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Short communication

Superior ductility in as-cast TiC/near-α Ti composite obtained by three-step heat treatment

J.Q. Qi [a], Y.W. Sui [a], Y. Chang [a], Y.Z. He [a, *], F.X. Wei [a], Q.K. Meng [a], Z.J. Wei [b]

[a] School of Materials Science and Engineering, China University of Mining and Technology, Xuzhou 221116, People's Republic of China
[b] School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, People's Republic of China

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ABSTRACT

In this paper, three-step heat treatment was developed and performed on 8vol.%TiC/Ti−5.8Al−2Zr−1.3Mo−1V composite prepared by *in situ* casting route. This heat treatment leads to significant changes in microstructure and tensile properties. Matrix microstructure was refined obviously and fine TiC particles with average diameter of 3.6 μm were obtained. The tensile strength and elongation are all improved at room temperature and 600 °C and room-temperature elongation increases to 5.86%.

1. Introduction

Titanium matrix composites have attracted much interest due to the enhancement in mechanical properties, especially in high strength and excellent creep resistance at high temperatures [1,2]. Improvement in these properties makes them the optimal candidate materials for commercial automotive, aerospace and military applications [1,2]. The research on TiC particle reinforced titanium matrix composites (TiC-TMCs) is of increasing interest [3,4]. However, low room-temperature ductility of TiC-TMCs is the main factor restricting their wide applications [5]. High temperature heat treatment is an effective method to improve microstructures and mechanical properties of TiC-TMCs castings with complicated structure [6,7]. TiB reinforced TMCs with high volume fraction of reinforcement possess high hardness, high Young's modulus and shear modulus [8]. In these composites, TiB is prone to grow into whisker [8], which can not be changed by single high temperature heat treatment. Research pointed out that TiC can be spheroidised after heat treatment and spheroidised particles are beneficial for the increase in ductility [6]. However, TiC particles are prone to be coarsened during high temperature heat treatment [7]. Hence, it is necessary to develop new heat treatment process to further enhance the ductility of TiC-TMCs.

In this study, three-step heat treatment was exploited and performed on a as-cast 8 vol.% TiC/Ti-5.8Al−2Zr-1.3Mo−1V composite. The main objective is to evaluate the influence of three-step heat treatment on microstructure and tensile properties.

2. Experimental procedure

In this paper, 8 vol.% TiC/Ti-5.8Al−2Zr-1.3Mo−1V composite was fabricated by VIM furnace. The composite melt was cast into a machined graphite mould to form composite flake casting with length, height and thickness of 200 mm, 200 mm, and 12 mm, respectively. The detailed fabrication process was described in our previous article [9].

The measured β-transus temperature of this composite through metallographic techniques is approximately 1095 °C [10]. The specimens for heat treatment were all first heated to 1120 °C and held for 10h. Some samples were cooled in air directly. This type of heat treatment is so called β heat treatment, referred to as HT1 here. The other specimens were cooled to 1045 °C about 50 °C lower than β-transus temperature and held for 30h. Subsequently, these specimens were directly put into a resistance furnace with temperature of 1120 °C and held for 5min. Then, these specimens were cooled in a furnace with temperature of 400 °C. This three-

* Corresponding author.
E-mail address: hyz0217@hotmail.com (Y.Z. He).

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step heat treatment is referred to as HT2.

Microstructures are observed by FEI Quanta 200F SEM. Flat tensile specimens with gauge length of 20 mm and cross section of 4 mm × 2 mm were carried out on an Instron 5500R testing machine with a strain rate of 0.5 mm/min at room temperature, 600 °C and 650 °C, Hitachi S-570 SEM was used to analyze the fracture surfaces of failed composites.

3. Results and discussion

Fig. 1 shows the X-ray diffraction patterns of the as-cast composite. The peaks of TiC and α-Ti can be seen in Fig. 1, meaning that *in situ* casting technique is feasible to fabricate TiC-TMCs.

Fig. 2 displays the microstructural characteristics of the composite before and after heat treatment. In as-cast state, primary TiC shows equiaxed or near-equiaxed shape with diameters of 3–9 μm, whereas eutectic TiC exhibits fine granular and strip shape in Fig. 2(a). Typical α-β colony structure with some extent of basket-weave characteristic can be seen in the matrix microstructure. The sizes of α lath and α colony measured are 1.3 μm and 14.5 μm, respectively.

After β heat treatment (HT1), eutectic TiC with fine granular and strip shape disappeared and a large number of spherical particles are observable (see Fig. 2(b)). TiC particle size in Fig. 2(b) measured is in the range of 1–11 μm and the average diameter is 7.6 μm. Basic matrix characteristic of the composite via HT1 in Fig. 2(c) is similar to that in Fig. 2(a). However, α lath and α colony are evidently refined and their average sizes are 0.3 μm and 11.2 μm, respectively. After three-step heat treatment (HT2), TiC particle still displays equiaxed shape but their sizes decrease remarkably with the average diameter of 3.3 μm (Fig. 2(d)). Matrix of the composite via HT2 shows fully lamellar structure with average α lath width and α colony size of 0.7 μm and 19.3 μm, respectively, (see Fig. 2(e)).

