Journal of Engineering and Applied Sciences 11 (12): 2577-2582, 2016
ISSN: 1816-949X

Microstructure and Hardness Improvement of Ti-6AL-4V Alloys VIA Boron Addition

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Abstract: Refined grain morphologies influence the mechanical properties of Ti-6Al-4V alloys. This work investigated the effects of adding different concentration of boron on the microstructural and hardness properties in as-cast and heat treated Ti-6Al-4V alloy. The alloys were prepared using laboratory arc furnace in inert gas atmosphere. XRD indexed patterns of samples were in agreement with established Ti-B binary phase diagram. SEM micrographs of samples showed reduced grain size in boron added samples. STA treatment resulted in higher hardness. Microstructures of the samples at different levels of boron (1.0, 1.64 and 2.0 wt%) were also compared.

Key words: Titanium alloy, boron, grain refinement, binary, laboratory

INTRODUCTION

Titanium and its alloys have become attractive materials for applications in the aerospace and petrochemical industries due to their exceptional properties such as high strength-to-weight ratio, high toughness, excellent corrosion resistance and considerably good fatigue properties (Boyer, 1996). Ti-6Al-4V is the most widely used Ti alloy in aerospace structures and propulsion systems. Its importance as an aerospace alloy has led to extensive research in the past decade to improve the mechanical properties of Ti-6Al-4V (Sen *et al*., 2007; Bermingham *et al*., 2008).

Prior beta grain size and alpha morphology have been reported to influence the microstructural and mechanical properties displayed by Ti-6Al-4V alloys. Fine grain microstructure will lead to higher ductility and better deformability in alloys. Several investigations were carried out to improve mechanical properties by alloying and thermo mechanical treatments (Bermingham *et al*., 2008; Tamirisakandala *et al*., 2005; Bilous *et al*., 2005; Chen and Boehlert, 2008; McEldowney *et al*., 2010) .

Grain refinement in Ti alloys by boron was initially achieved via inoculation of TiB_2 particles or AlB_{12} particles into Ti-4Al-2Cr-2Nb alloy (Godfrey and Loretto, 1996). While the base alloy consists of predominantly columnar and fully lamellar structures, the orientation of lamellar plates showed majority of grains grew as α plates. In samples with <0.1 at% boron, ribbon-like structures appeared mostly at boundaries between the lamellar orientations. As the boron concentration was increased, these structures became more randomly distributed. Significant reduction in grain size was observed until 1.0 at% boron. The concentration of TiB_2 in interdendritic regions rather than in the matrix phase led the author to suggest that they formed first but were pushed in front of the dendrites as solidification progressed.

Cheng (2000) argued that constitutional supercooling was the most significant factor in the grain refinement mechanism. The grain refinement process is a dynamic equilibrium between solute ejection at the solidification front, the formation of borides and nucleation ahead of the solidification front. Thus, a certain minimum level of boron will be necessary for grain refinement which would be composition dependent. Tamirisakandala *et al.* (2005) explained that grain size after solidification is determined by competition between nucleation and growth rates. The addition of trace boron in Ti alloy increases the rate of nucleation by influencing interfacial characteristics which in turn drives or slows down the growth rate. Coarse prior β grain boundaries are not present in Ti alloys containing 1% boron. Uniform distributions of TiB precipitates with needle-like morphology are present at hypoeutectic compositions.

Most research on the effects of boron addition in Ti alloys has been focused on hypoeutectic compositions. Bilous *et al.* (2005) investigated the influence of 0.01-2.5 wt% boron on the structure and

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mechanical properties of Ti-6Al-4V using the binary Ti-B composition of 1.7 wt% as the eutectic composition. Due to minor amounts of β phase identified in alloy samples containing 1.75-2.5 wt% boron it was suggested that Ti-6Al-4V-2B is closest to the eutectic composition. However, another research on tensile properties of boron added Ti alloy reported Ti-6Al-4V-1.7B as hypereutectic alloy (Sen *et al*., 2007, 2009). Tamirisakandala *et al*. (2006) mentioned that 1.55 wt% B is the most widely used eutectic limit for Ti-6Al-4V. There is ambiguity in determining the eutectic composition of boron in Ti-6Al-4V alloy. Hence, this work intends to compare three different compositions of boron in Ti-6Al-4V alloy, namely 1.0 wt% (hypoeutectic), 1.64 wt% (eutectic) and 2.0 wt% (hypereutectic). As-cast and heat treated samples were analyzed to determine the microstructural and mechanical changes that occurred with boron addition.

