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Effect of carbon content on microstructure and property of TiC/Ti-6Al-4V composites

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Abstract: TiC reinforced Ti-6Al-4V matrix composites were fabricated by consumable arc-melting technology utilizing the reaction between titanium and graphite. The phase composition, microstructure and hardness of the TiC/Ti-6Al-4V composites were investigated by XRD, SEM and hardness testing equipment, respectively. The results show that the reinforcements are distributed uniformly in the matrix alloy. With the carbon content of the composites increasing from 0.15% to2.0%, the morphology of TiC transforms from particle into short-bar shape or chain-type consisting of featheriness or wheat-shape and finally into dendritic. Simultaneously, the hardness of the composites increases. The formation mechanisms of TiC can be analyzed as follows: the growth of dendritic primary TiC before the peritectic reaction is dominated by the solute concentration gradient, after peritectic reaction, the nucleation and growth of TiC in β-Ti leads to its forming of short-bar shape. The dendritic TiC mainly is distributed in the matrix grain, but the short-bar shape TiC mainly segregates at the grain boundary, especially at the triangular grain boundaries.

Key words: TiC/Ti-6Al-4V composites; microstructure; hardness; formation mechanism

1 Introduction

Titanium alloy matrix composites have significant potential for aerospace, automobile and other civil industries due to their combination of high specific strength, elevated temperature resistance and low density as well as high elastic modulus[1−4]. Moreover, the particles reinforced titanium alloy matrix composites have attracted more attention because of the ease of fabrication and low cost[5−6]. Among the different producing techniques of the particle reinforced titanium matrix composites, reinforcements fabricated by smelting-casting method are in-situ and combine well with matrix[7−9]. Among titanium alloys, Ti-6Al-4V alloy, which has a fine microstructure with α and β phase, is considered to be a good matrix alloy because of its high strength, high fracture toughness and good deformability at high temperature[10]. As TiC particles are useful for wear resistance, they have been widely used to improve surface characteristic. They appear to be also proper materials as reinforcement of Ti-6Al-4V alloy matrix. It has been revealed that the primary TiC is on a large scale ranging from less than 1 μm to over 100 μm and is poor stability fabricated by smelting-casting method. This often makes the composites failure owing to fracture of TiC[11−12].

TSANG et al[13] broke the dendritic TiC into fine particles to improve the properties of the composites by forging method. However, this likely incurs cracks inside TiC particles. Heat treatment can change the morphology and size of TiC and prevent the occurrence of cracks in particles. It becomes one of the effective way to control the morphology of TiC[14]. If the growth of TiC crystal can be controlled during the fabrication of composites, the properties of composites can be improved significantly. Thereby the controlling of morphology and size of TiC has become the key factor in further improving the properties of the composites. In this paper, TiC particles reinforced Ti-6Al-4V alloy matrix composites were fabricated by consumable arc melting technique, and the morphology and evolution mechanism of TiC were studied.

2 Experimental

Firstly high purity titanium powder (purity of 99.2%, particle size of 45 μm), aluminum powder (purity of

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99.6%, particle size of 29 μm) and carbon powder (purity of 99.8%, particle size <0.05 μm= were ball-milled for 24 h according to certain stoichiometric. Then they were uniaxially pressed into green compacts with 50%−60% theoretical density and heated in vacuum high temperature SHS reactive furnace to synthesize an Al/TiC master alloy. Finally, the master alloy, the sponge titanium, vanadium power (purity of 99.9%, particle size of 20 μm) and aluminum powder were melted in a consumable vacuum arc furnace equipped with a water-cooled copper crucible. In order to ensure chemical homogeneity(mass fraction) of the composites, electron magnetic agitation was used and the ingots were melted at least three times. Carbon contents of the composites were 0.15%, 0.20%, 0.40%, 0.80%, 1.40% and 2.00%, respectively. Phase identification was carried out via X-ray diffraction (XRD) using Rikagu D/max-RB diffractometer. The FEI Sirion scanning electron microscope was used to analyze the microstructure of the composites. The rockwell hardness was measured with testing load of 150 kg for 15 s.

3 Results

3.1 Phase composition

The XRD results of TiC/Ti-6Al-4V composites with different content of carbon are shown in Fig.1. It can be seen that the composites are composed of α-Ti and TiC, and the diffraction peak intensity of TiC increases with the increasing of carbon content.