The evolution of microstructure of the composite via HT2 heat treatment can be divided into three stages. Firstly, as the composite was heat-treated in β phase field, TiC particles are spheroidised and then their sizes increase because of Oswald ripening mechanism, which can be confirmed by the result in Fig. 2(b). Secondly, when the composite was cooled from above β-trans temperature to a temperature 50 °C lower than β-trans temperature and hold at this temperature, most of β phase is transformed into α phase. More importantly, C at the surface of TiC particles diffuses into α phase during the process of heat preservation at 1045 °C since the discrepancy of the solid solubility of C in α phase and β phase is huge. As a result, substantial TiC dissolves into matrix, leading to the decrease in TiC particle size.

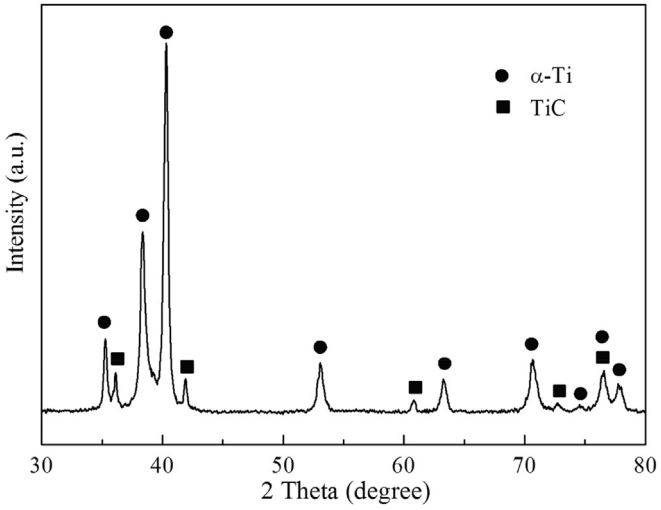

Fig. 1. X-ray diffraction patterns of the as-cast composite.

Finally, as the composite was heated to β phase district rapidly, transformed α phase is transformed into β phase also rapidly. Meanwhile, TiC precipitates from matrix and in this process TiC nucleates and grows again. Similar result was reported by Zhang et al. [11]. Owing to fast heating and short holding time, TiC has no time to grow up, resulting in the formation of fine TiC particles. At last the composite was cooled in a furnace with temperature of 400 °C with the purpose of decreasing the cooling rate. Because of this, α phase size in the composite via HT2 is larger than that in the composite via HT1 (Fig. 2(c) and (e)).

It should be noted that all temperatures used in three-step heat treatment are wide ranges. The temperature in the first step should be higher than β-trans temperature but should not be 50 °C higher than β-trans temperature since β grains are prone to coarsen at higher temperatures. Heat treatment temperature in the second step should be 40 °C lower than β-trans temperature. The lower the temperature is, the higher the content of α-Ti is. However, if the temperature is too low, the diffusion rate of carbon element will be very slow. Correspondingly, the heat treatment time will be very long. The temperature in the last step should also be higher than β-trans temperature. The higher the temperature is, the shorter the holding time is.

Table 1 presents the tensile properties for both as-cast and heat-treated composites at room temperature, 600 °C and 650 °C, which are all average values. In comparison with as-cast state, HT1 heat treatment can enhance yield and ultimate tensile strengths (YS and UTS) at the expense of tensile ductility (Table 1). The composite after HT2 heat treatment exhibits very high room-temperature elongation, which reaches to 5.86%. Meanwhile, the YS and UTS are all improved compared with those in the as-cast specimen. The YS and UTS of the composite via HT1 are a little higher than those of HT2 heat treatment (Table 1).

In the view of some researchers, the role of matrix strengthening is often dominant in the enhancement of tensile strength [12]. After HT1 heat treatment, the improvement of YS is mainly attributed to the obvious refinement of α lath and α colony at room temperature [13]. Similar result was obtained in Ti–6Al–4V–B alloys [14]. The increased α phase size after HT2 heat treatment results in the relatively low YS compared to that via HT1 (Fig. 2(c) and (e)).

It is well established that the refinement of α lath is beneficial for the enhancement of the ductility in titanium alloys with the lamellar structure [14,15]. Furthermore, spheroidised TiC particles are also in favor of the increase in ductility of TiC-TMCs [6]. Hence, the specimen via HT1 should possess very high tensile elongation. However, the elongation increases slightly after HT1 heat treatment. This result should be due to the present of TiC particles since TiC particle fracture dominates the damage of TiC-TMCs at room temperature [9].

Particle fracture is the main feature in fracture surface of the composite via HT1, as shown in Fig. 3(a). Based on Nardone et al.'s research [16,17], the improvement in tensile strength can give rise to the increase in the local stresses acting on TiC particles. In addition, the number of large particles increase after heat treatment (Fig. 2(b)). More importantly, TiC particle size has important influence on room-temperature ductility of TiC-TMCs. As a result, the fracture probability of TiC particles, especially those with large size, is enhanced. It is believed that cracks in fractured large reinforcements will spread into the matrix rapidly, which restricts the further increase in tensile elongation. Based on analysis above, α phase size should be controlled in order to enhance tensile ductility, which mainly depends on cooling rate. Hence, a new