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Influence of minor addition of boron on tensile and fatigue properties of wrought Ti–6Al–4V alloy

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ABSTRACT

Addition of boron to cast Ti–6Al–4V alloy leads to significant refinement in grain size, which in turn improves processibilty as well as the mechanical properties of the as-cast alloy. Room temperature tensile and fatigue properties of *Wrought* Ti–6Al–4V–B alloys with B up to 0.09 wt.% are investigated. Thermo-mechanical processing at 950 °C caused kinking of α lamellae and alignment of TiB particles in the flow direction with a negligible change in prior β grain and colony sizes, indicating the absence of dynamic recrystallisation during forging. Characterisation with the aid of X-ray and electron back scattered diffraction reveal a strong basal texture in B free alloy which gets randomised with the 0.09B addition in the forged condition. Marginal enhancement in tensile and fatigue properties upon forging is noted. B free wrought Ti–6Al–4V alloy exhibits better tensile strength as compared to B containing alloy, due to the operation of $\langle c+a\rangle$ slip on pyramidal planes with high value of CRSS as compared to $\langle a\rangle$ slip on basal and prismatic planes. Decrease in fatigue strength of Ti–6Al–4V–0.04B in as-cast and the wrought state is observed due to increase in the volume fraction of grain boundary α phase with B addition, which acts as a crack nucleation site. No significant effect of TiB particles on tensile and fatigue properties is observed.

1. Introduction

The Ti alloy, Ti–6Al–4V (referred to as Ti64 hereafter), is used extensively in aerospace applications due to its unique combination of specific strength, stiffness and fracture and fatigue properties [1]. This can be achieved by processing the alloy in the $(\alpha+\beta)$ or β field to obtain a precisely tailored microstructure, which depends on the intended application [2]. However, the alloy in the as-cast state consists of large prior β grains, whose size is of the order of few millimetres. This requires several thermo-mechanical processing steps to break the as-cast structure down. Recently, it has been shown that the addition of a small amount of B (~0.1 wt.%) reduces the as-cast grain size of Ti64 by an order of magnitude from ~2 mm to 200 μm due to constitutional under-cooling [3,4]. This in turn can potentially save cost and time involved in processing by reducing energy intensive high temperature thermo-mechanical processing steps. It also can minimize wedge cracking and cavity formation, which are associated with the initial large grain size, during the ingot breakdown. The microstructural refinement that occurs with the addition of B is also beneficial in enhancing room and elevated temperature strengths and fatigue properties [5–10]. For example, the addition of ~0.1 wt.% B to cast Ti64 alloy enhances room temperature quasi-static tensile and fatigue properties by ~15% [9].

Apart from grain refinement, B addition to Ti64 produces the intermetallic TiB phase during solidification by an in situ chemical reaction: $L\rightarrow\alpha+\mathrm{TiB}$. This is due to the negligible solid solubility of B in Ti (<0.02 wt.% [11]), Presence of TiB particles in the form of needles however does not lead to thermal residual stress generation during the cooling from the $\beta/\alpha+\beta$ phase because of the similarity in coefficients of thermal expansion of the TiB particles and alloy matrix [12,13]. The TiB needles encompass the prior β grain boundary and pin grain growth at high temperature due to Zener drag. Further, they provide stiffness to the Ti64 matrix by load sharing mechanism. Sen et al. [9,10] studied the influence of small addition of B up to 0.55 wt.% in cast Ti64 alloys on the microstructural evolution, tensile and fatigue properties. They have revealed that optimum mechanical properties can be achieved with addition of ~0.1 wt.% B, further B addition, being detrimental in terms of reducing ductility due to increased volume fraction of brittle TiB needles.

Cast Ti64 ingots are inherently associated with gas induced and shrinkage porosities as well as inclusions, all of which can act as potential sites for fatigue crack nucleation [14]. Additionally, cast Ti64 alloys display substantial amount of scatter in their mechanical properties which can be detrimental to the reliability

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Table 1
Microstructural parameters of the Ti64–xB alloys examined in this work.

	λ (μm)	c (μm)	d (μm)	V_α	V_β	V_{TiB}
AF Ti64–xB (wt.%)						
0	2.29 ± 0.87	250.78 ± 70.4	2367 ± 586.8	0.80 ± 0.01	0.20 ± 0.001	0
0.04	3.82 ± 1.12	62.7 ± 22	777.4 ± 138	0.845 ± 0.01	0.153 ± 0.001	0.002
0.09	2.60 ± 0.70	24.12 ± 7.3	216 ± 37	0.855 ± 0.01	0.14 ± 0.001	0.005
AC Ti64–xB (wt. %)						
0	2.48 ± 0.9	244.4 ± 51.1	2386 ± 870.9	0.88 ± 0.01	0.12 ± 0.001	0
0.04	6.05 ± 2	43.23 ± 16.58	732.8 ± 278	0.93 ± 0.01	0.07 ± 0.001	0.002
0.09	4.52 ± 1.3	37.8 ± 10.7	223.9 ± 52.8	0.90 ± 0.01	0.095 ± 0.001	0.005

estimations. Therefore, thermo mechanical processing (TMP) of cast Ti64–B alloys is essential to convert them into other product forms and desired structural efficiency with precisely tailored microstructures and properties. This is achieved through deformation and heat treatment. Modification in α morphology from lamellar to equiaxed results in improved fatigue crack initiation resistance [15]. Since Ti64 is a potential candidate for aerospace structures and prone to undergo cyclic loading, detailed understanding of the fatigue response of TMP B-modified Ti64 alloys is necessary. The current work focuses on the microstructure evolution, room temperature tensile and fatigue properties of Ti64–xB alloys thermo-mechanically processed in the $\alpha + \beta$ phase field.

