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Dramatically enhanced impact toughness of two-scale laminate-network structured composites

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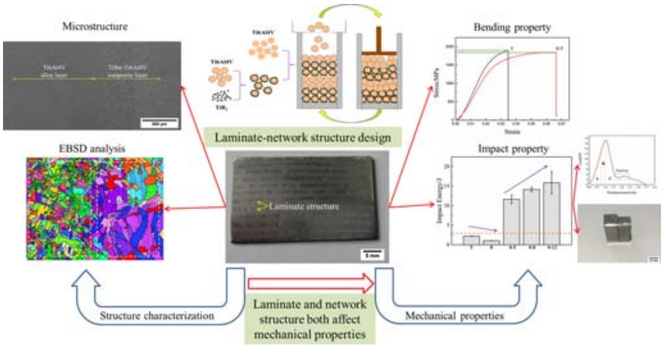
HIGHLIGHTS

- Two-scale laminate-network structure of composites is successfully fabricated by powder metallurgy.
- Bending strain remarkably increases with similar strength, implying a strength-ductile balance is achieved.
- Impact energy is enhanced due to two-scale structure, microstructure refinement and interface crack deflection.
- Increasing reinforcement fraction in two-scale composites can enhance energy in propagation stage during impact process.

GRAPHICAL ABSTRACT



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ABSTRACT

TMCs are well known materials for their potential use in many fields. However, there are few research on the toughness especially impact toughness of TMCs. To improve impact property of TMCs, one novel kind of titanium matrix composites with two-scale laminate-network structure was fabricated via powder metallurgy and reaction hot pressing. From macro-scale, the novel composites were constituted by Ti6Al4V alloy layers and TiBw/Ti6Al4V composite layers. Moreover, the composite layer exhibited network structure and refined matrix microstructure from micro-scale. Layer thicknesses were well controlled by the masses of Ti6Al4V powder and TiB_2-Ti6Al4V mixture powders, and the volume fraction of TiBw reinforcement in the composite layer was adjusted by controlling TiB_2 raw material. Bending test results exhibited that the ultimate strain of two-scale composite doubled while bending strength was similar compared with TiBw/Ti6Al4V composites. The impact toughness of two-scale composites was nearly fivefold enhanced compared with monolithic TiBw/Ti6Al4V composites. This phenomenon can be attributed to the introduction of laminate structure, microstructure refinement and interface crack deflection. The analysis of impact curves and fractographs suggests that introducing Ti alloy layers can enhance plastic stage. Increasing TiBw reinforcement volume fractions can enhance the energy absorbed during crack propagation stage.

1. Introduction

Titanium matrix composites (TMCs) and especially discontinuously reinforced TMCs (DRTMCs) exhibit high specific strength and specific stiffness compared with Ti-based alloy [1], which means the wide application prospect of TMCs in aerospace, military field and sports equipment [2,3]. To strengthen materials, volume fractions of reinforcement adding in TMCs must be increased, thus decreases the plasticity and fracture toughness as a result [1,4,5]. To improve the plasticity of TMCs, Huang et al. [6] developed a class of in-situ TiBw/Ti6Al4V DRTMCs with a network microstructure by powder metallurgy. The ductility of this kind of

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network DRTMCs improved without the loss of strength compared with TMCs with reinforcement distributing homogeneously [7]. Besides ductility, toughness is also an important mechanical property that is worth attention. The balance of strength-toughness is always the goal of an endeavor [8]. Multi-scale structure can be observed [9,10] in biomaterials such as bones and shells which have excellent strength-toughness balance. Therefore, constructing multi-scale structure in TMCs may be able to achieve the balance of strength and toughness.

The introduction of laminate structure seems to be a useful way to improve toughness [11–15]. In metal-intermetallic laminate (MIL) composites, for example Ti-Al_3Ti laminate composites, the introduction of laminate structure and the addition of Ti layer can obtain more than an order of magnitude improvement in toughness values over monolithic Al_3Ti [16]. As for Ti alloys, Ti6Al4V multilayer composites offered an excellent combination of specific strength and toughness [17]. Therefore, it can be speculated that if laminate structure can be created in DRTMCs by introducing ductile layers, the ductility and toughness will be improved. Based on Huang's work, it may be possible to retain ductility and strength and enhance toughness at the same time by the combination of two-scale structure together, the laminate structure and network microstructure.

Liu et al. [18,19] fabricated Ti-TiB/Ti multi-scale TMCs via diffusion welding. The plasticity of this kind of composites improved by nearly 100% compared with the matrix TiB/Ti composites. However, the fabrication process was too complicated and the interface bonding was not good. Wu et al. [20] used hot pressed and hot rolling methods to fabricate TiB/Ti_3Al multi-scale composites with well bonded interface. But the interface oxidation during hot rolling seems to be inevitable, and the control of interface reaction is difficult [21,22]. Considering these drawbacks, finding another way to fabricate multi-scale TMCs is necessary. Powder metallurgy is an ideal method to prepare discontinuously reinforced composites [23,24]. Zhu et al. [24] have fabricated a class of discontinuously reinforced aluminum composites with a sandwich structure via powder metallurgy, and the composites exhibited superior tensile strength and ductility. For DRTMCs in reference [25], the laminate TMCs obtained good interface via powder metallurgy and exhibited nearly 50% improvement of elongation compared with homogeneous ($TiB + La_2O_3$)/Ti composites. Therefore, powder metallurgy is used in this experiment to form a two-scale structure.

