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On the correlation between the morphology of α and its crystallographic orientation relationship with TiB and β in boron-containing Ti–5Al–5Mo–5V–3Cr–0.5Fe alloy

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While the role of borides on the microstructure of titanium alloys has been discussed in many previous reports, this paper presents the first experimental evidence of (i) the three-dimensional geometry of α precipitates confirming their equiaxed morphology, as determined by reconstruction of serially sectioned scanning electron microscopy images; and (i) the influence of the crystallographic orientation relationship between β, TiB and α phases on the morphology of α precipitates, investigated via detailed orientation microscopy studies on a boron-containing version of the commercial Ti–5Al–5Mo–5V–3Cr–0.5Fe alloy Ti5553.

Keywords: Ti5553; TiB; EBSD; Crystallography; Orientation relationship

There has been an increased interest in metastable β titanium alloys, such as Beta21S (Ti–15Mo–2.6Nb–3Al–0.2Si, all compositions in wt.%) due to their attractive properties, making them suitable candidates for applications requiring high specific strength and corrosion resistance. The excellent hot and cold workability of these alloys give them an edge over conventional $\alpha + \beta$ alloys. However, rapid grain coarsening at elevated temperatures restrict the temperature range over which these alloys can be used [1]. It has been proved that Zener pinning by insoluble precipitates like TiB, by addition of trace amounts of boron during casting, is an effective way to minimize coarsening of prior β grains and has been extensively discussed in the literature [2–6]. Apart from restricting grain growth at elevated temperatures, TiB precipitates have been reported to act as heterogeneous nucleation sites for α precipitation and have also been reported to alter the morphology of α by making it more equiaxed-like [3,7,8] as compared to the more classical lath-like morphology. Furthermore, the equiaxed α in boron-containing alloys has been reported to exhibit multiple orientation relationships with the TiB precipitates. For example, while Hill et al. [7] and Li et al. [9] have reported an orientation relationship of $(0001)_\alpha//(001)_{TiB}$ and $[11\bar{2}0]_\alpha//[010]_{TiB}$, the more recent study by Sasaki et al. [10] has shown the existence of multiple orientation relationships between α and TiB precipitates in the boron-containing Beta21S alloy. However, the rationale behind the formation of equiaxed α and the role of orientation relationship between β and TiB in governing the morphology of α nucleating from TiB has not been addressed in previously published literature. Therefore, the two primary aims of this paper are (i) to determine the true three-dimensional morphology of α precipitates nucleating from boride precipitates present in the β matrix of a titanium alloy; and (ii) to investigate the role of the presence or absence of orientation relationships between the α, β and TiB phases on the morphology of α nucleating from TiB in the Ti5553 alloy.

The base Ti5553 and boride-reinforced Ti5553 alloys were processed by arc-melting in a conventional vacuum arc furnace. The boride-reinforced Ti5553 composites were fabricated via an in situ reaction occurring during the arc-melting of pieces of commercial Ti–5Al–5Mo–

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5V–3Cr–0.5Fe (in wt.%) alloy together with elemental boron powder. The base alloy will henceforth be referred to as Ti5553 and the boron-containing alloy as Ti5553-0.5B (due to the nominal addition of 0.5 wt.% B). These alloys were subsequently sectioned into small pieces for heat treatment. Each sample was β-solutionized at 950 °C for 30 min, and furnace cooled to room temperature at an approximate cooling rate of 5 °C min^{-1}. The samples were then mounted and polished using conventional metallographic techniques. The scanning electron microscopy (SEM) and orientation microscopy (OM) studies were carried out using a FEI Nova 230 NanoSEM field emission gun scanning electron microscope equipped with an electron backscatter detector and an electron backscatter diffraction (EBSD) detector. The OM studies allowed for the determination of orientation relationships between the β, TiB and α phases present in the microstructure. Following the SEM studies, three-dimensional (3-D) microstructural information was acquired using a DualBeam™ focused ion beam (FIB) instrument, the FEI DB235, which uses a gallium liquid metal ion source to mill the sample surface and serially section the microstructure. With each milling step, the microstructure was imaged with the electron beam and a custom-designed backscatter detector in the FIB. Subsequently the 3-D microstructure was reconstructed using these backscatter SEM images.