2. Materials and experiments

Three grades of Ti64–xB alloys (x = 0, 0.04 and 0.09 wt.%) having the following nominal composition: Ti, 5.86Al, 4.1V, 0.15Fe, 0.15O, 0.0024H, 0.016C (all compositions in wt.%) were examined in this study. These alloys were induction skull melted to achieve homogeneity in composition. Induction stirring effect minimizes formation of solidification microstructure ahead of solidification front. These as-cast (AC) alloys were hot isostatic pressed at 900 °C under 100 MPa pressure for 2 h. They were further subjected to upset forging at 950 °C, i.e. in the $\alpha + \beta$ phase field, to 50% reduction in thickness at a nominal strain rate of 1 s^{-1} followed by air cooling. The β transus temperature (α completely transforms to β) of the alloy is ∼1010 °C with 0.04 wt.% B. The final billet size after forging was 150 mm × 100 mm in cross-section and 25 mm in thickness. These forged alloys will be referred to as AF hereafter.

Microstructural characterisation of the alloys was performed on 5 mm diameter specimens (3 mm thick) that were metallographically polished and etched with the Kroll's reagent. Optical microscopy was used for measuring the prior β grain size, d, and the α/β colony size, c [16]. A montage made of 100 scanning electron images over a region of ∼1 mm^2 on the specimen surface for each composition was constructed for this purpose. The volume fractions of α, β and TiB phases, V_α, V_β and V_{TiB} respectively have also been determined from the montages. They are listed in Table 1. A commercial software package, Sigma Scan Pro, was used for these measurements.

Room temperature (∼25 °C) tensile tests on AF alloys were performed according to ASTM E8 standard, at a strain rate of 10^{-3} s^{-1} using a screw driven machine. Four samples with dog-bone geometry (5 mm gage diameter and 25 mm gage length) were tested for each composition and their average values are reported.

Deformed microstructures of the AF alloys were investigated using X-ray diffraction (XRD) and electron back scattered diffraction (EBSD) on a longitudinal section parallel to the compression axis as shown in highlighted region in Fig. 1. Panalytical X-pert pro instrument with Cu Kα radiation operating at a voltage and current of 45 kV and 30 mA respectively, with step size of $2\theta = 0.017°$ is utilized for XRD. For EBSD analysis, samples were electropolished using an electrolyte containing 540 ml methanol, 350 ml n-butanol and 60 ml perchloric acid. An area of 1000 μm × 250 μm was scanned with a step size of 3 μm in a SEM equipped with an EBSD detector. OIM analysis software is utilized for EBSD data analysis. Only α phase is analysed here due to very fine size of β layer between α laths.

Dislocation characterisation in AF alloys after tensile testing was carried out using transmission electron microscope (FEI Tecnai T20) at 200 kV. Samples for transmission electron microscopy (TEM) were prepared by sectioning ∼100 μm thick slices from the transverse section of the gage length using low speed saw. The sliced samples were further thinned to ∼50 μm using 2500 grit emery paper. Finally, TEM foils were prepared using precision ion polishing system (PIPS).

Stress-controlled, room temperature rotating-bending HCF tests ($R = -1$) were performed on the AF alloys using hour-glass specimens with minimum section diameter of 4 mm and at a frequency of 100 Hz. The average surface roughness (R_a) of the specimens was <0.4 μm. For a given composition, about three to four specimens were tested at a given stress level, S, to obtain the number of cycles to failure, N_f [17]. The stress level was reduced by 25–50 MPa for the next test and the process is continued until the fatigue strength, FS, was determined. In this work, FS was defined as the maximum stress level at which at least three (out of a maximum of four) specimens survive 10^6 cycles. For AF alloys, specimens

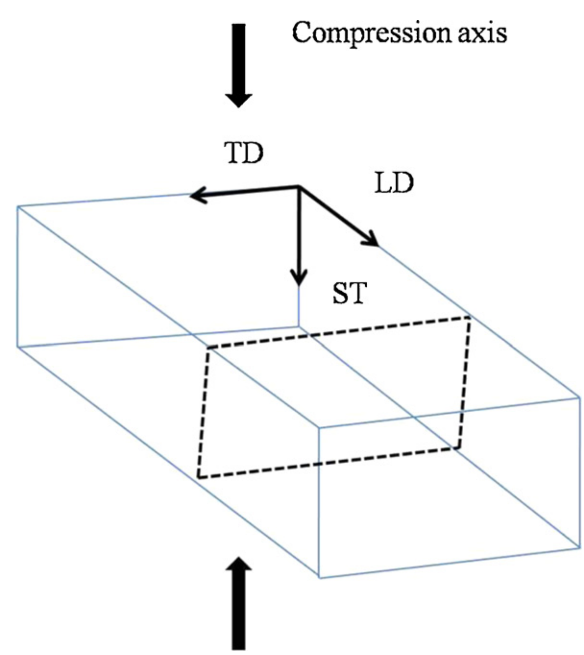

Fig. 1. Schematic representation of the ingot. All the ingots were forged at 950 °C to 50% reduction in thickness with direction of compression axis being vertical. Highlighted region (longitudinal section) shows plane of sectioning for XRD and EBSD analysis. (LD = longitudinal direction, TD = transverse direction and ST = short transverse.)