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Processing, Microstructure, and Properties of β Titanium Alloys Modified With Boron

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The development of next-generation βTi alloys is expected to involve very attractive combinations of strength-toughness-fatigue resistance at large cross sections, improved and affordable thermomechanical processing, and enhanced elevated temperature capability. This article describes the development of βTi alloys that are modified with small boron (B) additions to achieve these goals. Two important aerospace alloys, Ti-15Mo-2.6Nb-3Al-0.2Si and Ti-5Al-5V-5Mo-3Cr microalloyed (0.1%) with B were considered. Ingots that were 70 mm in diameter and 500 mm in length were cast using induction skull melting. A detailed microstructural characterization and tensile property evaluation were conducted. Microalloying with B refines the cast grain size to about 50 μm, which enhances strength and ductility. The effect of B additions on the microstructural stability and properties in the as-cast condition was established. The implications of B additions on the microstructural evolution and affordability of subsequent processing is also discussed.

Keywords β titanium alloys, B addition, cast alloys, microstructure, properties

1. Introduction

Beta Ti alloys are the most versatile class of Ti alloys offering a wide range of processing and physical-chemical-mechanical property combinations compared with any other class of Ti alloys (Ref 1). Despite this wide range of attributes, there were very few applications of β alloys in the early 1990s, accounting for only 1% of the total Ti market (Ref 2). In the past, the majority of the development of β alloys has been driven by performance, and the high cost factor has slowed down the integration of βTi alloys. The usage of βTi alloys has increased significantly in the last 10 years due to the focused effort in reducing the formulation and processing costs (Ref 3). Currently, βTi alloys are widely used in aerospace, automotive, biomedical, and sporting applications (Ref 1). More widespread use and the justification to replace existing materials with β alloys are envisaged if affordable processing methodologies are developed and adopted (Ref 2). The most important microstructural parameters that control the properties of βTi alloys are prior β grain size, the primary and secondary α, including their volume fraction, morphology, size, and distribution, and the grain boundary α morphology and volume fraction. Innovations in processing are the key to enhancing the affordability of β alloys while obtaining controlled microstructures. Titanium alloys modified with boron (B) are emerging as a new class of alloys with exceptional promise for achieving this goal (Ref 4, 5). Boron, unlike other interstitial elements such as oxygen and hydrogen, is almost insoluble in Ti in the solid state (Ref 6) and, thus, does not embrittle the lattice. Recent studies have demonstrated that micro-B additions to conventional α + β Ti alloys (Ti-6-4 and Ti-6-2-4-2S) produced dramatic (by a factor of 10) grain refinement in the as-cast condition (Ref 7). The optimum B concentration (i.e., in the range 0.05-0.1%) was established for producing an order of magnitude grain refinement in these alloys. The objectives of this research effort are to understand the effect of micro-B additions on the microstructural evolution and the mechanical properties of βTi alloys and to explore the influence of B additions on the affordability of βTi alloys.

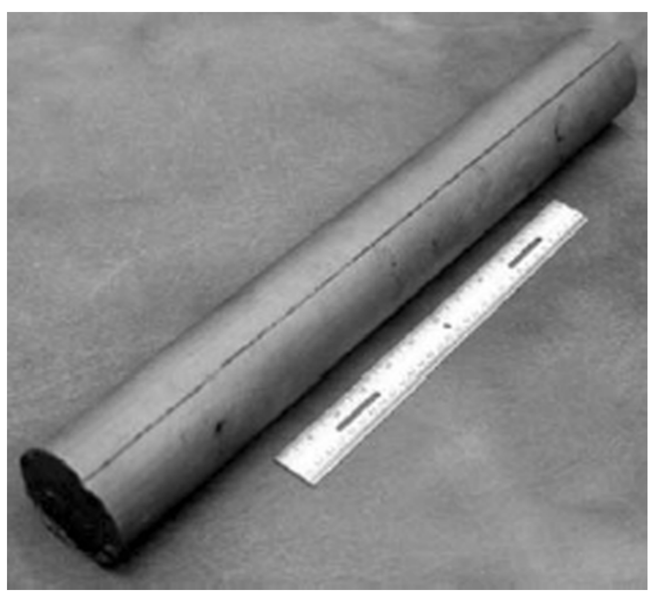

Fig. 1 Photograph of a typical βTi alloy cast ingot produced via induction skull melting