MATERIALS AND METHODS

Experimental: The starting materials for preparation of samples were titanium Grade 5 Ti-6Al-4V rods and boron chips (99.9% purity). Ti-6Al-4V-2B master alloy was prepared by argon arc melting. Ti-6Al-4V-1.64B and Ti-6Al-4V-1.0B were prepared by melting together specific wt% of the master alloy and Ti-6Al-4V chips in a laboratory arc furnace with non-consumable tungsten electrode on a water-cooled copper hearth. Melting was performed in an argon atmosphere (pressure of ~1 atm). Samples were then suitably sectioned and selected samples were heat-treated. Solution treatment was carried out at 940°C for 10 min and quenched in water to room temperature. Aging treatment was performed at 525°C for 4 h. Both as-cast and heat treated samples were then mounted for microstructural analysis and mechanical testing. The samples were ground and polished using standard metallographic techniques. The X-Ray Diffraction (XRD) patterns were recorded using a PANalytical X-ray diffractometer with 2θ range of 20-90°C. Polished samples were etched with Kroll's reagent (5% HF+10% HNO_3+distilled water) prior to observation under a Zeiss Supra 40VP Scanning Electron Microscope (SEM) equipped with attachment for Energy Dispersive X-ray (EDX) spectroscopy. A Mitutoyo MVK H1 hardness tester was employed to measure the microhardness of the samples using Vickers hardness test at an applied load of 10 N for 15 sec.

RESULTS AND DISCUSSION

The XRD data obtained from as-cast and STA samples in Fig. 1 show peaks of HCP-Ti, BCC-Ti and TiB phases in agreement with the Ti-B binary phase diagram

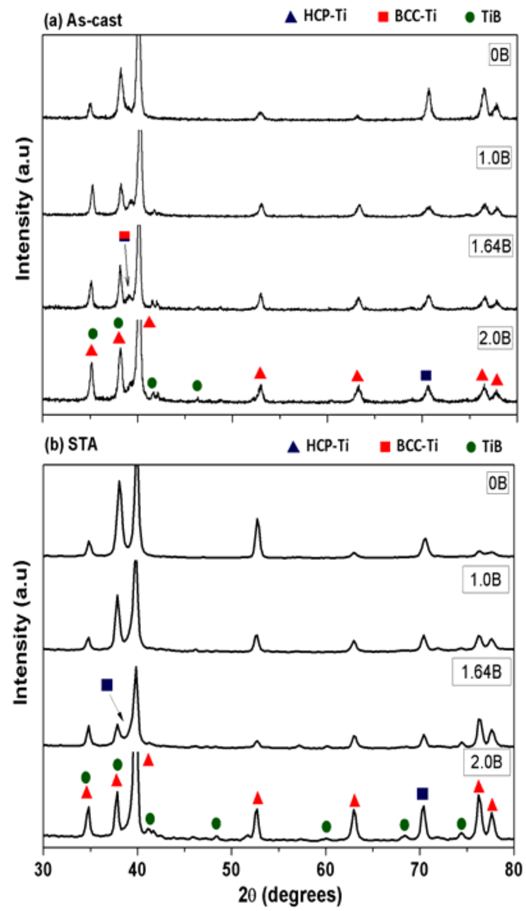

Fig. 1: XRD patterns of as-cast: a) and STA; b) samples showing the different phases in Ti-6Al-4V with 0, 1.0, 1.64 and 2.0 wt% boron

(Massalski *et al*., 1986). As-cast Ti-6Al-4V sample without boron, in Fig. 2a shows coarse acicular α′-laths intersect each other in a basket-weave structure. Formation of the acicular α′ could be attributed to the diffusionless martensitic transformation from prior β grains due to fast cooling rates during arc melting process.

Figure 2(b) shows finer α′ platelets aligned along more preferred orientations in STA treated Ti-6Al-4V compared to the samples in as-cast condition. With boron addition, the size of α-β colony is reduced. Both 1.0 wt% and 1.64 wt% added Ti-6Al-4V show the presence of prior β dendrite arms which indicate reduction in prior β grain size. In Ti-6Al-4V-1.0B and Ti-6Al-4V-1.64B, eutectic mixtures consisting of TiB phase in between α-β colony are observed at interdendritic arms and inter-grain regions (Fig. 2c-f).

