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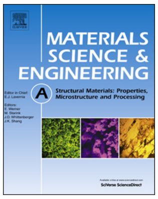

Influence of test temperature on cyclic deformation behavior of a near α titanium alloy

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ABSTRACT

Low cycle fatigue behavior of titanium alloy Timetal 834 has been studied at 300 °C, 450 °C and 600 °C under fully reversed constant total strain amplitudes ($\Delta\varepsilon_t/2$) ranging from 0.4% to 1.2%. The alloy exhibited initial cyclic softening followed by cyclic hardening at 450 °C for $\Delta\varepsilon_t/2 \geq 0.4\%$ while at 300 °C and 600 °C, cyclic softening followed by cyclic stability was noticed in the cyclic stress response curves for $\Delta\varepsilon_t/2 > 0.4\%$. Precipitate shearing was observed to be the micro-mechanism responsible for cyclic softening at all test temperatures. However, dislocation-dislocation and dislocation – solute interaction was observed to be the micro-mechanism responsible for cyclic hardening only at 450 °C. TEM observations revealed that the severity of planar slip is found to peak at 450 °C.

1. Introduction

Gas turbine aeroengines, especially military in origin, has to function over a wide ranges of temperature and pressure in order to produce huge thrusts [1,2]. Few of the components such as compressor as well as turbine discs are geometrically large rotating components. The temperature difference between various regions of a disc ranges from maximum at the rim region to minimum at the bore region leads to generation of thermal stresses and hence localised plasticity near the mechanical stress concentration sites such as fir tree or bolt hole regions [3]. Coupled with the fact that speed changes during operation leads to the development of centrifugal stresses of higher magnitude near the bore region of the discs, leading to low probability but high consequence events in terms of low cycle fatigue (LCF) behavior of disc alloys as a function of temperature and it holds paramount importance.

Titanium base alloys exhibits superior ratio of endurance limit to tensile strength and hence high fatigue strength at a given stress level, high ratio of strength to density and hence high specific strength, high passivation potential for getting corroded and hence high corrosion resistance [4]. Primarily these properties have driven the usage of titanium base alloys in most sectors of the industries [4–6]. Although the production of titanium is highly capital and energy intensive in nature due to its chemical reactivity, it has now acquired the name of a “well behaved material” due to its reliable performance in most of the demanding applications. The demands of titanium base alloys have, almost entirely, been driven by the requirement to improve the reliability and efficiency of gas turbine aero engines [5,6]. The constant drive for development of newer and newer gas turbine aero engines with improved thrust and efficiency has been commercially exploited in the case of titanium and titanium base alloys. In gas turbine aeroengines, titanium alloys are used for rotating (rotors, fan blade, compressor air foils) and static (frames, castings, manifolds, ducts and tubes) components [4–6]. One of the titanium alloy, a chemically complex titanium alloy as compared to any other titanium alloy, Timetal 834 (originally named as IMI 834) has been specifically developed as a high temperature titanium alloy primarily for rear stages of compressor module [7,8]. As a disc alloy, low cycle fatigue behavior of Timetal 834 has been widely studied by many researchers [9–24]. While most of these studies, and rightfully so, have been carried out on bimodal microstructure of Timetal 834 [9–21], few studied were reported on lamellar microstructure [22–24]. It has been reported that bimodal microstructure with finer prior β grain size exhibits superior low cycle

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fatigue resistance as compared to lamellar microstructure [22]. Detailed TEM studies at ambient temperature have revealed that fatigue damage accumulation occurs primarily by $< a >$ slip on basal planes [9]. Moreover, it has also been revealed that the slip character remains planar in nature up to 600 °C and it changes to wavy beyond 600 °C [10,20,21]. In cyclic stress response curves, while the alloy exhibited cyclic softening at room temperature and 600 °C [10–13], initial cyclic softening followed by cyclic hardening was observed at intermediate temperatures [10,14–16,23]. The micro-mechanism for cyclic softening was attributed primarily to precipitate (Ti_3Al) shearing [9–14]. On the other hand, the onset of secondary hardening was attributed to saturation of planar slip bands [19,23] and dynamic strain aging [14–16]. In terms of fatigue lives, it has been reported that the alloy exhibits higher fatigue lives at 600 °C as compared to room temperature due to homogenization of slip [12], reduced fatigue lives were reported at intermediate temperatures [14]. Reduced fatigue lives were attributed to the occurrence of dynamic strain aging at 450 °C [14]. Effect of environment on low cycle fatigue behavior has been reported by few researchers [17,18]. By carrying out controlled experiments at different partial pressure of water vapour and different levels of vacuum, it has been shown that the crack initiation mechanism is different at 400 °C and at 600 °C. While crack preferentially initiated at slip bands at 600 °C, crack initiation at slip bands could not be observed at 400 °C despite the presence of high density of dislocations in primary α grains.

