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Superplasticity of coarse-grained (TiB + TiC)/Ti–6Al–4V composite

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ABSTRACT

Superplastic deformation of coarse-grained (TiB + TiC)/Ti–6Al–4V composite was carried out at 840–980 °C and 10^{-4} to 10^{-2} s^{-1} in comparison with that of Ti–6Al–4V alloy. The composite had the same optimum superplastic temperature and strain rate as Ti–6Al–4V alloy did. A maximum elongation 462% of the composite was obtained at 920 °C and 10^{-3} s^{-1}. Based on the microstructure evaluation and the value of activation energy, superplastic mechanism and accommodation mechanism in superplastic deformation of the composite was discussed.

1. Introduction

Titanium matrix composites (TMCs) have became more and more potential for structural applications on aircrafts due to their outstanding combination of high specific strength and elevated temperature resistance and stiffness [1,2]. Compared with continuous-reinforced TMCs, discontinuous-reinforced TMCs possess isotropic behavior, ease of fabrication and low cost. In situ synthesized discontinuous-reinforced TMCs have attracted great attention because of their strong matrix-reinforcement bond, little contamination, ease of fabrication, and low cost [3–14]. The in situ synthesis methods include self-propagation high-temperature synthesis (SHS) [3,4], powder metallurgy (PM) [5–7], mechanical alloying (MA) [8], rapid solidification process (RSP) [9,10], ingot metallurgy (IM) [11–14], etc. TiB and TiC particulates have been considered as the two best reinforcements in the titanium matrix due to their high elastic modulus, high thermal stability, similar density with titanium alloys, and excellent interfacial bonding with titanium matrix [11]. The mechanical properties of in situ TMCs were enhanced significantly. The yield strength (YS) and the ultimate tensile strength (UTS) of the 15 vol.% TiC/Ti–6Al–4V composite are however about 100 MPa higher than those of Ti–6Al–4V at all temperatures [5]. The average Young's modulus of composite with 20 vol.% of aligned TiB whiskers was 169 GPa along the extrusion axis, compared to 109 GPa for unreinforced Ti–6Al–4V [6]. YS and UTS of 5 vol.% (TiC + TiB)/Ti–6Al–4V increased 8.3% and 14.5% than those of Ti–6Al–4V alloy [12]. The creep rupture life of the 8 vol.% (TiB + TiC)/Ti6242 was significantly higher than that of the matrix alloy throughout the ranges of stress and temperature [13]. A large amount (over 30 vol.%) of hard precipitates TiC and TiB improved the hardness and wear resistance of the surface composite layer 2 times and 6–9 times, respectively, greater than that of the substrate Ti–6Al–4V alloy [14]. However, the high hardness and wear resistance of ceramic reinforcements limit their machinability. Superplastic forming as a near-net-shape technique has generated strong interest for particles-reinforced composites [15–18]. Schuh and Dunand studied transformation superplasticity of TiB/Ti–6Al–4V [19] and TiC/Ti–6Al–4V [20] composites. Wang et al. reported fine-grained superplasticity of (TiB + TiC)/Ti1100 [21,22] and TiC/7715D composites [23]. In this paper, the superplastic deformation and microstructure evaluation of coarse-grained (TiB + TiC)/Ti–6Al–4V composite was investigated in comparison with those of Ti–6Al–4V alloy.

2. Experimental procedure

In this study, (TiB + TiC)/Ti–6Al–4V composite was prepared by common casting technique based on the following in situ reactions [2,12,13]:

$$5Ti + B_4C \rightarrow 4TiB + TiC \quad (1)$$

$$Ti + C \rightarrow TiC \quad (2)$$

The composite with 5 vol.% reinforcements (mole ratio of TiB and TiC is 1:1) was fabricated by consumable vacuum arc remelting. A stoichiometric ratio of sponge titanium, AlV alloy, pure Al, B_4C powder and graphite powder were blended thoroughly and melted homogeneously. The ingots were melted twice to ensure chemical homogeneity. After casting, the ingots were hot-forged into a rod of 25 mm in diameter. The total deformation degree was over 90%. For comparison, Ti–6Al–4V

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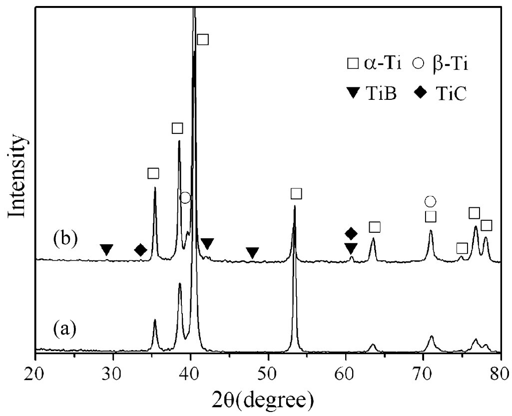

Fig. 1. X-ray diffraction patterns of Ti–6Al–4V alloy and the composite.

alloy was fabricated and processed in the same way. Phase identification was performed by a Siemens D-500 X-ray diffractometer (XRD).

