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Dry sliding wear characteristics of in-situ TiBw/Ti6Al4V composites with different network parameters

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ABSTRACT

Ceramics reinforced titanium matrix composites (TMCs) exhibited high specific strength especially with a special network architecture. This study investigated wear characteristics of the novel TMCs with different parameters, the results show that in-situ TiBw enhances hardness and resists abrasion effectively. Meanwhile, the mechanism varied from micro-cutting to brittle debonding with increasing TiBw content, and increasing network size caused the increase of COF and wear loss. Consequently, the composite with 8.5 vol.% TiBw and network size of 60 μm exhibited the best wear properties. Moreover, the subsequent heat treatment further enhanced the abrasion resistance by transformed β phase coexisted with network structure, which resulted in decrease of COF from 0.251 to 0.149 and reduced wear loss by 19.7%.

1. Introduction

Titanium Matrix Composites (TMCs) combine favorable mechanical properties, good corrosion resistance and high temperature durability that make them attractive in aerospace, submarine and automobile domains [1]. Kinds of reinforcements can be applied in titanium matrix, in which the TiBw was widely employed on account of good thermal stability, high elastic modulus and the similar thermal expansion coefficient and density with Ti [2–5]. In addition, the in-situ processed discontinuously reinforced TMCs (DRTMCs) were also developed to obtain a clean matrix/reinforcement interface without chemical reactions [6–8]. However, the composite with unfavorable brittleness and limited strength was usually generated when the reinforcement showed a homogeneous distribution, particularly for the vacuum hot-pressing sintered TMCs [8]. In our previous work, the TiB reinforcements with a novel quasi-continuous network architecture were fabricated and the corresponding composite showed a remarkable enhancement in mechanical properties, not only overcame the brittleness defect, but also effectively improved the strengthening effect [9–11]. Three-dimensional network distribution of reinforcement retained the large and connected matrix particles, which was beneficial for the improvement of ductility. Meanwhile, the branched TiBw could effectively enhance the strength of the DRTMCs. Moreover, the strength and ductility can be further adjusted by regulating the network structural parameters. Therefore, in-situ network structured TMCs are considered as potential candidates in aerospace and automobile applications.

Ti alloys were easily deformed and transferred to the counterparts under sliding wear condition, and their applications were restricted mainly due to the poor adhesion wear properties [12,13]. Most wear-resisting components are made of carbonitrided steels or superalloys with high density, which is not beneficial for reducing weight. Owing to high elastic modulus and hardness of reinforcements, the TMCs as an alternative to conventional wear-resisting materials has been made possible. To achieve this goal, the study on wear behaviors of TMCs should be as important as the tensile properties. However, the relative research has rarely been reported especially for the network structured TMCs. Kim and Choi et al. fabricated (TiB + TiC)/Ti6Al4V composites with a uniform reinforcements distribution by in-situ investment casting process. The sliding wear results showed that improved wear resistance of the TMCs is closely related to the reinforcement content, higher content resulted in less wear loss [14]. They also found that fine reinforcements synthesized with fine B_4C raw powder were more easily fragmented from Ti matrix than the coarse reinforcements. Besides, an adherent transfer layer was formed on the worn surface and produced two-body abrasion [15]. Attar et al. reported that TiB/Ti composite by selective laser melting performed better against sliding wear than pure Ti

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due to higher hardness [16]. Therefore, the wear performance of the promising network structured TMCs is worth investigated. By the way, mechanical properties of the composites can be further improved by heat treatment [17,18]. Mceldowney et al. pointed out that the highest strength can be obtained by solution and aging processes [17]. Our previous work also proved that the strength and hardness of the TMCs can be enhanced by the subsequent heat treatment [19,20], and it is well known that higher strength and hardness result in less wear loss, thus the research about effects of heat treatment on wear resistance of the TMCs is also meaningful.

In this work, TiBw/Ti6Al4V composites with different structural parameters (network size, TiBw content) were synthesized by in-situ powder metallurgical process. Dry sliding wear tests were carried out under various experimental parameters (applied load, sliding velocity). Moreover, the effects of heat treatment (solid solution and aging) on wear resistance of these special TMCs were also investigated. The present research is very useful for TMCs to be used as wear resistance components in aerospace and automobile industries.

2. Experimental procedures

2.1. TMCs fabrication

Spherical Ti6Al4V powders with three different diameters ($D_{50} = 60$, 100, 200 μm) and fine prismatic TiB_2 powders ($D_{50} = 3$ μm) were selected as raw materials in this study. Initially, the powder mixtures were low energy milled in pure argon environment to make the fine TiB_2 powders to be tapped on surface of Ti6Al4V powders, the fabrication details can be found in our previous work [11]. Subsequently, powder metallurgical process was selected to produce the TMCs, these mixed powders were hot pressed in vacuum (7.0×10^{-2} Pa) at 1200 °C under a pressure of 25 MPa holding for one hour to in-situ synthesize TiBw/-Ti6Al4V composites with different structural parameters and pure Ti6Al4V alloy was also manufactured using the same process for comparison.