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2. Experimental

2.1 Materials

Two metastable βTi alloys with nominal compositions of Ti-15Mo-2.6Nb-3Al-0.2Si (Beta-21S) and Ti-5Al-5V-5Mo-3Cr (Ti-5553) were considered in this study. Each of these compositions without and with 0.1% B were produced at Flowserve Corporation, Dayton, OH, via induction skull melting using graphite molds. The B was added in the form of elemental B that completely dissolves in the liquid melt and forms TiB precipitates in situ during solidification. The cast ingot dimensions were 70 mm in diameter × 500 mm in length. All of the ingots were subjected to hot isostatic pressing (HIP) at 900 °C and 100 MPa for 2 h. After HIP, the ingots were radiographed and were confirmed to be free from porosity. A photograph of a typical ingot is shown in Fig. 1, and complete chemical analyses of the program materials are presented in Table 1.

2.2 Metallography

Samples for microstructural examination were cut from the cast ingots, prepared by standard polishing techniques, and observed using both light microscopy (LM) and scanning electron microscopy (SEM). Polarized light was used for observations in LM, and the backscattered electron imaging mode was used in SEM. The grain sizes of the cast microstructures were measured using the linear intercept method.

2.3 Tensile Testing

Round threaded tensile specimens with a 5 mm gage diameter and 30.5 mm gage length were prepared via electric discharge machining and low-stress grinding. Tensile testing was performed according to ASTM standard E08 using a servohydraulic test frame. A 20 mm extensometer was used in the gage portion to measure the strain during room temperature testing, and the samples were pulled at a constant crosshead speed of 0.01 mm/s. Tests were also conducted at elevated temperatures up to 400 °C for the Ti-5553 alloys. The fracture surfaces of selected specimens were observed with SEM using secondary electron imaging.

3. Results and Discussion

3.1 Microstructures

Polarized light micrographs of the as-polished specimens of Beta-21S and Beta-21S-0.1B are shown in Fig. 2(a) and (b), respectively, which clearly illustrate the grain refinement effect caused by B addition. The grain size measurements revealed that the addition of 0.1 B refines the average cast grain size (or prior β grain size) from 150 to 50 μm. Backscattered electron images of the Beta-21S and Beta-21S-0.1B alloys are presented in Fig. 3, which reveal the morphology and finer structural details of the microconstituents. Beta-21S without B exhibits coarse prior β grains (Fig. 3a) that are decorated with a thin and continuous grain boundary α film (Fig. 3b) of approximately 0.5 μm width. Beta-21S-0.1B, on the other hand, exhibits fine grains (Fig. 3c) with grain boundary α as small platelets (Fig. 3d). The addition of 0.1 B produces TiB in situ, which is preferentially located at the grain boundaries (Fig. 3d). In both of the alloys, the intragranular structure consisted of acicular α in the β matrix, which is typically observed after the solution treatment of Beta-21S above the β transus (~810 °C) (Ref 8).

Polarized light micrographs of the Ti-5553 and Ti-5553-

Table 1 Chemical analysis of the cast βTi-B program materials

Alloy	Mo	Nb	Al	Si	Fe	B	O	H	N	C	Ti
β-21S	15.2	2.8	2.7	0.2	0.43	…	0.19	0.0007	0.022	0.02	bal
β-21S-0.1B	14.7	2.8	2.8	0.2	0.41	0.12	0.20	0.0008	0.022	0.02	bal
		V		**Cr**							
Ti-5553	5.2	5.0	5.1	3.0	0.4	…	0.21	0.0014	0.01	0.02	bal
Ti-5553-0.1B	5.0	4.9	5.2	3.2	0.5	0.1	0.19	0.0008	0.01	0.01	bal

