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Formation of TiC/Ti_2AlC and $\alpha_2+\gamma$ in *in-situ* TiAl composites with different solidification paths

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In order to improve the mechanical properties of TiAl alloys, TiAl composites with different solidification paths were synthesized by metallurgical method. Results show the TiC disappears and Ti_2AlC increases when the Al content is more than 42% (at.%, similarly hereinafter). Small TiC particles are located in Ti_2AlC grains with irregular shapes when the Al content is 40%, and they translate into clubbed Ti_2AlC with increasing of Al. This metallurgy method can solve the defects of the Al lacking and the residual TiC. The γ phase increases between lamellar colonies with the increasing of Al. When the Al content is 48%, the fully lamellar structure transforms into a duplex microstructure and there are small Ti_2AlC phases in γ phases, because the forming of Ti_2AlC phase must consume Al. The compressive strength increases up to 1678.68 MPa as Al content is 46 at.%, and then decrease to 1460.22 MPa, the compressive strain increases and then keeps stabilization with the increasing Al. The maximum strength improves 38.82% and the maximum strain improves 121.37%. The Ti_2AlC/TiAl composites fracture behaviors are load transferring behavior, crack deflection, trans-lamellar cracking and extraction of carbide reinforcements. The Ti_2AlC phase and the fully lamellar structure improve the mechanical properties.

1. Introduction

TiAl alloys have remarkable properties that are regarded as promising candidates in aerospace and automobile industry [1–3], such as low density, high creep, and oxidation resistance, as well as their high strength and modulus retention at elevated temperature [4–6]. However, low temperature ductility and poor formability limit the extensive application of TiAl-based alloys [7–9]. Researchers use the composite technology to improve this disadvantage. The ternary ceramic Ti_2AlC is a member of ternary carbides ($M_{n+1}AX_n$, where M is an early transition metal, A mainly groups 13–16 in the periodic table, X is either C or N, and n is an integer, commonly equal to 1, 2 or 3) [10]. It has attracted increasing attention owing to its unique combinative properties of both ceramics and metals, such as high fracture resistance, excellent damage tolerance and superior thermal conductivities [11,12]. Ti_2AlC phase has been identified as having thermo chemically stable reinforcing phases in the TiAl matrix composite. The Ti_2AlC and TiAl matrix have the similar density, which benefit fabrication of Ti_2AlC to reinforce TiAl matrix composites [13,14].

There are a variety of methods to prepare the Ti_2AlC/TiAl composites, such as mechanical alloying, reactive hot pressing, spark plasma sintering, and vacuum arc melting and combustion synthesis. Wang et al. [15] have found that the reaction of forming Ti_2AlC can be achieved below 950 °C, which is 150 °C lower than in the Ti-Al-TiC system and 250 °C lower than for the Ti-Al-C system due to the addition of carbon nanotubes. Janakarajan Ramkumar et al. [16] studied that by adding carbon to Ti–47Al–3W alloy, a composite can be produced smaller Ti_2AlC precipitates with fine B2 particles in the matrix. C.L. Yeh and Y.G. Shen [17] found that the addition of carbon particles promoted the sustainability of the synthesis reaction substantially to the reactant mixture for the preparation of the TiAl-Ti_2AlC composite, on account of more reaction heat was liberated from formation of Ti_2AlC than that of TiAl. The phase transition of Ti_2AlC/TiAl can be summarized as follows: melt Al + Ti → $TiAl_3$, $TiAl_3$ + Ti → TiAl + Ti_3Al, $TiAl_3$ + C → TiC, TiC + TiAl →Ti_2AlC [18–20]. The content of Al is the important factor on phases transforming and microstructure forming with little researches. Due to the reduction of the crucible and use an economical and direct method, the metallurgical method with the

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water cooled copper crucible was applied to fabricate Ti_2AlC/TiAl composites. Moreover, remelting of samples after inversion can overcome disadvantages, such as inhomogeneity microstructure or inadequacy reaction by indeterminate reaction rates. The metallurgical method can control the microstructure to acquire the high mechanical property, especially the content of Al that there is no attention on the component of TiAl matrix.

In this study, the main purpose is to research the effect of aluminum content on the formation of reinforced phases and the matrix, and the compression performance. Because Ti_2AlC exists only in a narrow region of the Ti-Al-C phase diagram and readily reacts with Al. There is little research on *in-situ* Ti_2AlC phase strengthening the Ti (40–48) Al based alloys by metallurgical method with different solidification paths.

2. Experimental procedure

The raw materials are titanium sponge (99.98% purity), aluminum (99.98% purity) and graphite (99.9% purity). The Ti-Al-C ingots were prepared by the metallurgy method with the different content of the aluminum element, which were Ti40Al2.6C, Ti42Al2.6C, Ti44Al2.6C, Ti46Al2.6C and Ti48Al2.6C, respectively. The phase constituents of the ingots and the samples were examined by X-ray diffraction (XRD). The ingot was cut in half longitudinally, and then polished and etched. The microstructure and the ingots were examined by Olympus GX71 Optical Microscope (OM), Quanta 200F scanning electron microscopy (SEM), Japan TM3030 and Energy Dispersive Spectrometer (EDS). The cylindrical specimens with size of Ø4 × 6 mm were used for compressive testing, which was operated on Instron 5569 Electronic Universal Material Testing Machine with 0.5 mm/min loading rate.

