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Isothermal and thermomechanical fatigue behaviour of Ti–6Al–4V titanium alloy

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ABSTRACT

In this study, the overall view of in-house development of thermomechanical fatigue (TMF) test capability has been presented. Using this test facility, mechanical strain controlled in-phase (IP) and out-of-phase (OP) TMF behaviour of Ti–6Al–4V alloy has been investigated in the temperature range 100–400 °C with ramp heating and cooling rate of 2 °C/s. Isothermal low cycle fatigue (IF) tests have also been conducted at 100 °C and 400 °C for comparison with TMF data. The combined effect of development of tensile mean stresses and metallurgical degradation due to oxidation led to detrimental OP-TMF fatigue life as compared to IP-TMF and IF loading.

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1. Introduction

Ti–6Al–4V alloy has been extensively used in low pressure compressor module of aeroengines due to its high specific strength, toughness and excellent corrosion resistance. Due to its usage in front end of the module, various in-service damage modes such as foreign object damage [1,2], low cycle fatigue [3,4], combined high cycle fatigue and low cycle fatigue [5], fretting fatigue [6,7], fatigue crack growth behaviour [8–12], wear and erosion [13] are operative. The synergistic combination of environment, temperature and thermal stresses limits the maximum service temperature of this alloy ∼350 °C [8]. Under these hostile conditions, stress concentration sites such as compressor disc bore and bolt holes accumulates plastic strain considerably under thermomechanical loads due to thermal transients [14]. Majority of material behaviour data generated in the laboratory which is used for design is only under isothermal fatigue (IF) test conditions. However, the use of IF data to predict the performance of components under thermomechanical fatigue (TMF) loading condition has been demonstrated to have several drawbacks.

The term 'TMF' describes fatigue under simultaneous changes in temperature and mechanical strain [15–17]. The mechanical strain arises from the external constraints or external applied loading. Material properties, strain rate, temperature, mechanical strain range, phasing between the temperature and metallurgical changes plays an important role in the type of damage formed in the material under investigation. Although the TMF behaviour of nickel based superalloys and single crystal blades are well reported in open literature [18–24] owing to their high temperature capability, the database of TMF research in titanium alloys is limited [25–27]. In recent past, some understanding has been developed on the TMF behaviour of titanium alloys IMI 834 [25], Ti-6-22-22 [26] and titanium based composites [28,29]. However, the TMF behaviour of Ti–6Al–4V alloy which is used in comparatively lower temperature range (∼350 °C) in early stages of compressor has not been explored as evident from literature. The purpose of the present paper is to give an overall view of the development of an in-house IR heating based TMF test facility to study the TMF behaviour of Ti–6Al–4V alloy in the temperature range between 100 and 400 °C.

2. Experimental

2.1. Material

The nominal chemical composition of the alloy is listed in Table 1. The material was initially forged and rolled at 950 °C followed by annealing at 700 °C for 2 h and then cooled in air. The microstructure of the alloy (Fig. 1) shows typical mill-annealed features. The microstructure shows equiaxed primary α grains surrounded by residual β phase. The average grain size and volume fraction of primary α has been estimated to be ∼20 µm and 65%, respectively. The microstructure also shows slight grain flow along the rolling direction. The TMF specimen used in the present investigation has been extracted from a 20 mm diameter rolled cylindrical rods.

2.2. TMF test facility

An in-house TMF test facility has been developed with the integration of an infrared (IR) based heating chamber to a MTS-880

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Table 1
Nominal chemical composition of the Ti–6Al–4V alloy (in wt.%).

Al	V	Fe	N	O	C	H	Ti
6.2	3.96	<0.20	<0.01	<0.03	<0.05	<0.003	Bal

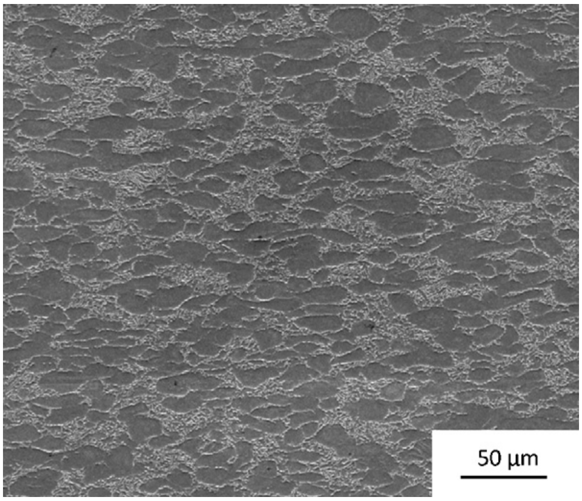

Fig. 1. Mill annealed microstructure of Ti–6Al–4V alloy.

servohydraulic test system as shown in Fig. 2a. The IR heating chamber has a circular arrangement of three IR lamps (1.5 kW each) and air vents as shown in Fig. 2b. In order to generate the prescribed cooling ramp of thermal cycle, a solenoid valve with pressure regulator and mass flow controller (MFC) has been incorporated with IR heating chamber. This mass flow controller essentially injects the controlled air through the air vents to impose a desired cooling rate on the specimen surface as per the feedback signal of the thermocouple. A digital temperature controller with a sample rate of 50 Hz has been used in the present investigation. An application software for defining TMF waveforms, mass flow and temperature controllers with a high resolution data acquisition has been especially developed in LabView instrument and integrated with the MTS-880 test controller, as shown schematically in Fig. 2c.