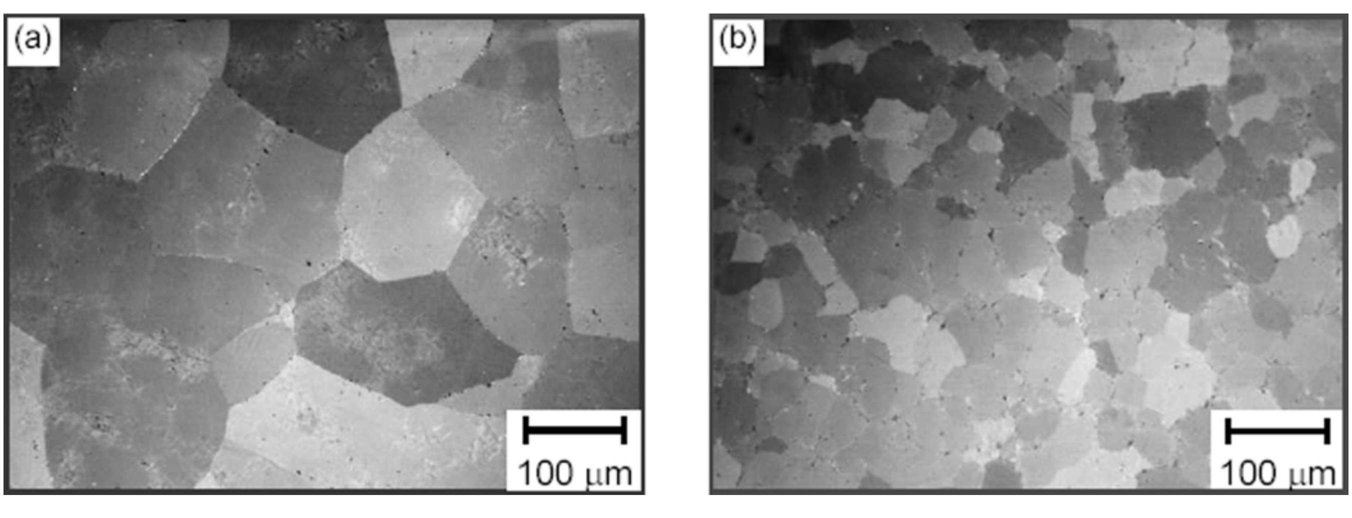

Fig. 2 Polarized light micrographs of the as-polished specimens of (a) Beta-21S and (b) Beta-21S-0.1B