The impact toughness is an important property for structural material especially for TMCs that will be used in military and sports fields. The strain rate will influence the mechanical property of materials [26,27]. According to Chichili et al. [28], the effective flow stress of α titanium was sensitive to strain rate. However, research on the impact property and impact mechanism of TMCs is seldom. Cepeda et al. [17] prepared Ti6Al4V multilayer composites and the result proved that the laminate structure can improve impact property to a large extent. Liu et al. [29] prepared Q235 steel and high chromium cast iron composites with a sandwich structure, and the result showed the impact toughness of this composite was almost three times higher than the as cast sample.

In this study, Ti6Al4V and TiB_2 particles were used as raw materials, and powder metallurgy method was used to fabricate two-scale TMCs with laminate structure and network microstructure. The microstructure, bending behavior and impact toughness of the composites were investigated. Subsequently, the impact behavior was explained using impact load-displacement curves and impact fractures.

2. Materials and experimental procedures

2.1. Material system and preparation method

The fabrication of two-scale composites includes three steps as illustrated in Fig. 1. First step was the preparation of two kinds of powders. Large Ti6Al4V powders with an average size of 150 μm and fine TiB_2 particles of 3 μm were used as raw materials. Two kinds of layers were made up by pure Ti6Al4V powder and TiB_2-Ti6Al4V mixture powder. TiB_2-Ti6Al4V powder was obtained via low energy ball milling. The ball milling process was carried out on QM-3SP4J planetary ball mill under argon atmosphere. The ball mill parameters were as followed: ball mill speed of 200 rpm, time of 5 h, and ball to material ratio of 3:1. TiB_2 particles would attach to large Ti6Al4V powders during ball milling process [6].

Next step was stacking powders in a graphite die. A sieve was used to make the powders distribute homogeneously. After finishing stacking one layer, a pressure head was used to ensure this layer flat. In this step, a laminate structure was constructed by stacking different kinds of powders in turn. The thickness of each layer was controlled by the mass of powders according to Eq. (1), where m is the mass of powders in each layer, R the radius of graphite die, h the layer thickness (1 mm in this experiment) and ρ the density of powders.

$$m = \pi \cdot R^2 \cdot h \cdot \rho \tag{1}$$

Finally, the stacked powders were hot pressed in vacuum (10^{-2} Pa) at 1473 K under a pressure of 20 MPa. At this point, the in-situ reaction happened according to Eq. (2) and TiB whiskers (TiBw) were obtained on the boundary of Ti6Al4V powders [7], thus constructed a network microstructure.

$$Ti + 2TiB_2 = 2TiB \tag{2}$$

In this experiment, monolithic 5 vol% and 8 vol% TiBw/Ti6Al4V composites with only network microstructure were prepared for comparison. To simplify expression, “vol%” is omitted and 5 vol% TiBw/Ti6Al4V composites with network microstructure is denoted as “5”. “8” stands for 8 vol% TiBw/Ti6Al4V composites and “0” represents monolithic Ti6Al4V without reinforcement. Similarly, “0–5”, “0–8” and “0–12” represent laminate-network structure Ti6Al4V-TiBw/Ti6Al4V composites with 5 vol%, 8 vol% and 12 vol% TiBw in composite layer. The volume fraction of TiBw in TiBw/Ti6Al4V was controlled by the weight percentage of TiB_2 [30], and the 5 vol%, 8 vol% and 12 vol% composites were fabricated by adding 2.94 wt%, 4.71 wt% and 7.05 wt% TiB_2 powders respectively.

2.2. Microstructure examinations

The microstructure morphology of the composites was characterized by scanning electron microscopy (SEM, SUPRA 55 SAPPHIRE) and samples for observation were etched in Kroll's solution. Grain sizes and strain distribution were analysed by electron backscatter diffraction (EBSD) of SEM, and the samples were prepared via electrochemical polishing using an electrolyte consisting of 20 ml perchloric acid ($HClO_4$), 60 ml butyl glycol ($C_6H_{14}O_2$) and 180 ml methanol (CH_3OH).

2.3. Mechanical property tests

Three point bending tests were carried out using an Instron-5569 universal testing machine at a constant crosshead speed of 0.5 mm/min. The dimension of specimens was 5 mm × 5 mm × 35 mm. The relative densities of composites were measured by Archimedes method using three-point bending specimens. Charpy V-notched impact specimens with a dimension of 10 mm × 10 mm × 55 mm were carried out on the drop hammer test machine (Instron-9250HV) at room temperature. For both bending and impact tests, the loading direction was perpendicular to the direction of layer thickness (crack arrester orientation, though there is no crack on bending specimen). For each kind of test and each material, at least three specimens were tested.