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The effect of heat treatment on mechanical properties of *in situ* synthesized 7715D titanium matrix composites

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ABSTRACT

7715D titanium matrix composites (TMCs) reinforced with TiB, TiC and La_2O_3 were *in situ* synthesized by common casting and hot-forging technology. Two kinds of heat treatments were adopted. Fully lamellar microstructures and equiaxed microstructures were obtained by annealing in β and α + β phases, respectively. The tensile properties of the composites at both ambient and elevated temperatures and also the creep rupture properties were tested. The TMCs with fully lamellar microstructures show superior comprehensive properties in comparison with those with equiaxed microstructures. Lamellar microstructure retarded the crack propagation which originated from cracked whisker more effectively. The strengthening effect of reinforcements can be given full play for the composites with lamellar microstructures.

1. Introduction

Discontinuously reinforced titanium matrix composites (TMCs) have considerable potential for improvement in properties and service temperature because of their high strength, excellent wear resistance and high temperature durability, which extends the application field such as aerospace, advanced weapon system and automotive [1–3]. Due to the favorable balance of stiffness, stability, and similarity of heat expansion coefficients, TiB_w and TiC_p are considered as most effective ceramic reinforcement for titanium alloys [4–6]. A novel processing techniques based on the *in situ* production of titanium matrix composites has attracted more attention because of the excellent interfacial bonding, ease of fabrication and low cost [7–10]. Rare earth elements (RE) are considered favorable in high-temperature alloys because RE can absorb the oxygen in the matrix and refine the microstructure [11]. Based on this, LaB_6 is preferred as a reactant during the fabrication of *in situ* synthesized TMCs [12].

7715D titanium alloy serve as an important structural material for aero-applications at the temperatures up to 600 °C. For higher serving temperatures, TiB whiskers and TiC particles are added to improve its mechanical properties. In our previous studies, *in situ* synthesized 7715D TMCs with lamellar structures have excellent creep resistance [13], and those with equiaxed structures obtain good superplasticity with maximum elongation 802% at 10^{-3} s^{-1} and 1050 °C [14]. However, the effect of lamellar and equiaxed microstructures on mechanical properties of 7715D TMCs at ambient and elevated temperature have been investigated little.

In this paper, three types of 7715D TMCs were *in situ* synthesized. Equiaxed α + β microstructures and fully lamellar microstructures are obtained through different heat treatments. The mechanical properties of TMCs with these microstructures at ambient and elevated temperature were studied in details.

2. Experimental procedures

In this study, grade I sponge titanium, B_4C powder and LaB_6 powder are chosen as raw materials for synthesizing TMCs. Alloying materials for synthesizing 7715D matrix alloy are TiSn (65% Sn), AlMo (50% Mo), AlCe (50% Ce), AlNb (50%Nb), Al, Zr and Si. Stoichiometric amounts of sponge titanium, B_4C, LaB_6, and alloying elements are blended and melt in a consumable vacuum arc-remelting furnace. *In situ* synthesized TMCs fabricated by vacuum arc re-melting (VAR) based on the reaction as follows [12]:

$$12Ti + 2LaB_6 + 3[O] = 12TiB + La_2O_3 \quad (1)$$

$$5Ti + B_4C = 4TiB + TiC \quad (2)$$

$$Ti + C = TiC \quad (3)$$

The weight percentage of reactants and volume percentage of products are listed in Table 1. The actual values have been derived using Rietveld refinements on XRD patterns. For TMC1 and TMC2, only the reaction (1) took place. But for TMC3, the reactions (1)–(3) all took place.

To ensure the homogeneity of composition, the ingot was remelted twice. After casting, the ingots were hot-forged at 1150 °C

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Table 1
Volume fractions of reinforcements in 7715D titanium matrix composites.

Specimen	Reactants (wt.%)			Reinforcement (vol.%)					
				Nominal values			Actual values		
	LaB_6	B_4C	C	TiB	TiC	La_2O_3	TiB	TiC	La_2O_3
TMC1	0.20	–	–	0.39	–	0.11	0.30	–	–
TMC2	0.72	–	–	1.42	–	0.40	1.28	–	0.32
TMC3	0.72	0.36	0.19	3.09	1.21	0.40	2.10	0.90	0.36

and rolled at 1000 °C. The final rods are about 15 mm in diameter with the reduction of 90% in cross-section area. Two different heat treatments (HT) were carried out for the TMCs and the details were listed in Table 2. The specific β transus temperature for TMC1, TMC2 and TMC3 are 1000, 1020 and 1095 °C, respectively.