2.2. Heat treatment

On the basis of the previous work, the quenching temperature for the TMCs should be higher than 800 °C and the aging temperature should be lower than 600 °C [20]. Hence the water quenching (WQ) was performed at 850, 900, 950 °C for half an hour and aging at 500 °C for 4 h to further investigate the effects of heat treatment on the wear properties of the composites.

2.3. Hardness test

The hardness of the samples was measured using a MC010-HRS-150 HRC tester. All the samples were polished with sand paper of grades 100, 400, 800, 1200, 1500 # and then cleaned by alcohol. The hardness tests were carried out with an applied load of 150 kg and a holding time of 6 s, each sample was measured for seven times and take the average value while ignoring the highest and lowest values.

2.4. Dry sliding wear test

Friction and wear tests of the TMCs were performed using a ball on disc type HF-1000 friction and wear tester. The TMCs discs were machined to a diameter of 20 mm and a thickness of 3 mm. First, the samples were polished with sand paper of grades 100, 400, 800, 1200 # and cleaned by alcohol. Then the wear tests were carried out for 30 min in atmospheric environment. The normal load was set to 5, 10 and 15 N and the sliding velocity was set to 400 and 600 r/min. The silicon nitride ceramic ball with a diameter of 6 mm and a hardness of 20 GPa was selected as counterpart, and the diameter of the friction track was 6 mm. The coefficient of friction was directly obtained after wear test. Moreover, each sample was tested for three times and computed the average weight loss.

2.5. Microstructure observation

The microstructures of the TMCs and cross-sections of wear tracks were etched using the Kroll's solution (5 vol.% HF + 15 vol.% HNO_3 + 80 vol.% H_2O) for 8 s and observed using an SEM (SUPRA 55), while the worn surfaces were directly observed by SEM without etching.

3. Results and discussion

3.1. Microstructure analysis

The structural parameters of TMCs were shown in Table 1, the original Ti6Al4V alloy was also fabricated to act as a comparative sample. The TMCs were named according to the volume fraction of TiBw and network size, for example, $V_{8.5}D_{60}$ means the TiBw volume fraction of the composite is 8.5 vol.% and the size of the network scale is 60 μm. Fig. 1 reveals the microstructures of the as-sintered samples. The eutectoid α grains grew along the direction with the least strain energy by hot pressing and finally formed a typical widmanstätten structure with α+β lamellar feature in the as-sintered Ti6Al4V alloy (Fig. 1a). As for the TMCs, phase identification of our previous work [11] revealed that needle-like TiB whiskers were in-situ synthesized on the Ti6Al4V surface and formed a quasi-continuous network distribution during the sintering procedure. Besides, Ti6Al4V particles around TiBw connected well with each other (Fig. 1b), TiBw also hindered the growth of Ti6Al4V matrix grains and obtained the equiaxed or similarly equiaxed matrix. Different network scale (60, 100, 200 μm) has been designed to study its effect on wear properties and the corresponding microstructures are shown in Fig. 1b-d. The local TiBw content increased with the increase of network scale and further caused the reduce of matrix connectivity as shown in Fig. 1d. Moreover, a small number of raw TiB_2 powders were not tapped on Ti6Al4V powder surface, which could not react with Ti alloy and remained in the network boundaries as illustrated in Fig. 1d. In addition, 12 vol.% TiBw/Ti6Al4V composite with a network size of 60 μm were also synthesized (Fig. 1e) to investigate the influence of the reinforcement content on the abrasion properties.

3.2. Friction and wear properties

The friction coefficients of Ti6Al4V alloy and network structural TMCs are shown in Fig. 2. The main difference of the COF is appeared in the steady-state region, and the COF varies as the structural and test parameters change.

Firstly, the wear tests of the composite samples with different structural parameters were carried out under a load of 10 N and velocity of 400 r/min. The average COF of Ti6Al4V, $V_{8.5}D_{60}$, $V_{12}D_{60}$ at steady region were 0.175, 0.164 and 0.143, respectively (Fig. 2a). Hence the COF decreased with the increase of TiBw content. According to Cao's report [21], the elastic modulus and hardness of TiB are 450 and 27.5 GPa by using a nanoindenter directly pressed into TiB phase, which were obviously higher than that of Ti matrix. Thus the addition of TiB would increase the hardness of the TMCs on the basis of the typical rule of mixtures [22]. Therefore, the COF reduced with increasing TiBw content mainly due to the enhanced surface hardness, but the increasing local TiBw content also reduced the matrix connectivity and decreased the plasticity. Moreover, the COF increased with the enlarged network scale, the results showed that COF of $V_{8.5}D_{60}$, $V_{8.5}D_{100}$ and $V_{8.5}D_{200}$ composites were 0.164, 0.182 and 0.188, respectively. The soft matrix areas and the local content of TiBw both increased with the increasing network scale, thus the matrix connectivity was also gradually reduced and resulted in a higher COF. In analogy with grain boundaries, refined grains imply more grain boundaries and cause strengthening effect. The special network boundaries of the TMCs increased with the refined Ti6Al4V matrix scale,