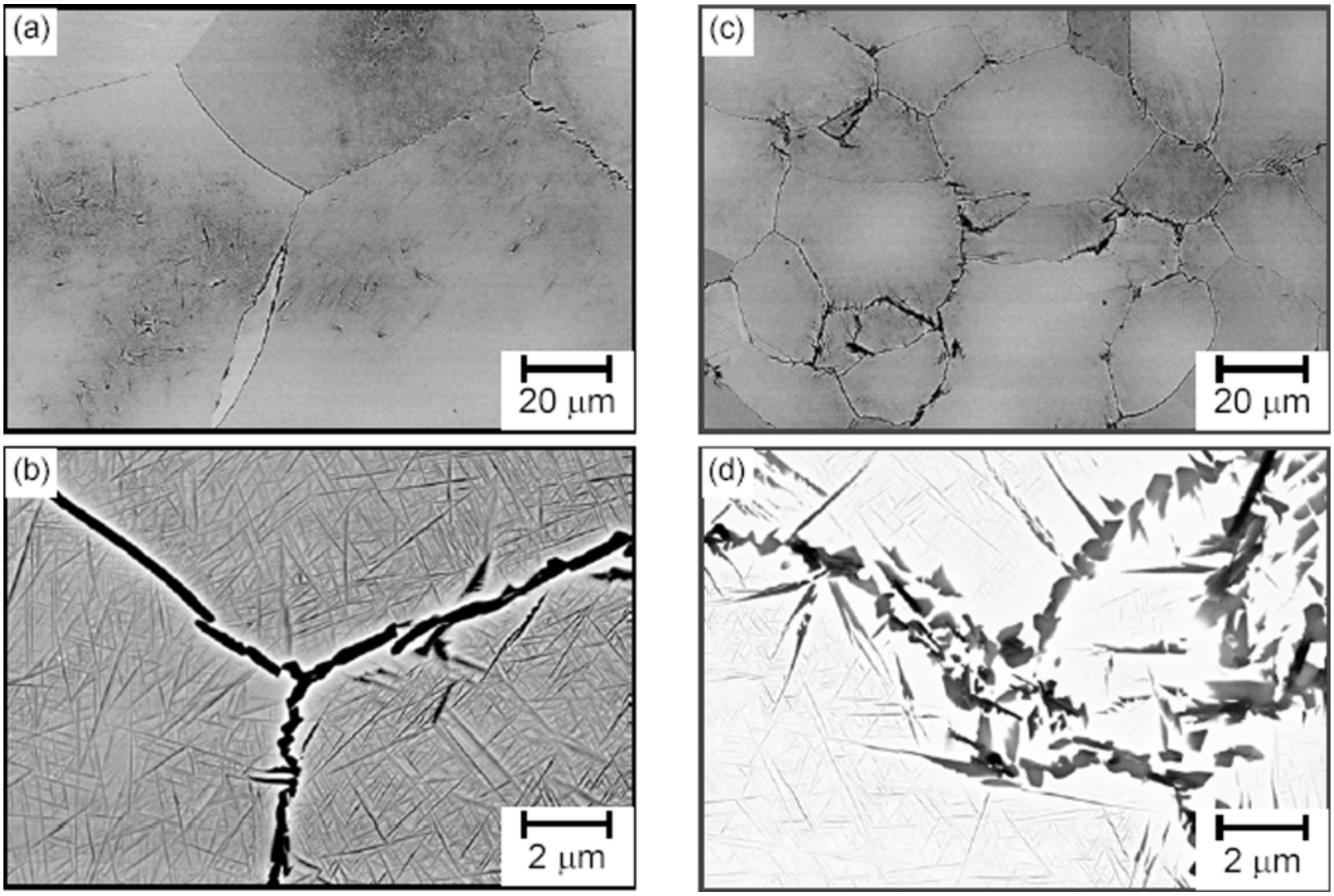

Fig. 3 Backscattered electron images of the as-polished specimens of (a, b) Beta-21S and (c, d) Beta-21S-0.1B. (a, c) are at low magnification, and (b, d) are at high magnification. The contrast of the micrograph (d) was digitally enhanced to reveal the difference between grain boundary α (gray) and TiB (black).

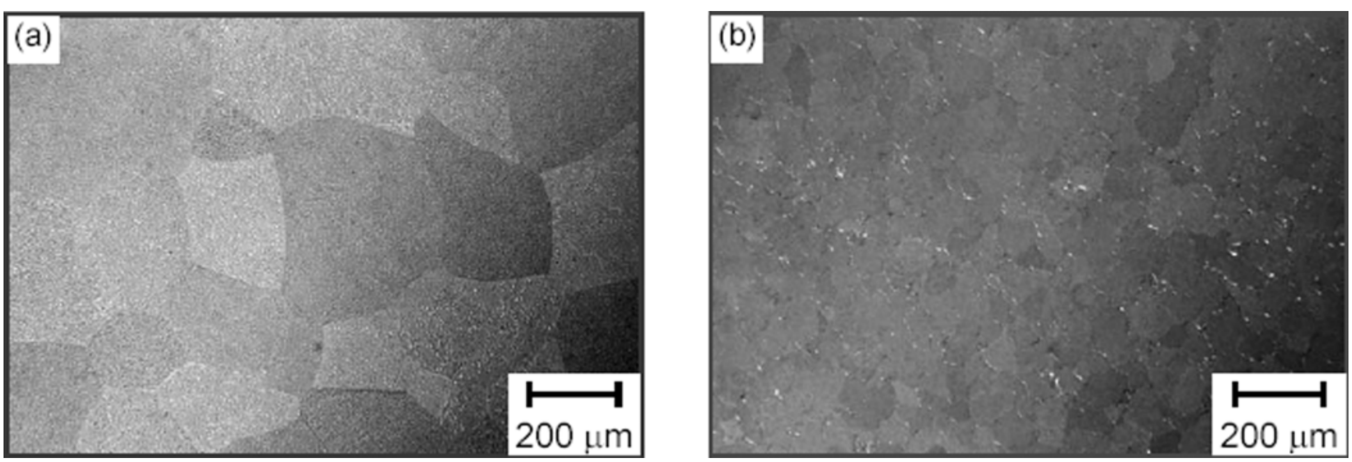

Fig. 4 Polarized light micrographs of the as-polished specimens of (a) Ti-5553 and (b) Ti-5553-0.1B