3. Result and discussion

3.1. Phase analysis

The in situ Ti_2AlC/TiAl composites are fabricated by the method of the vacuum arc melting with the water cooled copper crucible. The X-ray diffraction results are shown in Fig. 1. It can be seen that the peak of the α_2-Ti_3Al phase is higher than others, which the aluminum content of the sample is 40 at.%. The TiC phase peaks appear with the 40 at.% aluminum. With the more aluminum add, the TiC phase peaks disappear basically. In the reactions of Ti_2AlC forming, TiC is an intermediate product in the Ti-Al-C system that is formed from Al_3Ti and C, finally reacts with TiAl to synthesize Ti_2AlC. Both TiC and Ti_2AlC are formed by diffusion-controlled reaction rather than by dissolution-precipitation mechanism. Both Ti_3Al and TiC phases lack Al, which is connected with evaporation of Al during high temperature reaction and un-reacted TiC phase is also caused by tardy diffusion. In this paper, increasing the content of Al can effectively improve the lack of Al. The peaks of the α_2-Ti_3Al phase decrease and the peaks of the γ-TiAl phase and Ti_2AlC phase increase with the increasing Al. Under the condition of certain chromatography, having a certain content ratio of phases, the chromatographic peak area ratio is certain. Huang et al. [21] used this method to calculate the content of plutonium, rather than had to use the quality calibration instruments of plutonium standard sample. The results of the relative content of α_2-Ti_3Al, γ-TiAl, Ti_2AlC and TiC phases relative to α_2-Ti_3Al show in Table 1. The relative content of γ-TiAl and Ti_2AlC are also less than α_2-Ti_3Al with the content of 40 at.% Al. With the increasing addition of Al the relative content of γ-TiAl and Ti_2AlC are also more than α_2-Ti_3Al. The γ-TiAl and Ti_2AlC increase with the content of 42, 44, 46 at.% Al. The γ-TiAl have a high relative content values relative to α_2-Ti_3Al with the 48 at.% aluminum.

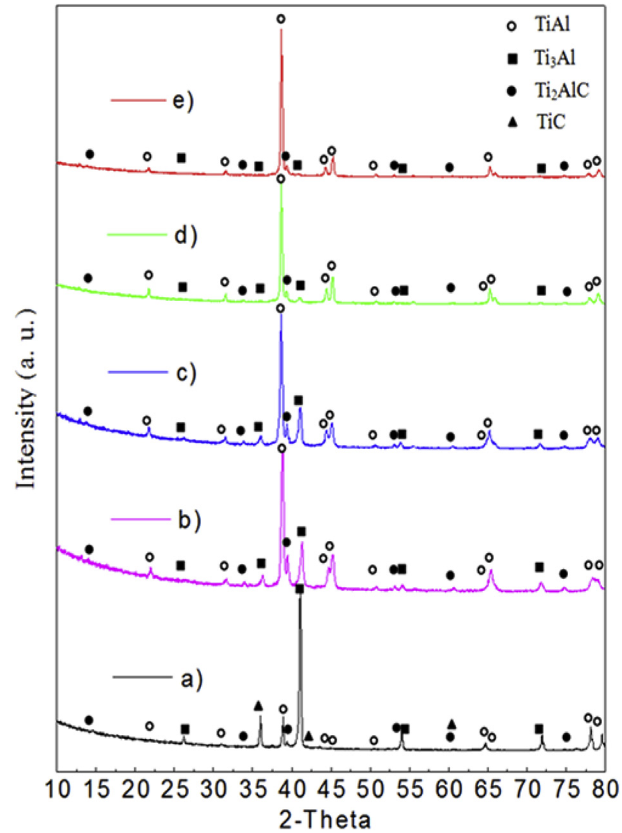

Fig. 1. XRD patterns of the sample with a) Ti40Al2.6C, b) Ti42Al2.6C, c) Ti44Al2.6C, d) Ti46Al2.6C and e) Ti48Al2.6C fabricated by the in situ method.

Table 1
The peak area ratio of phases in the alloy with different Al content.

	Relative content of phases in the alloy			
	α_2-Ti_3Al	γ-TiAl	Ti_2AlC	TiC
Ti40Al2.6C	1	0.167	0.020	0.177
Ti42Al2.6C	1	3.145	0.405	0
Ti44Al2.6C	1	3.442	0.416	0
Ti46Al2.6C	1	3.739	0.434	0
Ti48Al2.6C	1	6.671	0.561	0

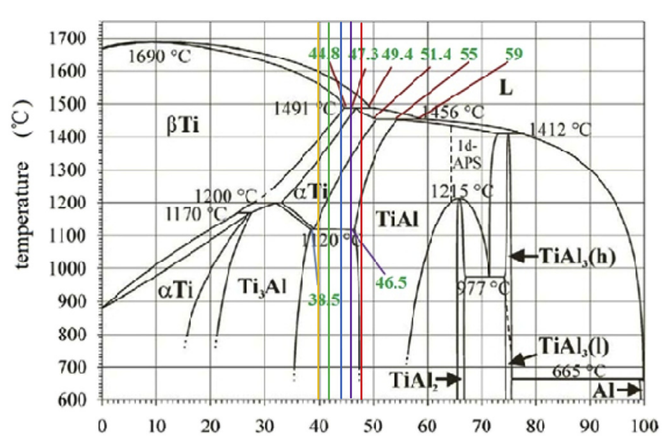

Fig. 2. Phase diagram of TiAl alloy.