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Fracture toughness and low cycle fatigue behaviour in boron modified Timetal 834 titanium alloy

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ABSTRACT

The effect of addition of 0.2 wt.% B to Timetal 834 alloy on the fracture toughness at room temperature and low cycle fatigue (LCF) behaviour at room temperature and 600 °C was studied in the thermomechanically processed condition after subjecting it to a standard heat treatment. The fracture toughness of the boron modified alloy was found to be only marginally lower than that of the base alloy in both L–T and T–L orientations. Both the B modified Timetal 834 alloy and the base alloy exhibited cyclic softening throughout their fatigue life at a total strain amplitude of 1.0% for LCF tests at room temperature and 600 °C. The fatigue life of the B modified Timetal 834 alloy was also found to be nearly same as that of the base alloy at both room temperature and 600 °C. The observed behaviour was attributed to the fact that the microstructure of the matrix alloy remains unaffected by the addition of 0.2 wt.% B in the thermomechanically processed and heat treated condition except for the presence of about 0.015 volume fraction of TiB whiskers and this results in similar deformation and fracture mechanisms in the base and boron modified Timetal 834 alloys.

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1. Introduction

Boron (B) containing titanium alloys have attracted considerable attention in recent times because of their superior strength and wear properties as compared to conventional alloys [1–14]. The B containing Ti alloys can be categorized into two classes viz. boron modified Ti alloys containing less than 1.5 wt.% B and Ti alloy–B composites which typically have B in the range 2–15 wt.%. While considerable amount of work has been carried out in the past on titanium alloy–boron composites [15–19], boron modified titanium alloys have been extensively studied only recently [1–14]. Most of these studies have been carried out on induction skull melted ingots in the as-cast condition [1–11] or on alloys fabricated using the powder metallurgy route [12–14]. These studies [1–11] have found that the minor addition of B results in the refinement of the grain size as well as improvement in the strength in the as-cast condition. Sen and coworkers have also reported the effect of B addition on fracture toughness [4] and fatigue behaviour [11] of Ti–6Al–4V alloy. Their study showed that the plane strain fracture toughness (K_{Ic}) decreased from 120 MPa m$^{1/2}$ to 50 MPa m$^{1/2}$ with increase in B content from 0.0 wt.% to 0.2 wt.% [4]. Similarly, an increase in fatigue strength from 350 MPa to 550 MPa was observed with increase in boron content from 0.0 to 0.55 wt.% B [11]. Chen and Boehlert have also reported a significant increase in fatigue strength in both B modified Ti–6Al–4V [8,10] and Ti–6242S [9] titanium alloys up to 0.1 wt.% B addition.

It should be noted that most conventional titanium alloys for aeronautical applications are processed using vacuum arc melting route followed by thermomechanical processing and heat treatment. Recent studies by Chandravanshi et al. [20] and Prasad et al. [21] have found that addition of 0.2 wt.% B results in an increase in yield and ultimate tensile strength at both room temperature and 600 °C in vacuum arc melted and thermomechanically processed near α Ti-1100 and Timetal 834 alloys, respectively, without any concomitant decrease in ductility. However, the effect of minor B addition on other mechanical properties such as fracture toughness and low cycle fatigue (LCF) behaviour in these thermomechanically processed B modified near α titanium alloys has not been investigated. This is especially important in Timetal 834 alloy as it has potential applications in compressor disks of modern aeroengine where both room temperature fracture toughness and high temperature low cycle fatigue behaviour are critical [22–24].

In light of the above, the effect of minor addition of B (0.2 wt.%) on room temperature fracture toughness and room temperature as well as high temperature (600 °C) LCF behaviour of near α Timetal 834 titanium alloy processed by vacuum arc melting followed by high temperature forging and rolling was investigated in the present study.

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Table 1
Nominal chemical composition of base and B modified Timetal 834 alloys.

Alloy	Elements									
	Al	Sn	Zr	Mo	Nb	Si	B	O	N	C
Base	5.78	4.01	3.71	0.72	0.55	0.30	–	0.09	0.007	<0.06
Modified	5.80	3.98	3.74	0.71	0.57	0.28	0.19	0.08	0.008	<0.06

2. Experimental procedure

The nominal chemical composition of the melted alloys is given in Table 1. The alloys were prepared by consumable vacuum arc melting. While Ti, Al, Zr, Sn, Si, and B were added in elemental form, Mo and Nb were added as Mo/Al and Nb/Al master alloys. The details of the melting are given in our earlier study [25]. The cast ingots were subsequently forged at 1100 °C to 32 mm thick billets. Small specimens (20 mm × 15 mm × 15 mm) were solution heat treated for 2 h at temperatures ranging from 975 °C to 1105 °C. The specimens were then water quenched and their microstructure was examined. β_T was taken as the temperature above which no primary α was seen in the microstructure. β_T of the base alloy and the boron modified alloy was determined to be 1045 ± 3 °C and 1075 ± 3 °C, respectively. Tamirisakandala et al. [26] have reported a similar increase in β_T in B modified titanium alloy. The ingots were subsequently rolled in the α–β region at a temperature of $\beta_T - 25$ °C to 16 mm thick plates. In our previous study, a series of heat treatments, involving solution treatment and aging, were employed for the evaluation of mechanical properties. Since solution treatment temperature of $\beta_T - 20$ °C was found to give the best combination of strength and ductility, it was chosen for all studies in the present investigation. All specimens were first solutionized at 1100 °C for 2 h followed by furnace cooling to room temperature and subsequently solution treated at $\beta_T - 20$ °C for 2 h, oil quenched and aged at 700 °C for 2 h and air cooled.

