



Effects of heat treatment parameters on the microstructure and mechanical properties of *in situ* TiBw/Ti6Al4V composite with a network architecture

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ABSTRACT

In situ 5 vol.% TiB whiskers reinforced Ti6Al4V (TiBw/Ti64) composites with a network architecture were heat treated with different parameters in order to further improve their mechanical properties. The microstructure results showed that the fraction of the transformed β phase in the matrix increases with increasing quenching temperatures, which leads to a significant improvement in strength at room and high temperatures. Both the size and fraction of fine $\alpha + \beta$ phases transformed from martensite phase increase with increasing aging temperatures, which decreases the strength of the composite. When the testing temperature is lower than 600 °C, the strength of the 5 vol.%TiBw/Ti64 composite is significantly enhanced by heat treatment consisting of water quenching and aging processes with proper parameters. This can be attributed to the superior heat treatment strengthening effect on the basis of the network boundary strengthening effect.

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1. Introduction

As a typical member of metal matrix composites (MMCs) family, titanium matrix composites (TMCs) offer a combination of good mechanical properties and high temperature durability that render them attractive materials for automotive, aerospace and military applications [1–5]. Discontinuously reinforced titanium matrix composites (DRTMCs) with a homogenous microstructure, especially those fabricated by *in situ* methods such as powder metallurgy (PM) and cast techniques are sought-after due to their superior properties and low cost [6–10]. However, experimental results in the past 40 years have adequately demonstrated that the composites with a homogeneous reinforcement distribution just can exhibit a limited improvement of mechanical properties, even inferior mechanical properties such as extreme brittleness for the TMCs fabricated by conventional powder metallurgy (PM) [11–15]. Maybe, that is why the previous researches have always focused on the microstructure, hardness, high temperature performance and compressive property without tensile property [6,12]. Tjong et al. [12] has concluded that *in situ* processing techniques offer several advantages such as easy fabrication, lower energy consumption and higher purity of ceramic reinforcements produced comparing to the *ex situ* route. Fortunately, in our previous work [1,2,16–18], not only the strength but also the ductility of the *in situ* DRTMCs is significantly improved by tailoring a novel

network reinforcement architecture compared with those of DRTMCs with a homogeneous reinforcement distribution. This work echoes a recent proposal by Lu [19] that the overall properties of composites can be further enhanced by assembling metals with other components in a controlled way to form novel multi-scale hierarchical structures, compared with a conventional or homogeneous composite structure.

Furthermore, the subsequent treatment can further improve the mechanical properties of MMCs [20–24]. Li et al. [22] pointed out that the tensile strength of (TiB + La₂O₃)/Ti composites increases while the ductility decreases sharply by heat treatment. The heat treatment including solid solution and aging processes, as one of the effective strengthening treatments, can further improve the strength of DRTMCs by strengthening the titanium alloy matrix [22–25]. Furthermore, Mceldowney et al. [23] also pointed out that the highest strength can be obtained by solution and aging processes. Strength is one of the most important characteristics for structural applications for DRTMCs [4]. However, there is little study on the heat treatment strengthening DRTMCs in the past 40 years. The main reason is that the conventional titanium alloy matrix composites with a homogenous microstructure, especially DRTMCs fabricated by PM always exhibit a very low ductility, even extreme brittleness [12–14]. In our previous work, not only the strength but also the ductility of 5 vol.%TiBw/Ti64 composites is significantly improved by tailoring a novel network microstructure [1,2]. Therefore, it is important and necessary to investigate the effects of subsequent heat treatment on these novel composites in order to further improve their mechanical properties.

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2. Experimental procedures

2.1. Composite fabrication

As reported in our previous work [1,2], 5 vol.%TiBw/Ti64 composite with a novel network reinforcement architecture was successfully fabricated by selecting the raw materials consisting of the large Ti64 powders and fine TiB₂ powders and processing by low-energy milling and reaction hot pressing. Fig. 1 shows the network microstructure of the typical 5 vol.%TiBw/Ti64 (200 μm) composite [2]. The synthesized TiB whisker reinforcements were distributed around Ti64 matrix particles and formed a three dimensional (3D) equiaxed network microstructure. Ti64 matrix consists the grey α phase and the bright β phase which is located between α phases.

In order to further investigate the effects of the subsequent heat treatment on the microstructure and mechanical properties of TiBw/Ti64 composites with a novel network microstructure, heat treatment was performed on the typical 5 vol.%TiBw/Ti64 (200 μm) composite with a network microstructure. Water quenching (WQ) was carried out at 840–930 °C and aging at 500–580 °C, which corresponds to the heat treatment parameters of Ti64 alloy shown in Fig. 2 [26]. As shown in Fig. 2, the α phase of Ti64 alloy begins to transform to β phase at 600 °C and thoroughly transforms to β phase at 985 °C. When the quenching temperature is higher than 800 °C, partial β phase can transform to martensite phase. Therefore, the quenching temperature has been selected higher than 800 °C, and the aging temperature lower than 600 °C.