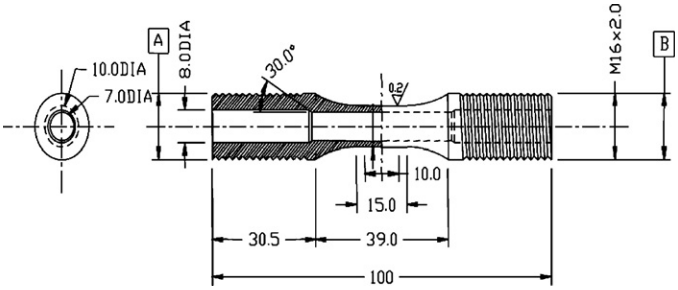

Fig. 3. Hollow specimen geometry for TMF testing.

2.3. TMF test procedure

Hollow cylindrical specimens with 1.5 mm thickness, 10 mm external gauge diameter and 15 mm gauge diameter were prepared from 20 mm cylindrical bars as shown in Fig. 3. Special care was taken while machining these hollow specimens to achieve best possible surface finish inside as well as outside surfaces. The average surface roughness (R_a) of outer gauge surface was measured to be $\sim$0.2 μm through mechanical polishing using fine emery papers. However, the inside surface roughness ($\sim$0.4 μm) was achieved using rimming technique. This hollow specimen design has been

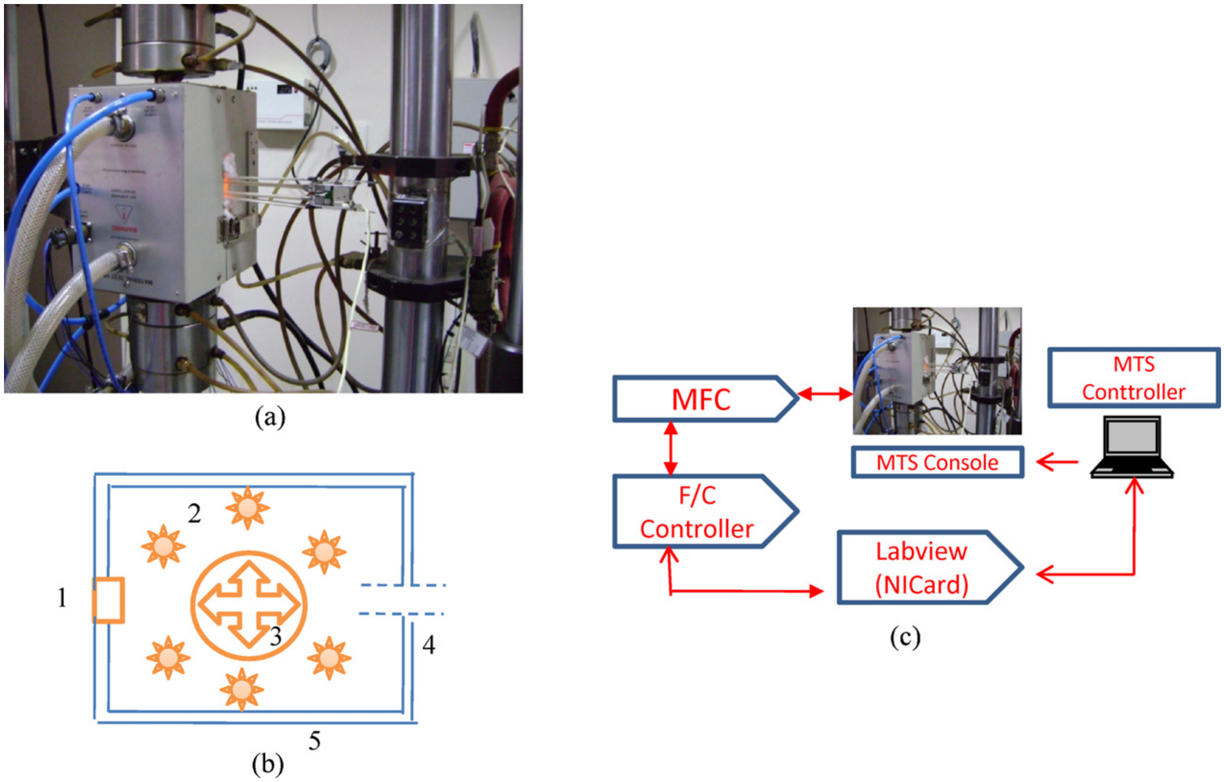

Fig. 2. TMF test facility developed at DMRL showing (a) actual photograph of infrared based heating chamber, (b) schematic drawing of top view of the furnace where 1 shows the mounting attachment of the furnace, 2 – infrared lamps, 3 – air vents, 4 – provision to put extensometer and 5 – protective water jacket and (c) schematic drawing of the test assembly.

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