The microstructures after heat treatment were examined using a FEI Quanta 400 scanning electron microscope (SEM). Dimensions of the TiB precipitates have been measured using high magnification SEM micrographs and volume fraction through image analysis software. A minimum of 10 measurements were made on the SEM micrographs, and the average values have been reported. The tensile properties at room temperature as well as at 600 °C were evaluated as per ASTM standard E-8M [27] on a screw driven Walter + Bai Ag testing machine at a nominal strain rate of 6.7×10^{-4} s^{-1}. The fracture toughness tests were carried out at room temperature using compact tension specimens in L–T and T–L orientations as per ASTM standard E-399 [28] on an Instron 8500 testing machine at a nominal displacement rate of 1 mm/min. A 5 mm clip-on gauge with 2 mm travel was used to measure the load-line displacement. Three samples each in L–T and T–L orientations for the base and boron modified alloy were tested.

LCF tests were performed on cylindrical specimens with a gauge length and gauge diameter of 15 mm and 6.35 mm, respectively, conforming to ASTM standard E-606 [29]. The specimens were oriented along the longitudinal direction. The low cycle fatigue tests were conducted in air at room temperature as well as at 600 °C under fully reversed ($R_\varepsilon = -1$), total strain control mode, employing a symmetrical, triangular waveform of 1% strain amplitude in a MTS servohydraulic closed loop testing system equipped with a resistance furnace. An extensometer with 12 mm gauge length and ±2.5 mm travel was used for controlling and monitoring the strain during the test. Specimen surfaces were polished by emery paper of 1/0 to 4/0 grades prior to testing. The final achieved surface roughness was measured to be ∼0.2 μm. Four samples each for the base and boron modified alloys were tested.

The fracture surfaces of the broken fracture toughness and LCF specimens were also examined under the SEM.

3. Results

3.1. Microstructure and tensile properties

SEM microstructures of Timetal 834 alloy under heat treatment condition ($\beta_T - 20$ °C/2 h/OQ followed by aging 700 °C/2 h/AC) are shown in Fig. 1a and b–d, respectively. Both the base alloy and the B modified alloy exhibit elongated primary α phase in a transformed β matrix. Fig. 1b clearly shows uniform distribution of TiB whiskers in the transformed β matrix. The B modified alloy also shows the presence of elongated dark precipitates (Fig. 1b–d). The representative higher magnification SEM micrograph showing these precipitates is given in Fig. 1d. Our previous study has confirmed that these precipitates are TiB and the α lath spacing remains same in base and B modified alloys [21]. The average length and width of these precipitates were measured to be 12.5 ± 1.4 μm and 2.0 ± 0.3 μm, respectively. The volume fraction of TiB precipitates was measured to be ∼1.5%. The microstructural parameters including α lath thickness, volume fraction of primary elongated α and prior β grain size are listed in Table 2. It is clear from Table 2 that the α lath spacing, volume fraction of primary elongated α and prior β grain size are similar for both base and boron containing alloys in the thermomechanically processed and heat treated condition.

The tensile properties at room temperature and 600 °C for both the base and the B modified alloys are listed in Table 3. The values listed are an average of three tests. It can be observed that the B modified alloy has higher 0.2% YS and UTS and marginally lower elongation to failure as compared to the base alloy at room temperature. It can also be seen that although there is decrease in 0.2% YS and UTS for both the base and B modified alloys at 600 °C as compared to that at room temperature, the B modified alloy retains its higher strength relative to the base alloy at 600 °C. The elongation to failure, on the other hand, does not change much for both the alloys at room temperature and 600 °C.

3.2. Fracture toughness

The conditional fracture toughness was calculated from the load versus load-line displacement plots in both L–T and T–L orientations using the equation given below as suggested in ASTM E-399 [28]

$$K_Q = \left(\frac{P_Q}{BW^{1/2}}\right) f\left(\frac{a}{W}\right) \quad (1)$$

where P_Q is the conditional load, B is the thickness, W is the width, a is the initial crack length and $f(a/W)$ is the geometry factor. The K_Q values for both the base and the B modified alloys were found to satisfy the LEFM and plane strain criteria in both L–T and T–L orientations and hence the K_Q values can be considered to be K_{Ic} or plane strain fracture toughness. The K_{Ic} values are enumerated in Table 4 and each value listed is an average of three tests. It can be observed that the B modified alloy exhibits lower fracture toughness as compared to the base alloy. The fracture toughness values

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