-0.02Y alloy.

developed CDA method considering the dwell condition was employed to predict both LCF and CFI life of the alloy. Finally, the different failure mechanisms of the alloy were discussed between LCF and CFI conditions.

2. Experimental procedure

The high-Nb TiAl alloy, Ti-45Al-8Nb-0.2W-0.2B-0.02Y (at.%) alloy, was fabricated by a Vacuum Arc Remelting (VAR) furnace and then Hot Isostatic Pressing (HIP) at 1300 °C and 130 MPa for 3 h under argon atmosphere. Further, the cast ingot was quasi-isothermal forged perpendicularly to its axis at 1275 °C and 0.05/s, with a total engineering strain of 70% and then followed by the annealing treatment at 1000 °C for 24 h As shown in Fig. 1, the alloy presented a uniform nearly-lamellar microstructure and consisted of relatively small lamellar colonies (average size of 50 μm), γ phase, a small amount of borides, Y_2O_3 in bulk particles, which has been reported by Xu et al. [14–16]. The alloy contained more γ phases than traditional high-Nb TiAl alloy. Prior to LCF and CFI tests, the tensile tests have been conducted and the yield strength, ultimate strength and elongation of the alloy at 750 °C were 419 MPa, 488 MPa and 2.3%, respectively.

Button-ended cylindrical specimens with a gauge diameter 6 mm, gauge length 14 mm and total length 90 mm were prepared as shown in Fig. 2. The surfaces of specimens were carefully mechanical polished in order to minimize the effects of surface irregularities on mechanical properties. The strain-controlled LCF and CFI tests referred to ASTM E606/E606M-12 < Standard Test Method for Strain-Controlled Fatigue Testing > were conducted on a closed-loop servo-hydraulic test machine, *i.e.* MTS-810. All the tests were controlled by the strain ratios $R_\varepsilon = -1$ at a constant strain rate of 5×10^{-3}/s at 750 °C and the temperature variation in the resistance wire heating furnace was kept within 1 °C over the specimen gauge length. Prior to LCF and CFI loadings, the specimens were heated at 750 °C for 30 min in the high temperature furnace to ensure their homogeneity of temperature. The loading waveforms of LCF and CFI tests were illustrated in Fig. 3. It should be noted that "t_T/t_C" in the above parenthesis meant holding t_T seconds at maximum strain and t_C seconds at minimum strain. In the present study, there are four types of fatigue tests, *i.e.* continuous fatigue test(0/0), tensile dwell condition test(60/0), balanced dwell condition test(30/30) and compressive dwell condition test(0/60). The conventional LCF tests were carried out for comparison to the CFI ones caused by dwell time. The total strains ranging from 0.22% to 0.45% were employed in this study.

3. Results and discussion

3.1. Hysteresis loops

The stationary hysteresis loops of high-Nb TiAl alloy in LCF and CFI tests are shown in Fig. 4. As for LCF test results shown in Fig. 4(a), both width and area of the hysteresis loop increase with increasing the strain amplitude, which indicates that more inelastic strain produces at larger strain amplitude. It is well known that the inelastic strain has an important influence on the fatigue behavior and would decrease the fatigue life obviously [17,18]. In addition, the peak stress of stationary hysteresis loop increases with increasing the strain amplitude. As for CFI test results with the strain amplitude of 0.35% shown in Fig. 4(b), the shape of stationary hysteresis loop with different dwell conditions is similar to that in LCF tests. However, the stationary hysteresis loop shifts and the stress relaxation occurs due to the dwell condition introduced at maximum and/or minimum strain [19–21]. Specifically, the stationary hysteresis loop shifts downward for holding 60 s at maximum strain (*i.e.* tensile dwell condition) while that shifts upward for holding 60 s at minimum strain (*i.e.* compressive dwell condition). Compared to LCF, the stationary hysteresis loop of the balanced dwell condition expands uniformly along the diagonal of the stress-strain.

3.2. Cyclic stress response

The cyclic stress response of LCF tests with different strain amplitudes and CFI tests with different dwell conditions is shown in Fig. 5. It can be seen from Fig. 5(a) that the cyclic stress response strongly depends on the applied strain amplitude in LCF tests. The initial cyclic stress increases with increasing the strain amplitude. For three different strain amplitudes (*i.e.* 0.26%, 0.30% and 0.35%), the alloy exhibits similar cyclic stress response upon fatigue cycling. Specifically, an initial strain softening to a minimum stress followed by a nearly stable peak stress and then a rapid drop in the stress value due to formation of macrocrack. This is similar to that reported by Valsan et al. [22]. The gradual cyclic softening beyond saturation period has a correlation with the evolution of dislocation substructure from a random structure to a clean cell structure associated with lower stress response during cyclic deformation. It can be seen from Fig. 5(b) that the cyclic stress response strongly depends on the dwell condition in CFI tests with the strain amplitude of 0.35%. An initial cyclic hardening to a maximum stress and then a rapid drop in the stress value is observed at balanced dwell condition. The initial cyclic hardening is attributed to the individual or combined effects of (a) mutual interaction among dislocations, (b) formation of fine precipitates on dislocations during testing and (c) interaction between dislocations and solute atoms [23]. Under both tensile and compressive dwell conditions, the alloy exhibits continuous cyclic softening throughout the whole fatigue life.

Another noticeable effect of the dwell condition is related to the mean stress [24–26]. Fig. 6 is a plot of the mean stress at half-life as a function of the total strain amplitude in both LCF and CFI tests. It is

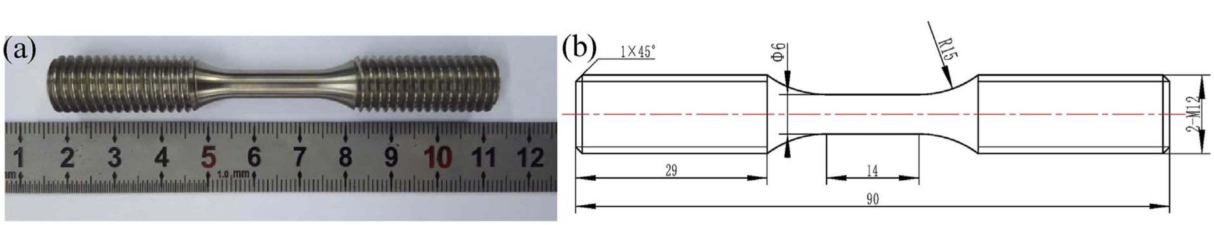

Fig. 2. Actual solid specimen (a) and detailed dimensions of specimen (dimension in mm) (b).