0.1B alloys shown in Fig. 4 illustrate the dramatic grain refinement effect of B, which is similar to that of Beta-21S. The average cast grain size was refined from 350 to 50 μm due to micro-B addition to Ti-5553. Backscattered electron images of these alloys at low and high magnifications are presented in Fig. 5. The Ti-5553 alloy modified with B exhibits fine prior β grains (Fig. 5c) with discontinuous grain boundary α and fine TiB precipitates at the grain boundaries. The grain interior structure in both of the alloys is acicular α in the β matrix, which is typical of the β solution-treated condition (Ref 8).

Grain refinement improves many of the metallurgical properties such as strength, ductility, and fatigue life, while mitigating the tendency for cracking and slowing the crack growth rate. Typically, Ti alloys are subjected to extensive thermomechanical processing (TMP) to refine the microstructure (Ref 1, 8). The ability to obtain fine grain sizes in the as-cast condition

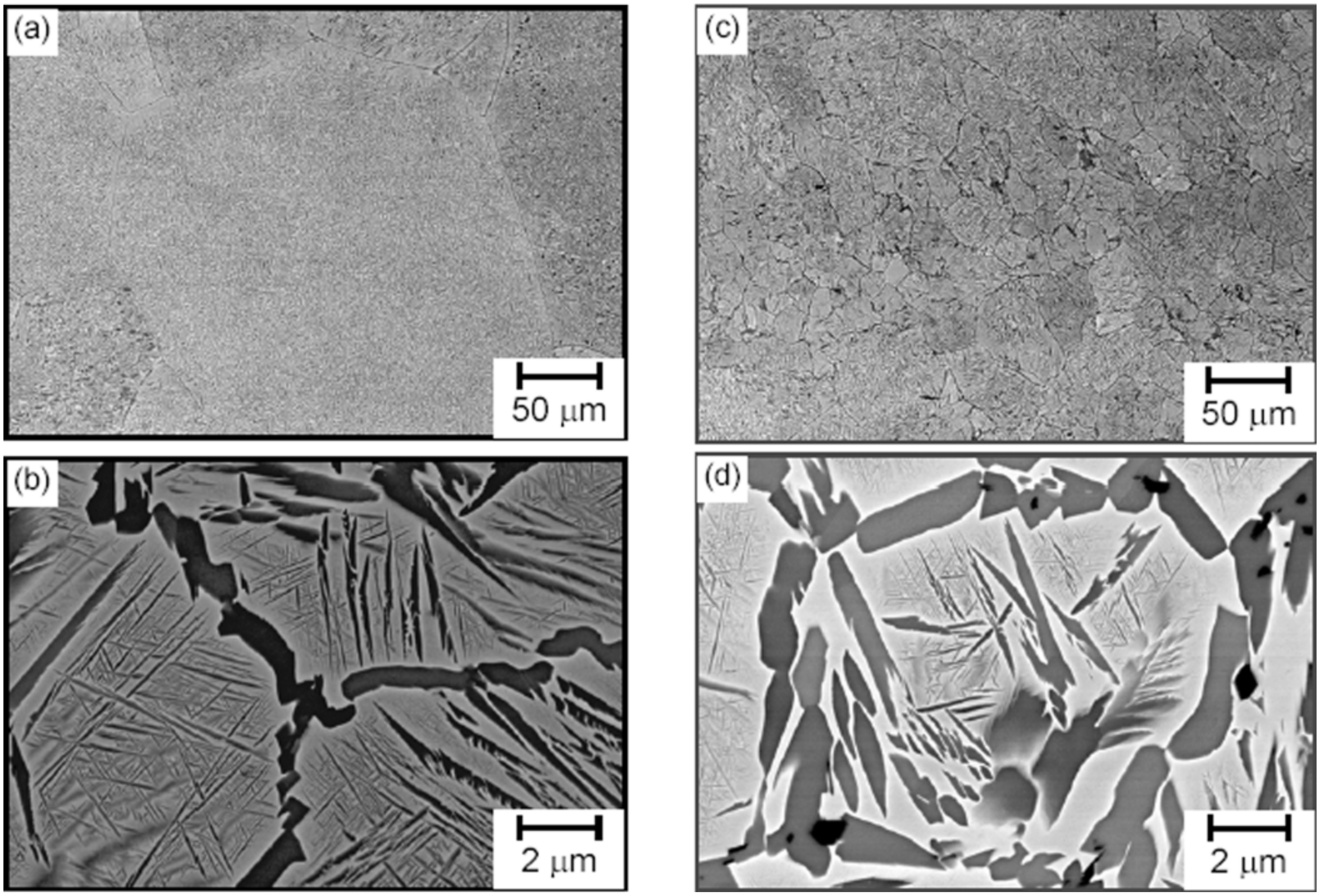

Fig. 5 Backscattered electron images of the as-polished specimens of (a, b) Ti-5553 and (c, d) Ti-5553-0.1B

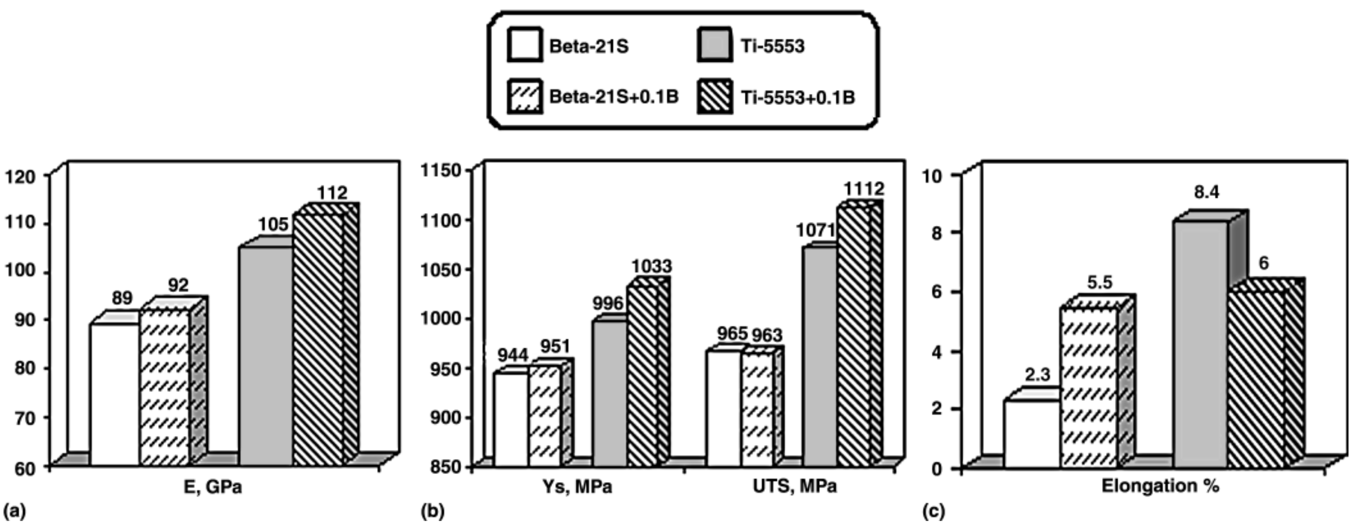

Fig. 6 Room temperature tensile properties of Beta-21S and Ti-5553 alloys containing 0 and 0.1 B: (a) elastic modulus; (b) 0.2% yield strength and ultimate tensile strength; and (c) elongation

could significantly enhance the affordability of βTi alloys. Boron additions could possibly eliminate/reduce several conventional TMP steps, which further enhances affordability.