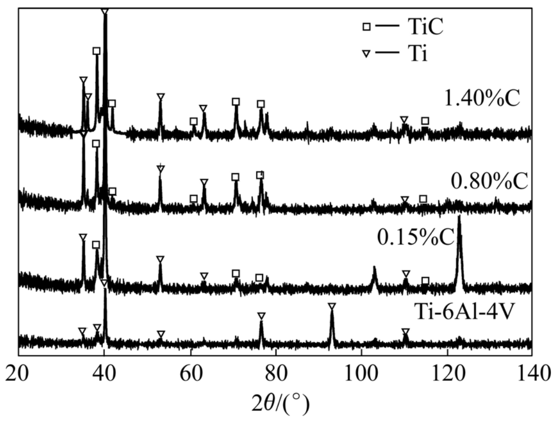

Fig.1 XRD patterns of TiC/Ti-6Al-4V composites

3.2 Effect of carbon content on morphology of TiC

Fig.2 shows the microstructure of TiC/Ti-6Al-4V composites with 0.15%C and the energy spectrum analysis result of TiC particles. It can be seen that particles segregate mainly at the grain boundary and contain mainly carbon and titanium. The results of energy dispersion X-ray spectrometer(EDS) show that the particle reinforcements are TiC. Moreover, according to the characteristics of size and distribution of TiC particles, these particles should be precipitated in the solidification process of alloys because of the supersaturation of local carbon for its solid solubility decreasing in titanium matrix. TiC firstly nucleates at grain boundary, which has great lattice distortion, high energy and is a channel where the carbon atoms diffuse easily. The microstructures of TiC/Ti-6Al-4V composites with different content of carbon are presented in Fig.3. It shows that TiC reinforcements are distributed uniformly in the matrix alloy. When the carbon content is about 0.20%, TiC is of short-bar shape, as shown in Fig.3(a). With the increasing of the carbon content, TiC is mainly of short-bar shape and there chain-type TiC (Fig.3(b)). The chain-type TiC consists of featheriness and wheat-shape TiC. There is a corresponding coarsening of TiC when the content of carbon increases continuously (Figs.3(e), (g)). When the carbon content is up to 0.80%, TiC is of short-bar shape(Fig.3(d)). When the carbon content reaches 1.40%, TiC is mainly of short-bar shape and the exiguous dendritic shape TiC appears(Fig.3(f)). The dendritic TiC becomes well developed as the carbon content arrive at 2.00%, as shown in Figs.3(g) and (h).

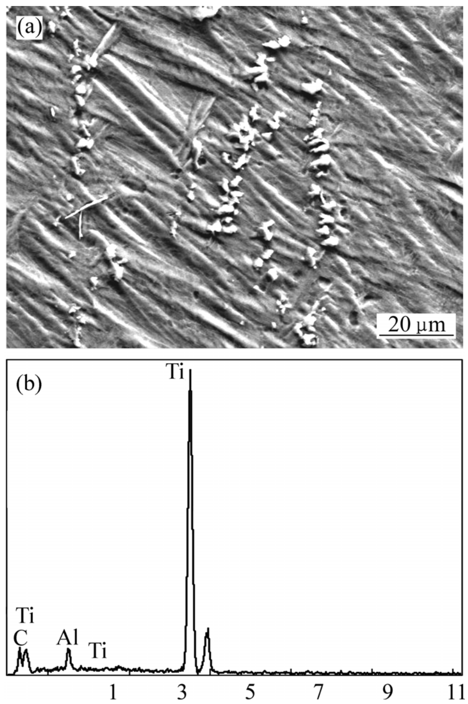

Fig.2 Microstructure(a) and EDS pattern(b) of reinforcement in TiC/Ti-6Al-4V composites

The evolution of morphology of TiC with the different contents of carbon in the composites is specific as that: with the carbon content increasing from 0.15% to 2.00%, the morphology of TiC transforms from particle into short-bar shape or chain-type consisting of featheriness or wheat-shape and finally into dendritic.