While low cycle fatigue properties as well as cyclic deformation behavior of Timetal 834 Ti-alloy close to its service temperature (≥ 500 °C) have been studied to a great extent [10,12,20–24], studies on its low cycle fatigue behavior in the intermediate temperature range are rather limited in open literature [10,14–16]. Hence, in this study, cyclic deformation behavior of Timetal 834 Ti-alloy has been studied to understand the effect of intermediate temperatures (300 °C and 450 °C) and strain amplitudes (0.4–1.2%) on fatigue lives. In order to complement the low cycle fatigue behavior of these two intermediate temperatures which typically represents the bore/web region of high pressure compressor disc, low cycle fatigue behavior has also been studied at 600 °C which is a representative temperature of rim region of disc. The cyclic stress-strain curves, widely used by the designers, of Timetal 834 have been reported at 300 °C, 450 °C and 600 °C. The possible role of dynamic strain aging on low cycle fatigue behavior of this alloy at 450 °C has also been assessed in this study.

2. Experimental procedures

2.1. Material and its processing

The nominal chemical composition of the near α Timetal 834 titanium alloy is 5.75%Al-4.02%Sn-3.54%Zr-0.71%Nb-0.505%Mo-0.305%Si-0.065%C-0.09%O-0.002% N, all in wt%. Thick plates of 18 mm of Timetal 834 were solution treated (ST) in $\alpha + \beta$ region at 1025 °C (β- transus temperature ~1045 °C) for 2 h followed by oil quenching. The solution heat-treated plates were subjected to a stabilization treatment at 700 °C for 2 h before air cooling to room temperature. The microstructure of the heat treated alloy was examined under scanning electron microscopy (SEM; model FEI Quanta 400). The heat treated microstructure as observed is shown in Fig. 1. The alloy shows a bi-modal microstructure which consists of equiaxed primary α in the transformed β matrix. The average size of primary α and prior β grain size was found to be ~10 μm and ~40 μm, respectively. The volume fraction of primary α was estimated to be ~15%. The heat treated blanks were subsequently machined to cylindrical specimen geometry as per ASTM Standard E 606/E606M-12. Circumferential machining marks in the gauge length portion of the specimens were fully removed by polishing parallel to the stress axis to an average surface roughness (R_a) less than 0.2 μm.

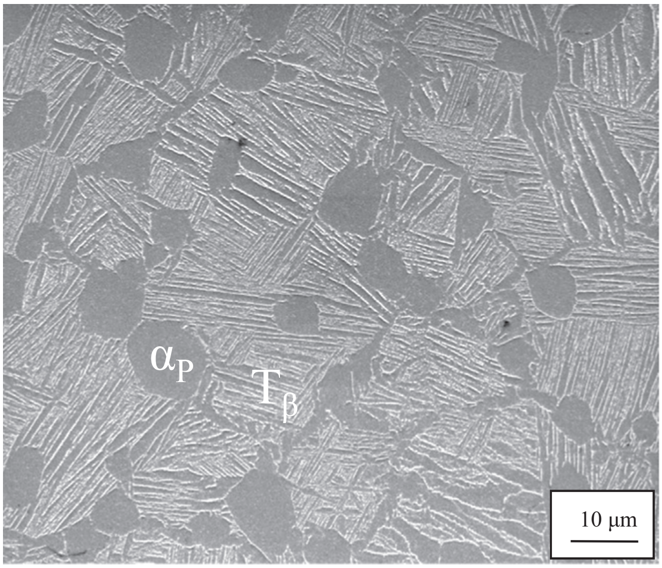

Fig. 1. SEM microstructure of Timetal 834 Ti-alloy showing 15% volume fraction of equiaxed primary α (α_P) in transformed β matrix.

2.2. Low cycle fatigue testing

Low cycle fatigue (LCF) tests were carried out at 300 °C, 450 °C and 650 °C in fully reversed mode ($R = -1$, triangular waveform) imposing constant total strain amplitudes, $\Delta\varepsilon_t/2$, of 0.4%, 0.6%, 0.8%, 1.0% and 1.2% using an extensometer of 12 mm gauge length. To study the temperature dependency of cyclic flow stress, additional low cycle fatigue tests were carried out at 350, 400, 425, 475 and 500 °C at only $\Delta\varepsilon_t/2$ of 0.6%. Tests at different strain amplitudes were carried out at appropriate frequencies which would result in a strain rate of $1 \times 10^{-3}\ s^{-1}$. Tests were conducted as per ASTM Standard E 606/E606M-12 in a closed loop servo-hydraulic machine (MTS 880) of 100-kN load capacity equipped with resistance-heated three-zone split furnace. All the tests were started after soaking the specimen for 30 min at the test temperature. Temperature during the test was monitored using K-type thermocouples. Minimum 3 tests were conducted at most of the test conditions to confirm reproducibility of results.

2.3. Characterization for cyclic deformation behavior

Transmission electron microscopy (TEM) examination of deformed specimens was carried in a FEI Tecnai G^2 TEM operating at 200 kV to investigate the sub-structure evolution. Sample preparation for TEM studies involved sectioning of thin discs at 45 °C to the loading axis from the middle portion of gauge length of interrupted LCF tested samples. Subsequently thin discs were mechanically polished to 100 μm in thickness using SiC paper and electro-polished in twin jet electro polisher (FISCHIONE Instruments). Electro-polishing was done using 5% H_2SO_4 and methanol as electrolyte at −50 °C and the voltage was maintained at 20 V.