Figure 1(a) and (b) shows representative backscatter SEM images of the microstructure of the base Ti5553 alloy and the Ti5553-0.5B alloy respectively, after β solutionizing and furnace cooling. Comparing these two images, the influence of the boride precipitate (exhibiting the darkest contrast in Fig. 1(b)) on the morphology of α precipitates is quite evident. While the classical lath-like morphology of the α precipitates that have either nucleated in an intra-granular fashion or from grain boundary α is clearly visible in case of the base Ti5553 alloy (shown in Fig. 1(a)), the α precipitates associated with the boride precipitate exhibit a more equiaxed-like morphology in the case of the Ti5553-0.5B alloy (shown in Fig. 1(b)). However, it is important to note that the 3-D morphology of these α precipitates cannot be uniquely determined based simply on these 2-D SEM images. Therefore, serial sectioning of the Ti5553-0.5B alloy was carried out in a dual-beam FIB instrument and SEM images were recorded after each stage of the serial sectioning process. Figure 1(c) shows one such 2-D SEM image from this microstructure, with the specific boride precipitate that was reconstructed marked within the box. Subsequently, this sequence of images was processed using standard image processing techniques and stacked up to reconstruct the true 3-D morphology of both the boride precipitate and the α precipitates associated with the precipitate. An example of this is shown in the series of images shown in Figure 1(d–f), where different views of the 3-D reconstructions of this boride precipitate and two α precipitates associated with this specific boride precipitate are shown. Viewing these α precipitates from different directions, their equiaxed morphology in 3-D is clearly evident from this series of images. Additionally, it should be noted that the boride precipitate also exhibits a plate-like morphology in this 3-D reconstruction.

The orientation relationships between the β, TiB and α phases have been investigated in detail via OM studies carried out using an EBSD detector. Figure 2(a) shows the overall phase map of one of the regions investigated in the Ti5553-0.5B sample. This map has been pseudo-colored, with the yellow-colored regions corresponding to the boride precipitates, the green-colored regions corresponding to the β matrix phase and the red-colored regions corresponding to the α precipitates. The electron backscatter diffraction patterns as well as transmission electron diffraction patterns (not shown in the figure) from the boride precipitates could be consistently indexed based on the TiB phase with an orthorhombic B27 crystal structure. Three specific regions (1, 2 and 3) from this area of the microstructure have been marked in Figure 2(a) and will be discussed subsequently. Figure 2(b) shows a magnified view of Region 1, including three variants of α precipitates (α_1, α_2 and α_3), none of which appear to be associated with any TiB precipitates. While Figure 2(b) shows a pseudo-colored map of the three α variants, the corresponding $\{0001\}$, $\{11\bar{2}0\}$ and $\{10\bar{1}0\}$ pole figures are plotted in Figure 2(d–f) respectively. Additionally, the $\{011\}$, $\{111\}$ and $\{112\}$ pole figures for the matrix β grain, within which all three α variants appear to have precipitated, are shown in Figure 2(c). All three α variants display a lath-like morphology and clearly exhibit Burgers orientation relationships (ORs) with

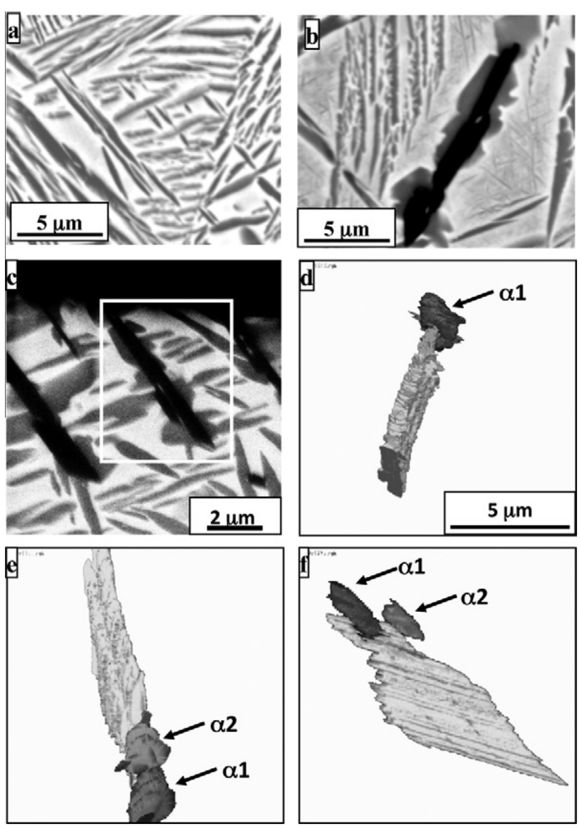

Figure 1. Microstructures of (a) base Ti5553 alloy, (b)Ti5553-0.5B alloy, (c) TiB selected for serial sectioning and (d–f) TiB and associated α in a 3-D view.