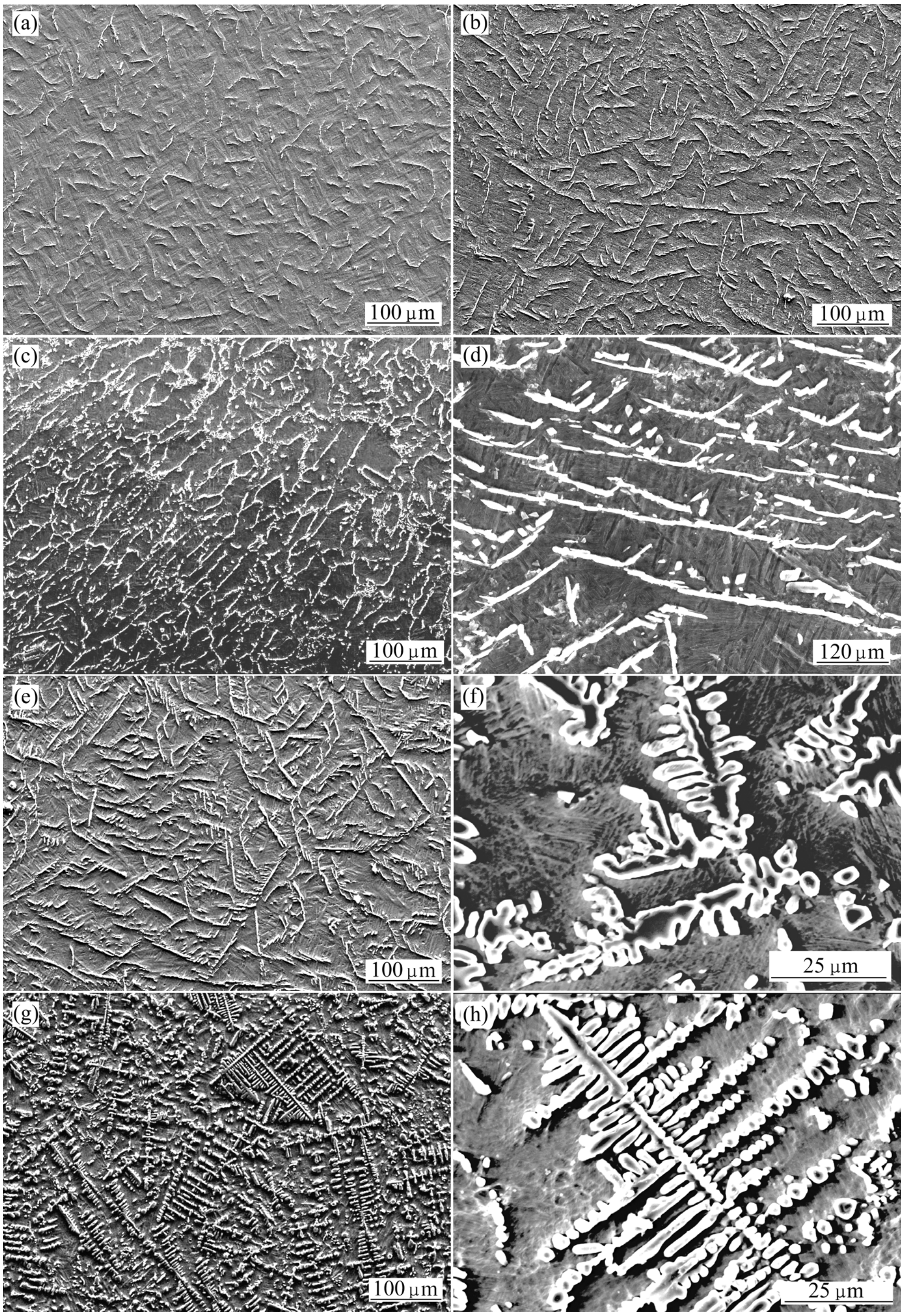

Fig.3 Morphologies of TiC in TiC/Ti-6Al-4V composites with different content of carbon: (a) 0.20%C; (b) 0.40%C; (c), (d) 0.80%C; (e), (f) 1.40%C; (g), (h) 2.00%C

3.3 Effect of carbon content on hardness of composites

The effect of carbon content on TiC/Ti-6Al-4V composites is shown in Fig.4. It can be seen that with the increasing of the carbon content, the hardness of the composites also increases.

4 Discussion

TiC/Ti-6Al-4V composites which contain 2.00%C and 0.4%C respectively are taken as examples to analyze solidification process of the composites. There is eutectic reaction in the Ti-rich corner at 1 650 ℃ with the carbon content of about 0.5% in the Ti-C phase diagram[15]. There exists peritectic reaction in the Ti-rich side in the Ti-Al phase diagram. Therefore, it is a eutectic-peritectic ternary phase diagram for Ti-Al-C system in Ti rich corner. When the carbon content is 2.00%, the composite is in two-phase region of TiC and liquid phase in initial