Phase identification was carried out via X-ray diffraction (XRD) using a D-max IV A X-ray diffractometer at 25 °C under the conditions of Cu Kα, 35 kV, and 40 mA. Microstructure observations were carried out by optical microscope (OM). The specimens were prepared using conventional techniques of grinding and mechanical polishing. The specimens were etched with 5 ml HF, 10 ml HNO_3 and 85 ml H_2O. Specimens with a gauge section of Ø6 mm × 30 mm were tested on MTS-810 at ambient temperature. High-temperature specimens with a gauge section of 4 mm × 2 mm × 16 mm were prepared from the above bars by electro-spark wire-electrode cutting. The high-temperature tensile tests were performed on a CSS-3905 test machine at 600, 650, and 700 °C with strain rate of 10^{-3} s^{-1}. Specimens for creep behaviors test with a gauge section of Ø5 mm × 25 mm were also conducted on CSS-3905 test machine with 150 MPa stress at 650 and 700 °C. JSM-6700F scanning electron microscope (SEM) was used to examine fracture surfaces of the tensile specimens as well as the morphology of the fractured reinforcement along the load sections.

3. Results and discussion

3.1. Microstructural characterization

Fig. 1 shows the XRD patterns of the TMCs after rolling. It can be concluded that TiB, TiC and La_2O_3 were *in situ* synthesized successfully. Compared with TMC1, the increased intensity of TiB peaks reflects more volume fraction of TiB in TMC2.

The microstructures of TMCs via heat treatment 1 (HT1) and heat treatment 2 (HT2) are shown in Fig. 2. TMCs obtained equiaxed and fully lamellar structures via HT1 and HT2, respectively. Through image analysis of micrographs, the volume fractions values of α phase are 90%, 92% and 96% for TMC1, TMC2 and TMC3, respectively. The volume fraction of equiaxed α becomes larger with the increase of volume fraction of reinforcements. This can be attributed to the significant increase of the β transus temperature. As α stabilizers, both boron and carbon have increased the β transus temperature [15,16], and the equilibrium volume fraction of α phase increases along with the enrichment of α stabilizers at the same temperature.

Table 2
Heat treatments on 7715D titanium matrix composites.

Condition	Description	Specimen
HT1	Solution treated at 980 °C for 1 h, air cooled and aged at 570 °C for 3 h, air cooled	TMC1
		TMC2
		TMC3
HT2	Solution treated at the temperature which is 20 °C above the β transus temperature for 1 h, air cooled and aged at 570 °C for 3 h, air cooled	TMC1
		TMC2
		TMC3

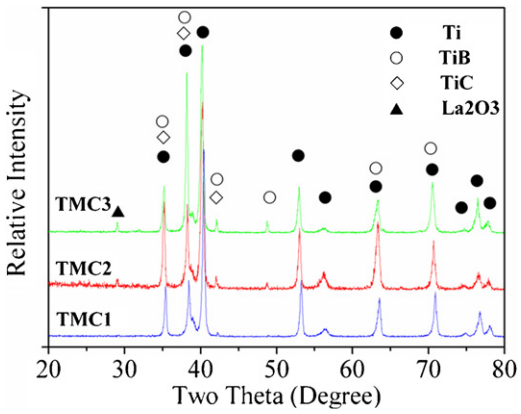

Fig. 1. X-ray diffraction patterns of the TMCs after rolling.

Fig. 2(d)–(f) shows fully lamellar microstructures of TMCs formed via HT2. Our previous studies [8,9] indicated that the short fibers are TiB and the near-equiaxed particles are TiC. La_2O_3 cannot be clearly observed in the optical microscopy as the La_2O_3 particles in TMC are extremely refined [12]. Compared with TMC1, the alpha lamina colonies of TMC2 are refined. Considering the solidification process and following annealing treatment, more boron elements caused constitutional super-cooling which refined the grains of matrix in casting process [15] and more TiB whiskers impeded the growth of β grains during the following β-annealing process [17]. Through image analysis of micrographs (Fig. 2(d–f)), the aspect ratios of α lath are 22.4, 14.9 and 9.2 for TMC1, TMC2 and TMC3, respectively. In general, the width of α lath is determined by the cooling rate from the homogenization temperature, however the α lath of TMC3 is much thicker than those of TMC1 and TMC2 although they were at the same cooling rate. In this study, the Al atom of 7715D alloy plays the role of interstitial atom, so the layered ternary Ti_2AlC which always forms in TiAl alloys can hardly form [18,19]. In previous studies [8–17], during β-annealing process, there is no intermediate in the matrix. The different width of α lath may be explained by the addition of carbon element which related to the recrystallization kinetics in the (α + β) two-phase field, as the diffusion rate of interstitial carbon is much faster than that of other stabilizers (Al and Mo) during the recrystallization which facilitate the growth of α lath.

3.2. Tensile properties

The detailed tensile properties of TMCs at ambient temperature are shown in Table 3. With the increase in volume fraction of reinforcements, the Young's modulus, yield strength and ultimate tensile strength of TMCs are improved for both equiaxed microstructures and lamellar microstructures. TMC3 have obtained the highest strength at the expense of ductility due to the addition of carbon element. In this study, as the volume fraction of TiC par-