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Effect of boron on the structure and mechanical properties of Ti–6Al and Ti–6Al–4V

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Abstract

Boron alloying was found to have a beneficial effect on the plasticity of Ti–6Al and Ti–6Al–4V (wt.%) as-cast alloys for contents within the solubility limits (up to around 0.05 wt.%) and to enhance their strength and hardness HV in the range of the existence of metal-boride eutectic (up to 2.0 and 2.5 wt.% B studied, respectively). The boride reinforcement contributes much to the hardness and strength of the Ti–6Al and Ti–6Al–4V alloys, increasing them by 1.5–2 times at room temperature to 400 °C. Monovariant eutectics ($Ti_{88.8}Al_{11.2}$) + TiB and ($Ti_{84.9}Al_{11.4}V_{3.7}$) + ($Ti_{96.9}V_{3.1}$)B were found to solidify at compositions Ti–6Al–1.8B and Ti–6Al–4V–2B (wt.%) and at temperatures of 1530 and 1515 °C, respectively.

Keywords: Metal matrix composite; Titanium alloy; Eutectic; Boride; Hardness; Phase equilibria

1. Introduction

Boron alloying is of interest in both content ranges, microadditives (dopants) within the solubility limits and significant additions (boride reinforcement). The positive influence of boron dopant, such as grain refining and plasticity enhancing, was known long before for a number of metals [1–5], including titanium alloys alloyed with Al, Cr, Fe, Si and containing 0.01 wt.% B [6]. No data were found on doping the Ti–6Al–4V alloy.

In parallel, titanium matrix composites based on the Ti–6Al–4V alloy with boride reinforcement have been developed over the past 10–15 years [7–15]. There are a number of works reported on the Ti–6Al–4V alloy with variable volume fraction of boride reinforcement, where samples were prepared via consolidation technologies involving sintering of blended powders [7,8] (up to 30 and 20 vol.% boride), mechanical alloying [9] (up to 2 wt.% B) and rapidly solidified powders [10–13] (up to 1 wt.% B [10,11], 2 wt.% B [12] and 40 vol.% boride [13]). The only work [14] applied melting to produce an alloy Ti–6.5Al–4.2V–0.48B (wt.%) that was then extruded at 1065 °C and an extrusion ratio of 13.7:1. This alloy was hypoeutectic, far from the eutectic composition (the binary eutectic Ti–B contains 1.7 wt.% B [16], i.e. 9 vol.% TiB), and no data are available on titanium-boride eutectic alloys, excepting the binary eutectic Ti–B alloy studied in [17].

The objective of the current work is to study the effect of B additions, from the contents dissoluble in a Ti solid solution to compositions close to the metal-boride eutectic, on the microstructure and strength/hardness of as-cast Ti–6Al and Ti–6Al–4V (wt.%) alloys, with the alloys being melted at constant Al and V contents of 6 and 4 wt.%, respectively.

2. Experimental procedure

The starting materials that were used for alloys preparation were iodide titanium (99.9 wt.% purity); aluminium (99.99 wt.%), electron-beam melted vanadium (99.9 wt.%); TiB_2 (30.0B, 0.7C, 0.6Fe, 0.52O, 0.0005N, wt.%) and a

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master alloy Ti–2B (2.0B, 0.05O, <0.0005N, wt.%), where the TiB_2 and Ti–2B compositions were estimated from chemical analyses. The latter was melted from Ti and TiB_2 (composition from wet chemical analysis) previously prepared by arc melting of the elements. The prepared alloys contained less than 0.1 wt.% oxygen and less than 0.005 wt.% nitrogen.

The alloys were melted in a laboratory arc furnace with a nonconsumable tungsten electrode on a water-cooled copper hearth. Melting was done under an argon atmosphere (pressure of ∼80 kPa) that had previously been gettered by melting titanium getter for 5 min. Mixtures of the master alloy Ti–2B (together with TiB_2 at high boron contents) and metals (cuts) of 10 g were fused with a weak arc, and then melted six times with inversion between meltings. Cooling rate was estimated to be about 100 °C/s. Since the total weight losses of ingots on melting were always less than 0.2% and that boron was inserted as a component of the master alloy, the intended compositions of alloys were adopted.