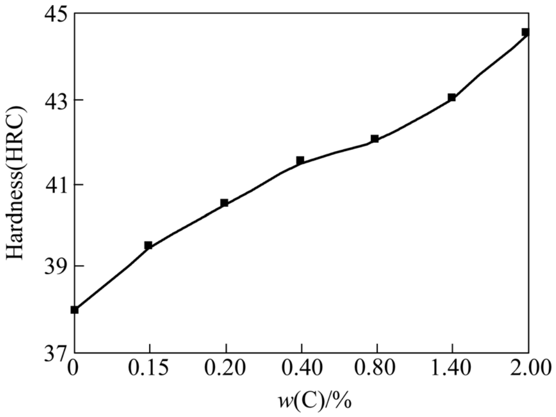

Fig.4 Effect of carbon content on hardness of TiC/Ti-6Al-4V composites

period of solidification. With the decreasing of the temperature, the composite is in two-phase region of TiC and β-Ti, then in two-phase region of TiC and α-Ti. The solidification process of the composite can be described as follows:

$$L \rightarrow TiC + L_1 \quad (1)$$

$$L_1 \rightarrow \beta\text{-}Ti + TiC \quad (2)$$

$$\beta\text{-}Ti \rightarrow \alpha\text{-}Ti \quad (3)$$

When the carbon content is 0.40%, the composite is in two-phase region of β-Ti and liquid phase in initial period of solidification. With the decreasing of the temperature, the composite steps successively from two-phase region of TiC and β-Ti into single-phase region of α-Ti. The solidification process of the composite can be described as follows:

$$L \rightarrow \beta\text{-}Ti + L_1 \quad (4)$$

$$L_1 \rightarrow \beta\text{-}Ti + TiC \quad (5)$$

$$\beta\text{-}Ti \rightarrow \alpha\text{-}Ti \quad (6)$$

The crystal structure of TiC is fcc. According to Jackson's theory that the interface of equilibrium structure has the lowest free energy and the criterion of interface structure[16], the solid-liquid interface of TiC is rough and it grows freely in a continuous growth way. The composites is solidified in water-cooled copper crucibles and the cooling speed is high, so the undercooling degree at the solid-liquid interface front is high. When the primary TiC grows in supercooled melt, small destabilization of the solid-liquid interface front induces small projecting portion which can attain more precipitation potential and continue to grow into the liquid alloy. And the secondary and thirdly dendrite arms can grow further at both sides of the projecting portion. Thus the morphology of the primary TiC is usually dendrite.

From the Ti-C phase diagram, it can be seen that the peritectic point is about 0.80%C. When the carbon content of the composites is less than 0.80% during equilibrium crystallization, primary TiC translates into β-Ti completely through peritectic reaction, so there is no dendritic TiC. Ti-6Al-4V alloy has the solute aluminum of 6.0% and is non-equilibrium solidification, so the peritectic point may move. From the results of the experiment, when the carbon content is 0.8%, there is no dendritic TiC, but when the carbon content is 1.40%, dendritic TiC appears. The results indicate that the peritectic point of the composites is between 0.80%C and 1.40%C. When the carbon content of the composites is less than 0.80% and the temperature of the composites is below liquidus, dendritic TiC appears. During peritectic reaction, β-Ti nucleates on the surface of dendritic TiC and envelopes it. Thus the solution of TiC and componential homogenization are difficult to proceed sufficiently. When the peritectic reaction finishes, there may be some carbon-rich areas or residual dendritic TiC in β-Ti. With the temperature decreasing continuously, TiC precipitate in β-Ti for supersaturation of carbon. The growth of TiC depends on solid state diffusion of Ti, Al, V and C. As the result of the limitation of diffusion velocity and distance, TiC is prone to form short-bar shape and distributes in β-Ti. When eutectic reaction begins, α-Ti nucleates and grows at grain boundaries of β-Ti primarily. So the short-bar shape TiC in β-Ti transfers to grain boundaries or triangular grain boundaries of α-Ti.

5 Conclusions

1) TiC/Ti-6Al-4V composites were fabricated by consumable arc-melting technology. The reinforcements distribute uniformly in the matrix alloy.

2) Carbon content has significant influence on the morphology of TiC. With the decreasing of carbon content from 2.0% to 0.15%, the coarse dendrite TiC disappears and only short-bar shape, chain-type or granular TiC exists in the composites. The dendritic TiC is the primary TiC which freely grows in a continuous growth way in supercooling liquid metal before the peritectic reaction and is distributed mainly in the matrix grain. The short-bar shape TiC nucleates and grows in β-Ti after peritectic reaction through solid state diffusion of Ti, Al, V and C and mainly segregates at the grain boundary.

3) With the increasing of carbon content, the hardness of TiC/Ti-6Al-4V composites also increases.

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