The mechanism of grain refinement due to B additions is not expected to be similar to the classic inoculation effect observed in Al alloys (Ref 9), because the TiB phase precipitates after the β phase during solidification under equilibrium conditions for B concentrations below the eutectic limit (Ref 10). Grain refinement in TiAl-based alloys by B additions was well-studied and documented (Ref 11). Although different mechanisms have been proposed previously for B-induced grain refinement in these alloys, an alternative hypothesis based on renucleation in the constitutionally supercooled zone ahead of the solidification front appears to correlate well with the ex-

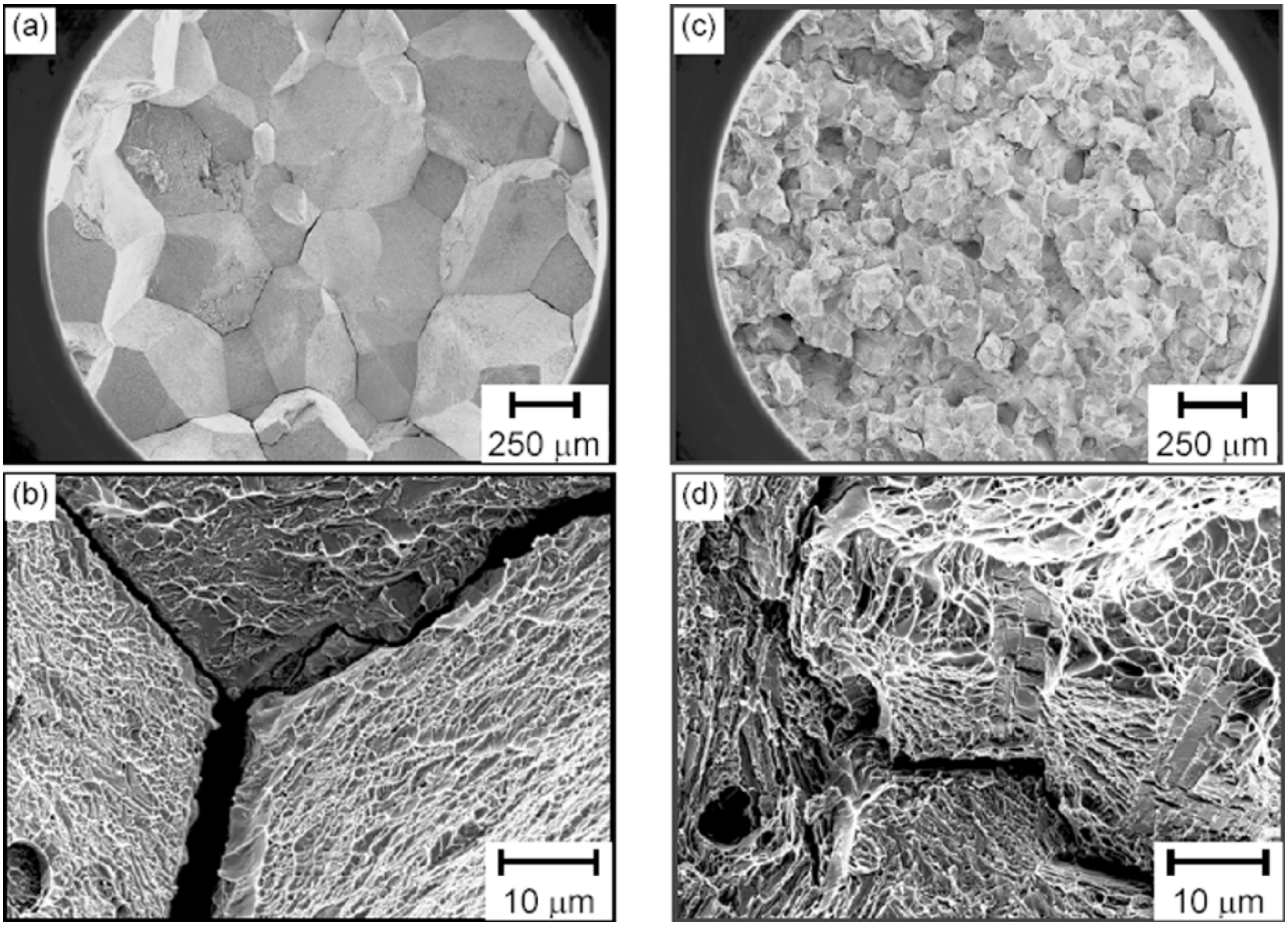

Fig. 7 Fractographs of (a, b) Beta-21S and (c, d) Beta-21S − 0.1B tensile fracture surfaces

perimental observations (Ref 12). A similar mechanism could be expected in the conventional Ti alloys (Ref 13). The preferential segregation of TiB to the grain boundaries could reduce grain growth at high temperatures via Zener pinning. More work is underway to understand the mechanism of grain refinement and to correlate with microstructural observations.