The microstructure of Ti-6Al-4V-2.0B in Fig. 2g, h show coarse proeutectic TiB_p whiskers along with uniformly distributed eutectic mixture of finer eutectic TiB_e

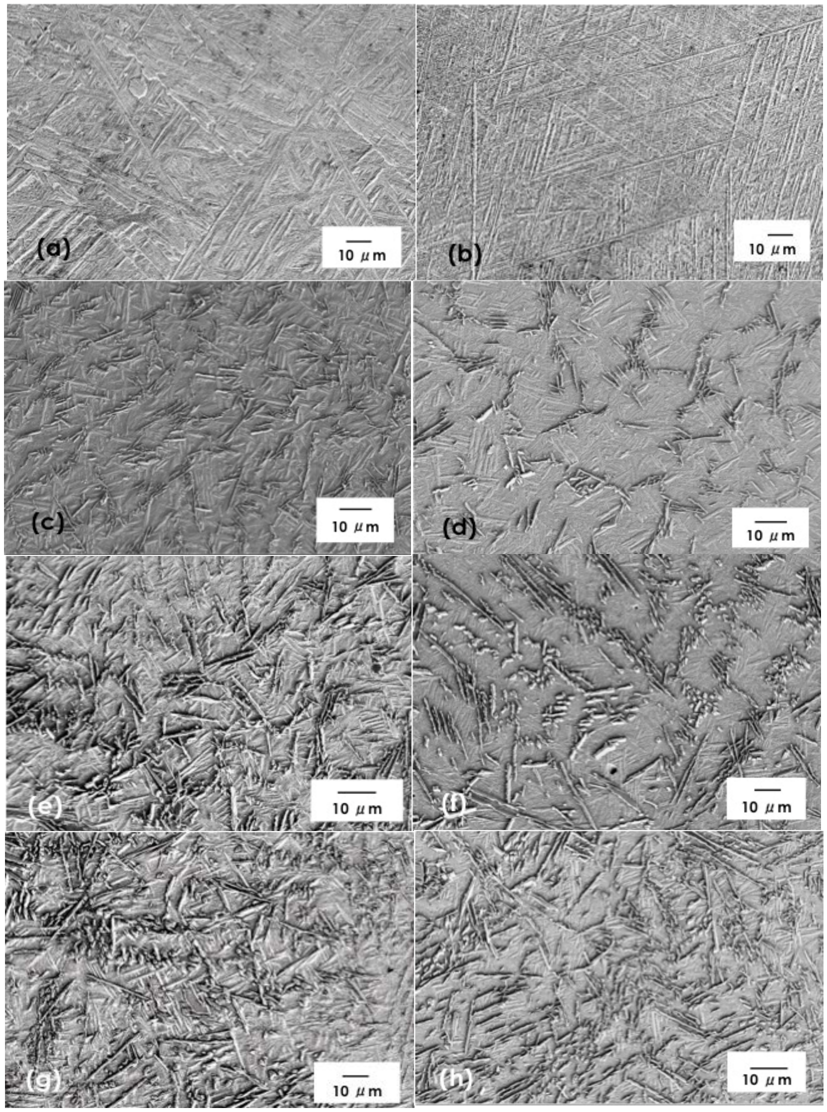

Fig. 2: SEM images of as-cast Ti-6Al-4V with addition of: a) 0B; b) 0B; c) 1.0B; d) 1.0B; e) 1.64B; f) 1.64B; g) 2.0B; heat treated Ti-6Al-4V and h) 2.0B

and α-β colony. Based on binary Ti-B phase diagram, prior β grains nucleate and grow upon cooling between liquidus and eutectic temperatures in titanium rich alloys. Upon cooling below the eutectic temperature, the remaining liquid solidifies, forming eutectic mixture of β and TiB phases. Further cooling to room temperature retains the prior β grain boundaries. Solidification of hypoeutectic Ti alloys starts with proeutectic beta grains formation prior to eutectic TiB formation. Thus TiB particles cannot act as nucleation site for proeutectic β grains and grain refinement via inoculation by TiB do not occur. The instability at the liquid/solid interface due to constitutional supercooling creates additional force that drives nucleation of fine β grains. Concentration of boron at solid/liquid interface increases as a result of boron rejection from the solid into the melt.

