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Effects of heat treatments on the microstructure and mechanical properties of as-extruded TiBw/Ti6Al4V composites

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ABSTRACT

In order to further exploit the superior mechanical properties of *in situ* formed TiBw/Ti6Al4V composites, solution and aging heat treatments were performed on the as-extruded composites. The results show that, with increasing solution treatment temperatures, the volume fraction of primary α phase decreases, while that of the transformed β phase increases correspondingly. Both the size and volume fraction of the fine α and β phases formed from the quenched martensite phase increased with increasing aging temperatures. The hardness and tensile strength of the composites increased on increasing the solution temperature from 930 to 990 °C; however, both decreased on increasing aging temperature from 500 to 700 °C. A superior combination of tensile strength (1365 MPa) and elongation (7.9%) of the as-extruded 5 vol% TiBw/Ti64 composite has been obtained by water quenching from 990 °C and aging at 600 °C for 6 h.

1. Introduction

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 [1,2]. Discontinuously reinforced titanium matrix composites (DRTMCs), especially those fabricated by *in situ* methods are more and more attractive owing to their superior and isotropic properties, easy processing and low cost since the 1990s [3–12]. Furthermore, subsequent treatments such as hot extrusion and heat treatment can further improve the mechanical properties of MMCs [13,14]. 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. However, there have been very few studies on the strengthening of DRTMCs by heat treatment in the past 20 years [15–17]. The main reason is that the conventional titanium alloy matrix composites with homogenous microstructure, especially DRTMCs fabricated by PM, always exhibit a very low ductility, even extreme brittleness. In our previous work, not only the strength but also the ductility of TiBw/Ti64 composites was significantly improved by tailoring a novel network microstructure [1,2]. Therefore, it is important and necessary to investigate the evolution of microstructure and mechanical properties of the as-extruded TiBw/Ti64 composites that have undergone subsequent heat treatments with different parameters in order to further improve their mechanical properties.

2. Experimental procedures

Based on the system of Ti6Al4V and TiB_2 powders, TiBw/Ti6Al4V composites were fabricated by *in situ* reactive hot processing [2]. TiB whiskers were synthesized *in situ* by the reaction between Ti and TiB_2 during the sintering process, and then were distributed around the boundaries of Ti6Al4V matrix particles [2], as shown in Fig. 1(a). The as-sintered TiBw/Ti6Al4V composites were extruded at 1100 °C with an extrusion ratio of 16:1 followed by air cooling. Fig. 1(b) reveals that TiB whiskers were oriented along the extrusion direction after the extrusion deformation. The laminar α phase and β phase were observed from the cross section as shown in Fig. 1(c).

Solution and aging treatments were performed following the hot extrusion process. In the present study, 930, 960 and 990 °C were selected as solution temperatures followed by water quenching (WQ), and the aging temperatures were 500, 550, 600, 650 and 700 °C for 6 h followed by air cooling (AC).

Vickers hardness tests were carried out on an HVS-1000 micro Vickers hardness tester. The test load was 500 g and time of packing was 10 s. Hardness was obtained by measuring the diagonal distance of indentation. Each specimen after being polished on the cross section was tested 15 times at different positions and the average value was obtained (on the cross section of as-extruded TiBw/Ti6Al4V composites, the region of indentation covered both titanium matrix and the TiB whiskers). Room temperature tensile tests were carried out using an Instron-5569 universal testing

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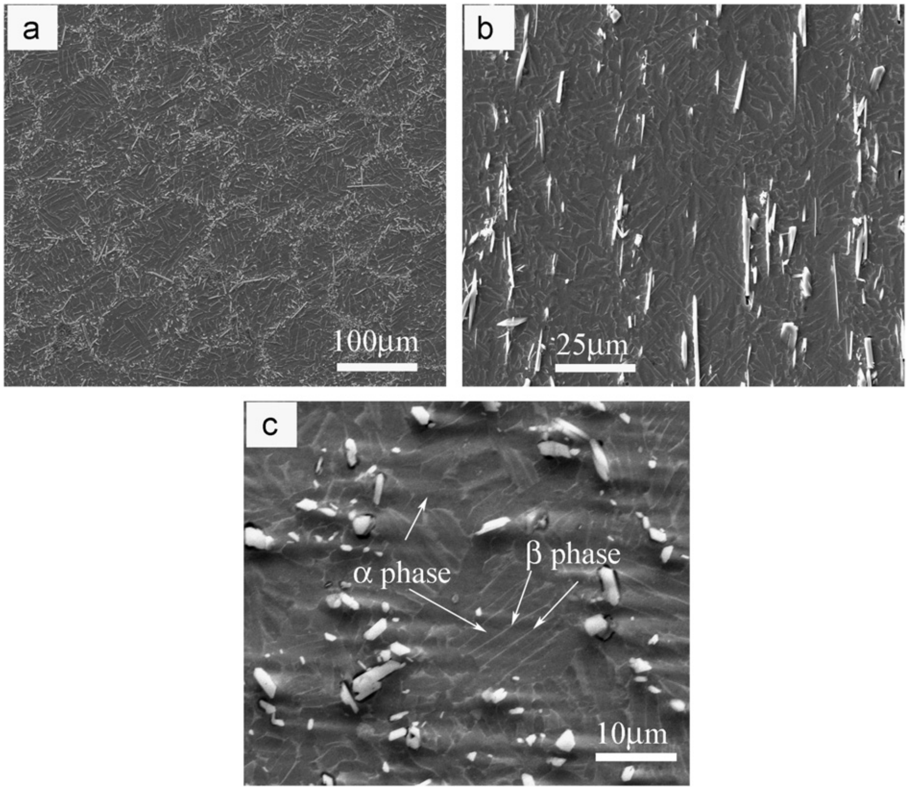

