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Development of solidification microstructure in boron-modified alloy Ti–6Al–4V–0.1B

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Abstract

Hypoeutectic boron addition (0.1 wt.%) to Ti–6Al–4V is known to cause significant refinement of the cast microstructure. In the present investigation, it has been observed that trace boron addition to Ti–6Al–4V alloy also ensures excellent microstructural homogeneity throughout the ingot. A subdued thermal gradient, related to the basic grain refinement mechanism by constitutional undercooling, persists during solidification for the boron-containing alloy and maintains equivalent β grain growth kinetics at different locations in the ingot. The Ti–6Al–4V alloy shows relatively strong texture with preferred components (e.g. ingot axis‖[0 0 0 1] or [1 0 $\bar{1}$ 0]) over the entire ingot and gradual transition of texture components along the radius. For Ti–6Al–4V–0.1B alloy, significant weakening characterizes both the high-temperature β and room-temperature α texture. In addition to solidification factors that are responsible for weak β texture development, microstructural differences due to boron addition, e.g. the absence of grain boundary α phase and presence of TiB particles, strongly affects the mechanism of β → α phase transformation and consequently weakens the α phase texture. Based on the understanding developed for the boron-modified alloy, a novel mechanism has been proposed for the microstructure and texture formation during solidification and phase transformation.

Keywords: Titanium alloy; Boron addition; Solidification; Microstructure; EBSD

1. Introduction

Titanium alloys, owing to their high specific strength and excellent corrosion resistance, constitute an important class of materials for aerospace and other applications [1]. Such applications, however, require multi-step thermomechanical processing (TMP) since coarse and non-uniform cast microstructures do not provide the desired property combinations for fracture-critical applications. In addition, titanium alloys in the cast condition exhibit strong and inhomogeneous solidification textures that are deleterious for in-service applications as well as secondary processing of the cast alloys [3–5]. The first step in the manufacture of titanium components, therefore, involves ingot breakdown [6,7], during which extensive hot working is performed in the β phase field to create fine microstructures with weak textures throughout the ingot. High energy consumption and high yield loss are significant issues during ingot breakdown. Hence, methods of obtaining homogeneous and refined microstructure and weakening of crystallographic texture in the as-cast condition are desirable for improving affordability of titanium alloy processing [8].

One of the most widely used titanium alloys for aerospace applications is Ti–6Al–4V (all compositions expressed in wt.%). The microstructure of this alloy at room temperature consists of the hexagonal close-packed

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(hcp) α phase in combination with the body-centered cubic (bcc) β phase [9]. The alloy, when prepared by ingot metallurgy, solidifies in β phase and subsequently transforms to (α + β) phase constituents at room temperature. Significant grain growth occurs in the β phase field, resulting in coarse prior β grains in the cast microstructures. In this regard, Zhu et al. [10] first reported grain refinement for commercial purity Ti (CP Ti) by elemental boron addition in the hypoeutectic range for small dental castings. Later on, Tamirisakandala et al. [11] showed that the cast grain size reduces by about an order of magnitude in Ti alloys (Ti–6Al–4V and Ti–6Al–2Mo–4Sn–2Zr) with an addition of 0.1 wt.% of boron. Significant improvements in the mechanical properties due to refined cast microstructure have been reported since then mainly for the boron-modified Ti–6Al–4V alloy [12–18]. These experimental findings indicate the increasing importance of boron-modified Ti alloys for structural applications.

However, the microstructural refinement in the cast condition needs to be revisited since the property attributes strongly depend on finer microstructural details including crystallographic texture throughout the cast ingot. Subsequently, a fundamental understanding of microstructural evolution due to boron addition is highly desirable. These aspects are still unclear and thus form the basis of the present study. The spatial variation of microstructure and texture has been studied using scanning electron microscopy with electron back-scatter diffraction (SEM-EBSD) and X-ray diffraction (XRD) techniques at selected locations in the cast ingot. The study further aims at examining the subtle mechanisms of microstructural evolution (morphology as well as orientation) governed by phase transformation in the boron-modified Ti–6Al–4V alloy.

2. Experimental

2.1. Materials

Alloys of nominal compositions Ti–6Al–4V and Ti–6Al–4V–0.1B (hereafter referred to as Ti64 and Ti64 + B, respectively) were used in this study. Ingots of 65 mm diameter × 500 mm length of both compositions were produced via induction skull melting and graphite mold casting under identical conditions at Flowserve Corporation, Dayton, OH. Boron was added as amorphous elemental powder directly to the melt. As-cast ingots were subjected to a standard hot isostatic pressing treatment at 900 °C and 100 MPa for 2 h to heal any microporosity. Chemical compositions of cast alloys measured via inductively coupled plasma spectroscopy (ICPS; JY 24, Horiba, Jobin–Yvon, France) technique are given in Table 1. An appropriate section of the titanium–boron phase diagram is shown in Fig. 1 with the composition under investigation marked.

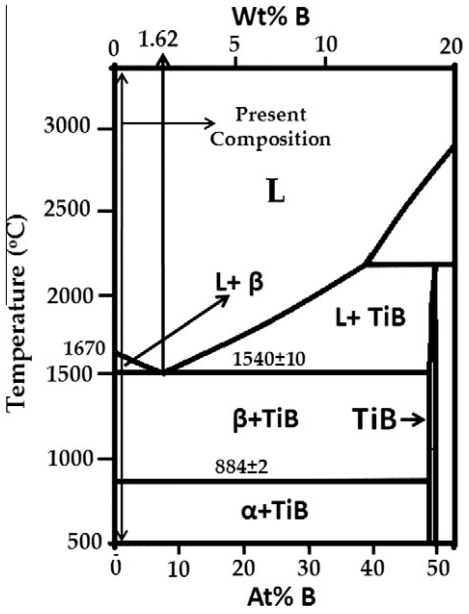

Fig. 1. A section of the titanium–boron phase diagram showing the composition of the hypoeutectic alloy used for the present study.

2.2. Microstructural characterization

For microstructural analysis at various locations, strips 30 mm long, 5 mm wide and 2 mm thick were cut from the radial–transverse planes of the two ingots as shown in Fig. 2a. The horizontal surfaces of the strips were mechanically polished using SiC grit papers and finally electropolished using an electrolyte containing 600 ml methanol + 360 ml butoxyethanol + 60 ml perchloric acid. Polished surfaces were etched with a solution containing 5% HF, 10% $HNO_3$and 85% distilled water for 10 s and examined in a field emission scanning electron microscope (SEM; QUANTA 200, FEI, the Netherlands). Microstructural mapping of ingot strips was performed on 30 mm × 5 mm area for Ti64 and 30 mm × 2 mm area for Ti64 + B as shown in Fig. 2b. Macro-montages were created by stitching SEM images captured via sequential, regulated, and controlled movement of the SEM stage in horizontal and vertical directions. For ease of visual inspection, prior β boundaries were traced on these

Table 1
Chemical compositions (in wt.%) of the two alloys used in the present study.

Alloy	Al	V	B	O	H	C	N	Fe	Ti
Ti64	6.6	4.1	–	0.18	0.008	0.02	0.01	0.23	Balance
Ti64 + B	6.0	4.0	0.1	0.15	0.005	0.02	0.01	0.13	Balance