The consequent boron-rich layer retards the growth of nuclei in the melt resulting in finer grain size. Therefore grain refinement depends on the degree of latent heat production and heat extraction at the solid/liquid interface. Since the rate of latent heat production is limited by the solute partitioning at the solid/liquid interface and diffusion in the melt, the influence of a solute on the grain size can be described by the growth restriction factor, Q given as (Tamirisakandala *et al*., 2005):

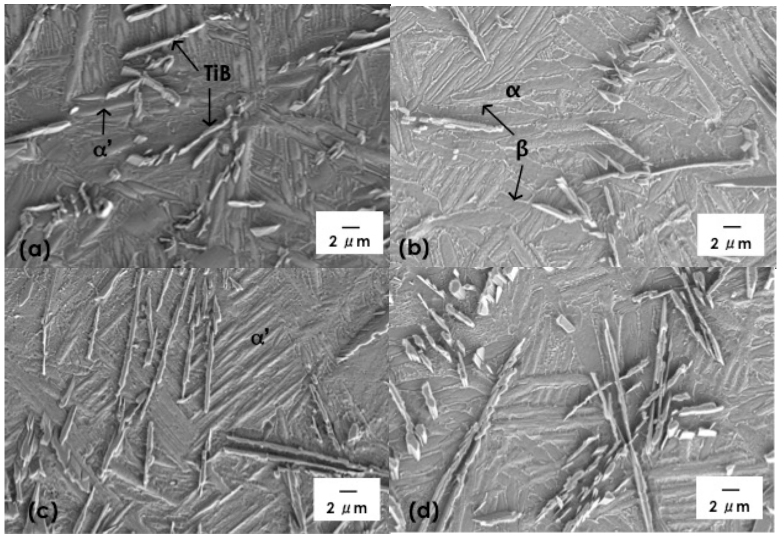

Fig. 3: SEM images at 1000X magnification showing: a-b) α, α', β and TiB phases in Ti-6Al-4V with 1.0B; c-d) 1.64B

$$Q = m(k-1)C0 \quad (1)$$

where m is the slope of the liquidus, k is the solute partition coefficient ($k = C_s/C_l$; C_s and C_l are the solute contents of the solid and liquid in equilibrium at the interface between them), C_0 is the solute content.

By referring to the analysis of growth restriction factor (Bermingham *et al*., 2008), the value of m(k-1) for boron is 65.0 for a solute content of 1 wt. This value is much higher compared to most other elements including Al and V. Therefore, boron contents of 1.64 and 2.0 wt% will give Q values of 106.6 and 130.0, respectively suggesting that the growth restriction factor becomes more significant to grain refinement mechanism as higher concentration of boron is added to Ti-6Al-4V alloy. At low concentrations, Al and V are highly soluble in titanium. Hence, these individual solutes do not partition ahead of the solidification front unlike boron which segregates and results in a high Q value.

Higher magnification SEM of as-cast Ti-6Al-4V containing 1.0 and 1.64 wt% boron in Fig. 3a-c and respectively shows acicular α' platelets among α-β colony. The α' platelets formed by martensitic transformation are not visible in STA samples where α-β colony are more clearly observed in Fig. 3b, d. This suggests that the α' phase has been transformed to α-β colony via diffusion during the heat treatment process. HCP-Ti peaks obtained from the XRD analysis depicted in Fig. 3a-d.

Consist of α and α' phases as both are hexagonally close-packed structures. Heat treatment at a temperature above the β transus which in this case was 940 °C and subsequent water quenching at room temperature resulted in formation of α' phase through martensitic transformation. Upon aging the α' martensites are converted into α-β colony which explains the absence of needle-like shaped α' in the STA samples. The STA samples show relatively higher hardness compared to the as-cast samples (Table 1). This could be due to the refined α-β colony as result of STA treatment.

Table 1: Hardness values of as-cast and heat-treated Ti-6Al-4V alloys with and without boron

Specimens	Hardness (Hv)	
As-cast	Heat	Treated (STA)
Ti-6Al-4V	413.9	465.0
Ti6Al-4V-1.0B	430.0	505.9
Ti6Al-4V-1.64B	525.0	580.1
Ti6Al-4V-2.0B	542.6	668.9

Figure 4 shows the computed liquidus projection of Al-B-Ti (Witusiewicz *et al*., 2008) and Ti-V-B (Artyukh *et al*., 2006) systems. Although, the eutectic composition of Ti-B is predicted lower than 1.6 wt boron in Al-B-Ti system, the liquidus projection for Ti-V-B system predicts that the eutectic composition of Ti-B is higher than 1.7 wt% boron at lower boron concentrations. Furthermore, the presence of prior β dendritic arms in the Ti-6Al-4V-1.64B specimen suggests that it is a hypoeutectic composition.