The alloy and composite were annealed at 920 °C and 960 °C for 1 h, respectively, to obtain stable and coarse-grained microstructure. The superplastic tensile specimens were cut with axes parallel to the hot-forging direction. The gauge section of the specimen was 4.4 mm × 1.6 mm × 8 mm. Superplastic tensile tests were carried out in air on a SHIMADZU AG-10KNA test machine. The testing temperatures ranged from 800 °C to 980 °C and the initial strain rates ranged from $10^{-4}\,s^{-1}$ to $10^{-2}\,s^{-1}$. All specimens were coated by enamel to resist oxidization. The samples for optical microscopy were prepared using conventional grinding and mechanical polishing techniques. The polished samples were etched in Kroll's reagent (composition: 1–3 ml HF, 2–6 ml HNO_3 and 100 ml water). Optical microstructure (OM) was observed on an OLYMPUS BX41M optical microscope. The samples for transmission electron microscope (TEM) were electropolished using a twin-jet electropolisher at 50 V in a solution consisting of 300 ml methanol, 175 ml 2-butanol and 30 ml perchloric acid (70%). The temperature of the solution was controlled in a range −40 to −50 °C. TEM observation was conducted on a Philips CM200 transmission electron microscopy.

3. Results and discussion

3.1. Phase identification

Fig. 1 shows the X-ray diffraction patterns of Ti–6Al–4V alloy and the composite. There were only α-Ti, β-Ti, TiB and TiC phases in the composite. It can be concluded that TiB and TiC reinforcements were in situ synthesized successfully.

3.2. Original microstructures observation

The annealed microstructures of Ti–6Al–4V alloy and the composite are shown in Fig. 2. The mean grain sizes of Ti–6Al–4V alloy and the composite are about 11 μm and 14 μm, respectively. Traditionally, the grain size of fine-grained Ti–6Al–4V alloy is smaller than 10 μm [24]. In general, TiB appears whisker-like shape while TiC displays particulate-like feature. The different shapes of the reinforcements are related to their crystal structures [13]. TiB has a B27 structure, so it grows faster along the (0 1 0) direction than normal to the (1 0 1) and (1 0 0) planes, thus leading to a whisker-like morphology. TiC exhibits a NaCl-type structure with symmetric framework, which leads to particulate-like morphology. Fig. 2(b) shows the reinforcements distribute homogenously on the matrix of the composite.

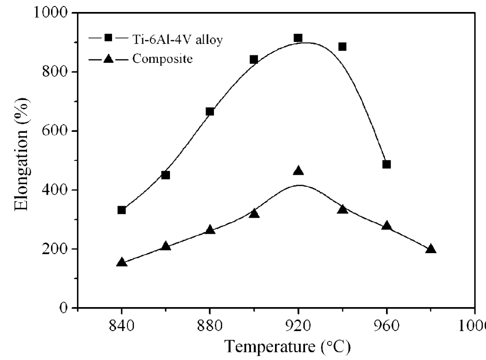

Fig. 3. The elongation of Ti–6Al–4V alloy and the composite as functions of testing temperature at $10^{-3}\,s^{-1}$.

3.3. Superplastic deformation behavior

Fig. 3 shows the elongation of Ti–6Al–4V alloy and the composite as functions of testing temperature at $10^{-3}\,s^{-1}$. The alloy exhibits good ability of superplastic deformation and obtains the maximum elongation 914% at 920 °C. The composite obtains its maximum elongation 462% at the same temperature. The reinforcements and the coarse microstructure significantly reduce the superplastic elongation of the composite. However, the optimum superplastic temperatures of the two materials are identical.

Fig. 4 shows the elongation of Ti–6Al–4V alloy and the composite as functions of initial strain rate at 920 °C. The two materials have the same change law with the initial strain rate. The elongation of the composite first increases and then decreases with increasing initial strain rate as the alloy behaves. The optimum superplastic strain rates of the two materials are also identical.

The profiles of fractured specimens of Ti–6Al–4V alloy and the composite are illustrated in Fig. 5. The gauge section of the composite specimens deformed uniformly, even at the maximum elongation 462%. The fracture of Ti–6Al–4V alloy is thin and the reduction of area is very large. However, the necking phenomenon on the composite specimens is not obvious. That is to say, the

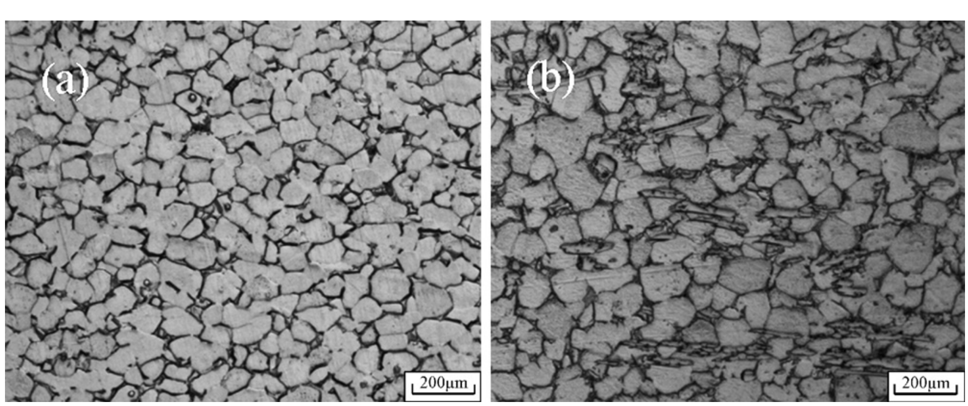

Fig. 2. Recrystallization microstructures of Ti–6Al–4V alloy and the composite.