Fig. 1. SEM micrographs of 5 vol% TiBw/Ti6Al4V composites: (a) as-sintered; (b) as-extruded along the longitudinal section and (c) as-extruded along the cross section.

machine at a constant crosshead speed of 0.5 mm/min (approximate strain rate is 5.5×10^{-4}/s). A total of five tensile specimens with dimensions of 15 mm × 5 mm × 2 mm were tested for each composite. Microstructural characterizations were performed using a scanning electron microscope (SEM, Hitachi S-4700) and an optical microscope (OM, Olympus PEM-3).

3. Results and discussions

3.1. Microstructural evolution during the heat treatment

Fig. 2 shows OM images of the as-extruded TiBw/Ti6Al4V composites followed by water quenching from different temperatures. During the solution treatment process, the primary α phase continuously transforms into the β phase until a dynamic balance is reached at a stable temperature. Some of the high temperature β phase converted into martensite α′ phase during the cooling process, and then others remained as the residual β phase. The transformed β phase constituting of α′ phase and the residual β phase is formed during the solution treatment and WQ processes. With increasing solution temperatures, the volume fraction of the primary laminate α phase decreases and that of the transformed β phase increases as shown in Fig. 2. For the sample quenched from 990 °C, the laminate α phase can hardly be observed, as shown in Fig. 2(c). Additionally, the martensite α′ phase converted from the high temperature β phase increases with increasing solution temperatures [18].

Fig. 3 shows the SEM micrographs of the as-extruded TiBw/Ti6Al4V composites quenched from different temperatures of 930, 960 and 990 °C and aged at 500 °C for 6 h. Comparing Fig. 3 with Fig. 1, the volume fraction of the transformed β phase in the heat treated composites is much higher than that of the β phase in the as-extruded composite. Fig. 3 also indicates that the volume fraction of the transformed β phase increases with increasing solution temperatures. The fine α+β phases formed from martensite α′ phase during the aging process are well-distributed in the transformed β phase in which the brighter fine phase is the stable fine β phase. The volume fraction of the fine α+β phases increases with increasing aging temperatures as seen in Fig. 3. This phenomenon indicates that with increasing quenching temperatures the volume fraction of martensite α′ phase increases, while the fraction of the residual β phase in the transformed β phase decreases, which is beneficial to the hardness and the strength of the composites.

Fig. 4 shows the high magnification SEM micrographs of the as-extruded TiBw/Ti6Al4V composite aged at different temperatures for 6 h after quenching from 990 °C. Firstly, it can be seen from the insert image in Fig. 4(a) that the fine α+β phases are well distributed in the transformed β phase after the aging process. Secondly, the fraction of the fine α+β phases increases with increasing aging temperatures as shown in Fig. 4. Thirdly, the size of the fine α+β phases increases with increasing aging temperatures, and the fine α+β phases grow into coarse phases when the aging temperature is higher than 600 °C as shown in Fig. 4. It is certain that the coarsening of the α+β phases is harmful to the hardness and strength of the Ti6Al4V matrix. Additionally, the size of the primary α phase slightly grows after the aging process, as seen by comparing Fig. 2 with Fig. 4(a), and then increases with increasing aging temperatures as shown in Fig. 4. This phenomenon indicates that the martensite α′ phase along the edge of the primary α phase is prior formed into the stable α+β phase. The laminate α phase with a larger size is observed by integrating the disintegrated α phase with the primary α phase, which may be beneficial to the ductility of the composites.

3.2. Mechanical properties evolution during the heat treatment

Fig. 5 reveals the Vickers hardness of the as-extruded 5 vol% TiBw/Ti6Al4V composites quenched from different temperatures