The small quantities of coarse proeutectic Ti-B whiskers along with eutectic mixture of TiB and α-β colony in 2.0 wt% boron added specimen allows us to suggest that the eutectic concentration of Ti-6Al-4V-B is at a point above 1.64 wt% and <2.0 wt%.

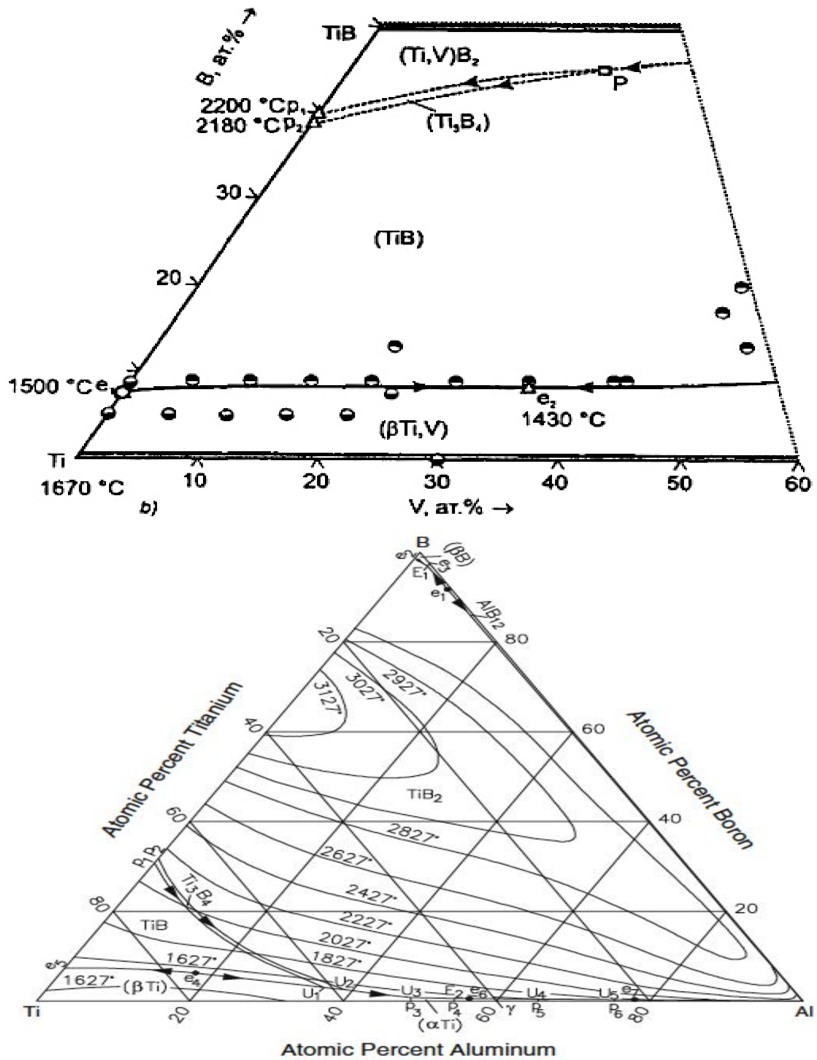

Fig. 4: Computed liquidus projection of AI-B-TI and TI-V-B system from (Witusiewicz *et al*., 2008; Artyukh *et al*., 2006)

CONCLUSION

Boron addition to Ti-6Al-4V alloy has resulted in reduction of α-β colony size. Prior β dendrite arms observed in the microstructural analysis of 1.0 wt% and 1.64 wt% added Ti-6Al-4V indicate reduction in prior β grain size. STA treatment refined α-β colony in Ti-6Al-4V alloy and contributed to the higher hardness values in aged samples compared to as-cast samples. Liquidus projections of Al-B-Ti and Ti-V-B systems and hypoeutectic structures observed in Ti-6Al-4V-1.64B suggest that the eutectic concentrationof Ti-6Al-4V-B is at a point above 1.64 w% but below 2.0 wt% boron.

ACKNOWLEDGEMENTS

The researchers are grateful to Universiti Teknologi MARA (UiTM) for funding provided for the research project under FRGS Grant 600-RMI/FRGS 5/3 (68/2013).

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