3.2 Tensile Properties

The tensile properties at room temperature of all of the β alloys considered in this study are shown in Fig. 6. The addition of 0.1 B increases the elastic modulus and strength by about ~5% while retaining good ductility. Both the fine grain size (Hall-Petch strengthening) and TiB (load-sharing mechanism) are expected to contribute to the strengthening in the B-modified alloys. A modeling effort is underway to quantify the contribution of each mechanism.

The ductility of the Beta-21S alloy in the cast condition is very low, but the B addition significantly enhanced the elongation (Fig. 6c). To understand the damage mechanism, the fracture surfaces were observed with SEM. Fractographs of the Beta-21S alloys are presented in Fig. 7. Intergranular fracture was observed in both of the alloys. However, the fracture path was straight due to the continuous grain boundary α in the Beta-21S alloy (Fig. 7b), whereas a more tortuous fracture path was observed in the Beta-21S-0.1B alloy (Fig. 7d), which explains the enhanced ductility.

The tensile strengths of the Ti-5553 and Ti-5553-0.1B alloys at elevated temperatures up to 400 °C are shown in Fig. 8. These plots show that the strength enhancements resulting from B addition observed at room temperature (Fig. 6b) are maintained at elevated temperatures. Higher strength at elevated temperature due to B additions could lead to the enhanced elevated temperature capability of these alloys, which further enhances the affordability of βTi alloys.

4. Conclusions

Two metastable βTi alloys (Beta-21S and Ti-5553) that were microalloyed (0.1%) with B were produced using conventional melt processing. The influence of B on the microstructures and tensile properties in the cast + HIP condition was established. The following conclusions are made based on the observations in this study.

- Beta Ti alloys modified with B were successfully produced using a conventional casting method.
- The addition of 0.1% B to Beta-21S and Ti-5553 alloys significantly refines the cast grain size by a factor of ~5. Micro-B additions produce a cast grain size of ~50 μm, which is typically obtained after thermo-mechanical processing (TMP) in the β phase field.
- Micro B additions provide a ~5% increase in strength and stiffness while maintaining good ductility.

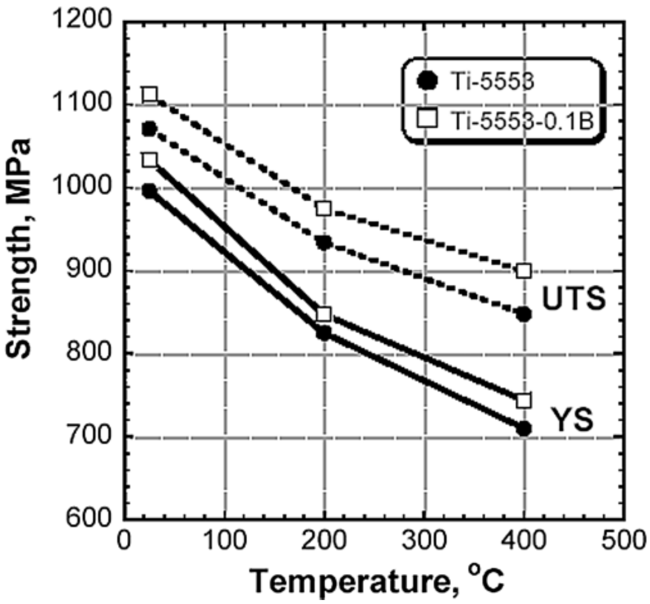

Fig. 8 Elevated temperature strengths of Ti-5553 and Ti-5553-0.1B. YS, yield strength; UTS, ultimate tensile strength

- Strength enhancements due to B additions to Ti-5553 are also maintained at elevated temperatures up to 400 °C. The ability to retain higher strength enables a better elevated temperature capability for βTi alloys.
- Micro-B additions enhance the affordability of βTi alloys via grain refinement, enhanced mechanical properties, and enhanced elevated temperature capability, and may also reduce the processing costs via the reduction/elimination of TMP steps.

Acknowledgments

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