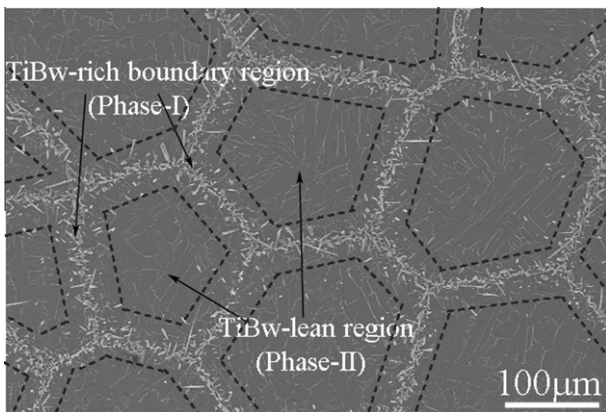


Fig. 1. SEM micrograph of the *in situ* 5 vol.%TiBw/Ti64 composite with a network TiBw distribution [2].

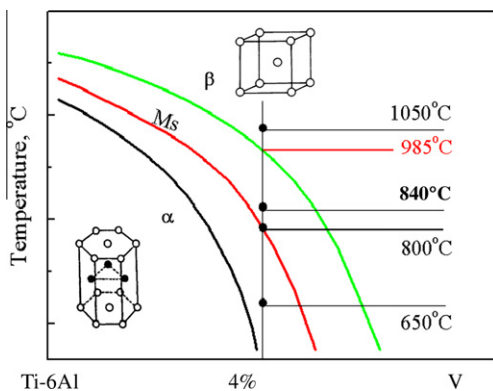


Fig. 2. Schematic illustration of martensitic phase transformation of Ti64 alloy [26].

Microstructural characterizations were performed using a scanning electron microscope (SEM, Hitachi S-4700). Room temperature and high temperature tensile tests, which refers to the metal materials testing standards of ISO 6892: 1998 [27] and ISO 783: 1999 [28], were carried out using an Instron-1186 universal testing machine at a constant crosshead speed of 0.5 mm/min (approximate strain rate is 5.0×10^{-4} /s). A total of five tensile samples with dimensions of 15 mm × 5 mm × 2 mm were tested for each sample.

3. Results and discussions

3.1. Microstructure

Fig. 3 shows the schematic illustrations of the microstructure evolution of Ti64 alloy during different heat treatment processes. It can be seen that the primary α phase is converted into hot temperature β phase during heating process (Figs. 2 and 3), and the fraction of β phase increases with increasing the heating temperatures. During this process, the content of Al element in both the decreased α phase and the increased β phase increases due to the decreasing fraction of α phase [26]. In the following WQ process, martensite α' phase is formed from the high temperature β phase, and the fraction of martensite phase increases with increasing the quenching temperatures [22–26]. It is certain that there is a partial residual β phase remained [26]. The martensite phase and the residual β phase compose the transformed β phase, marked as β_T. During the final aging process, a partial martensite α' phase disintegrates into fine α + β phases, and the fraction and the size of the fine α + β phases increase with increasing the aging temperature [22–24].

Fig. 4 shows the SEM micrographs of the composite samples by WQ at 840 °C and 870 °C followed by aging at 500 °C for 6 h. After heat treatment, the bright β phase in the previous Ti64 matrix is converted into the transformed β phase, which consists of the residual β phase, martensite α' phase formed in the WQ process and the disintegrated fine α + β phases transformed during the aging process (Figs. 3 and 4). Comparing Fig. 4 with Fig. 1, the volume fraction of β_T in the as-heat treated composite is much higher than that of the stable β phase in the original composite. Fig. 4 also indicates that the volume fraction of β_T increases with increasing the WQ temperature. These phenomena are consistent with the schematic illustrations of Ti64 alloy (Fig. 3). In Mceldowney's work [23], the authors also found that the α grain size, volume fraction and morphology of primary α phase, transformed β phase can be influenced by heat treatment with different parameters. After the heat treatments, the increasing transformed β phase must lead to the enhancement of the hardness and strength of the Ti64 matrix in the present work according to the previous similar system [22,23]. In addition, the contrast between the primary α phase and the transformed β phase decreases with increasing the quenching temperature, which indicates the increasing fraction of the martensite and the decreasing fraction of the residual β phase in β_T. Increasing the fraction of the martensite is beneficial to the hardness and the strength of the composite [22–25].

Fig. 5 shows the SEM micrographs of 5 vol.%TiBw/Ti64 composite undergone WQ at 900 °C and aging at 500 °C and 580 °C for 6 h. As shown in Fig. 5, the volume fraction of β_T has no evident change due to the same quenching temperature. However, the contrast between the primary α phase and the transformed β phase increases with increasing the aging temperature, which can be attributed to that the disintegrated fine α + β phase transformed from martensite increases with increasing the aging temperatures as shown in Figs. 3 and 5. Moreover, the size of the fine α + β phase increases with increasing the aging temperature, which is consistent with

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