As-cast alloys were studied by metallography, electron probe microanalysis (EPMA) performed with a JEOL Superprobe 733 instrument, X-ray diffraction (XRD) (mainly in a DRON-3M diffractometer on cross-sections using a filtered Cu Kα radiation), differential thermal analysis (DTA), hot hardness after Vickers (HV), Vickers microhardness (H_μ) at room temperature (RT) and RT compression test (strain rate of $\sim 6 \times 10^{-4}\,s^{-1}$). The Vickers hot hardness HV from RT to 800 °C was measured in a vacuum of 10^{-3} Pa at the 9.8 N load for 1 min, and the duration of long-term Vickers hardness was 1 h. The 1 min hardness was used for estimation of yield stress in compliance with the Hill ratio $HV = 3\sigma_{0.2}$ [18–20] confirmed in [21], and the long-term 1-h hardness served as a characterization of creep behavior [20,22]. DTA was carried out using string W/W-20Re thermocouples [23] under high purity helium with heating and cooling rates of 50 °C/min. Owing to possible interactions between molten alloys and the crucible material (Ta), only heating curves were taken into consideration. Further experimental details are provided elsewhere [24].

3. Results and discussion

3.1. Alloys Ti–6Al + B

Structure and properties of the Ti–6Al (wt.%) alloy were investigated at the boron additions from 0.01 to 2.0 wt.%. The XRD, DTA and metallography data obtained for the initial Ti–6Al binary alloy (Table 1) are in good agreement with the phase diagram of the Ti–Al binary system from [25,26]. The alloy consists of the hcp αTi phase of the Mg structure type (Fig. 1a), which was formed as a result of the β → α transition in the course of cooling after solidification (where β is the phase based on the bcc βTi of the W structure type). Boride grains were not observed at magnifications up to 3000 in the alloys with boron content up to 0.05 wt.%. The TiB phase of FeB structure type was detected with XRD at 0.5–2.0 wt.% B and also with metallography starting with 0.1 wt.% B (Fig. 1b and c). The lattice parameters of α and TiB phases do not practically depend on boron contents in alloys and are equal to $a_\alpha = 293.2 \pm 0.3$ pm, $c_\alpha = 468.2 \pm 0.3$ pm and $a_{TiB} = 612 \pm 2$ pm, $b_{TiB} = 306.3 \pm 1.0$ pm, $c_{TiB} = 456.5 \pm 1.5$ pm. Since there is EPMA evidence that the Al solubility in TiB is negligible (not exceeding 10^{-2}% from the current data), the composition of the metal (Ti,Al) matrix phase may be easy

Table 1
XRD and DTA data for the Ti–6Al + B and Ti–6Al–4V + B as-cast alloys

Composition (wt.%) (Ti to balance)			Phase constituents from XRD	Lattice parameters of α-phase (pm)		Temperature of solid phase transformation (°C)	Melting point (°C)
Al	V	B		*a*	*c*		
6.0			α	293.5(1)	467.9(3)	1005 (in.tr.)[c]	1660
6.0		1.0	α + TiB	293.5(1)	468.0(3)	980 (in.tr.)[c]	1525
6.0		2.0	α + TiB	292.9(1)	468.1(3)	985 (in.tr.)[c]	1530
6.0	4.0		α	292.4(1)	466.3(6)	935 (compl.)[d]	1645
6.0	4.0	0.01	α	292.7(1)	465.8(4)	935 (compl.)[d]	1625
6.0	4.0	0.02	α	293.2(2)	467.0(6)		
6.0	4.0	0.05	α	293.0(1)	466.8(6)	935 (compl.)[d]	1600
6.0	4.0	0.1	α + (TiB)[a]	293.1(1)	466.8(8)	940 (compl.)[d]	1515
6.0	4.0	0.5	α + (TiB)	292.8(1)	466.7(2)	950 (compl.)[d]	1515
6.0	4.0	1.0	α + (TiB)	293.2(1)	467.1(3)	950 (compl.)[d]	1515
6.0	4.0	1.5	α + (TiB)	292.6(1)	466.9(2)	950 (compl.)[d]	1515
6.0	4.0	1.75	α + β[b]+(TiB)	292.7(1)	467.0(3)		1515
6.0	4.0	2.0	α + β[b]+(TiB)	293.4(2)	468.2(7)		1515
6.0	4.0	2.25	α + β[b] + (TiB)	293.4(3)	467.7(2.0)		1515
6.0	4.0	2.5	α + β[b] + (TiB)	293.6(2)	467.6(1)		1505

[a] From metallography.
[b] Diffraction peaks of β-phase are deficient due to its small content.
[c] Temperature of incipient solid phase transformation.
[d] Temperature of completion of solid phase transformation.