

Effects of grain size and precipitated phases on mechanical properties in TiAl gradient materials

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ABSTRACT

Effects of grain size and precipitated phases on creep properties, fracture toughness and crack propagation behavior are investigated in Ti-44Al-6Nb-1Cr-2V/Ti-44Al and Ti-44Al-6Nb-1Cr-2V-BY/Ti-44Al-6Nb-1Cr-2V gradient materials. Creep tests were performed at 850 °C/200 MPa and fracture toughness tests were performed at room temperature. Results show that the prepared gradient materials have continuing and subtle variation in composition. In Ti-44Al-6Nb-1Cr-2V/Ti-44Al, the content of $\gamma + B2$ precipitated phases increases with the increase of pulling length. The creep life decreases with the increase of the content of precipitated phases and the precipitated phases promote the crack and cavity nucleation. In Ti-44Al-6Nb-1Cr-2V-BY/Ti-44Al-6Nb-1Cr-2V, the grain size decreases with the increase of pulling length. The creep life decreases with the decrease of grain size and the fine lamellar colony provides an increasing opportunity for cavity nucleation at colony boundary. After fracture toughness tests, the crack tends to propagate along the precipitated phases and lamellar interface. The K_{IQ} values decrease with the increase of the content of precipitated phases and they decrease with the decrease of grain size.

1. Introduction

Titanium aluminide intermetallics have attracted a lot of attention due to their high specific strength, low density, excellent creep properties, and good oxidation resistance [1–3]. In particular, the high-Nb TiAl alloys, which exhibit the higher high-temperature creep properties and oxidation resistance than the ordinary TiAl alloys, have attracted a lot of attention in recent years [4,5]. However, the high-Nb TiAl alloys with the high content of β -stabilizers usually induce the formation of the $\beta(B2)$ precipitated phases in the matrix due to the elemental segregation. The B2 phase is much harder than γ and α_2 phases at room temperature, which causes stress concentration at the interface of B2 phase and reduces mechanical properties [3,6,7]. However, the fine dispersed B2 phase precipitation can provide a greater strengthening effect during creep [8]. Therefore, the effects of B2 phase on creep behavior require further study. It is well known that the TiAl alloys which possess the good balance of mechanical properties, need to be refined by the addition of grain refiners [8–10]. The addition of grain refiners, such as B and Y, can improve the mechanical properties of TiAl alloys, especially for the high-Nb TiAl alloys [9,10]. The common addition of B and Y in TiAl alloy will significantly refine lamellar colony. However, the fine lamellar colony is detrimental to the high-temperature creep properties, since the increase of colony boundary provides

the increasing nucleation sites for cavity and crack [11,12]. Therefore, it is essential to investigate the effect of grain size on creep behavior in high-Nb TiAl alloys. Moreover, the fracture toughness of TiAl alloys strongly depends on microstructure, and the precipitated phases and grain size will strongly affect the fracture toughness and crack propagation behavior.

Previous studies about the effect of elements additions on mechanical properties mainly focused on the preparation of multiple ingots, but the actual composition and solidification process of each ingots are difficult to control [8,11]. Fortunately, the gradient materials are spatial composites that display discrete or continuously varying compositions over a definable geometrical length, which is suitable for studying the effect of composition gradation on mechanical properties [13–15]. In addition, the gradual changes in volume fraction of the constituents and non-homogenous structure can provide continuous and graded macroscopic properties [16,17]. However, there are a few reports on the TiAl gradient materials [18] because of the high activity and melting point of TiAl-based alloys. Cold crucible directional solidification (CCDS) technology (Fig. 1) provides an effective solution to avoid the melt contamination and offer the chemical homogeneity microstructure, and this method can be used for preparing TiAl-based gradient materials [19]. During the CCDS process, the molten pool can be thoroughly mixed under the confinement of electromagnetic force

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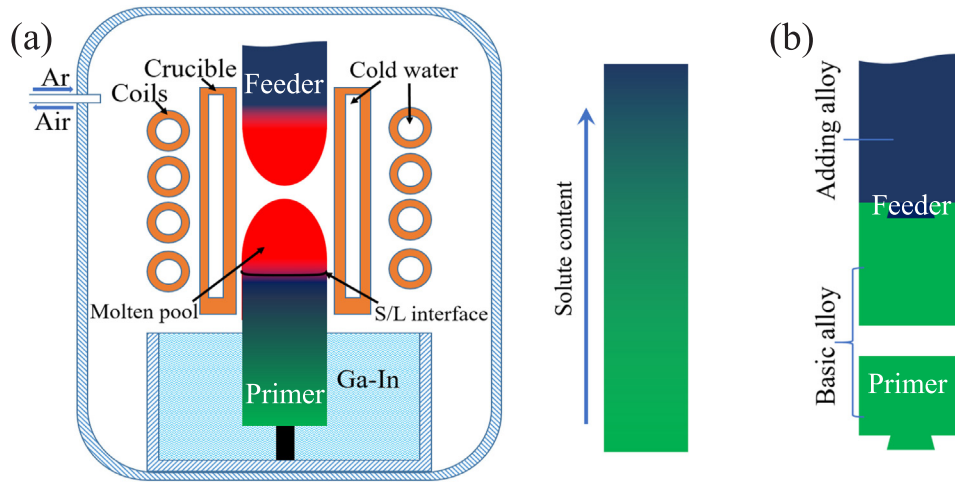


Fig. 1. Diagrams of the CCDS equipment and the ECCDS process, (a) schematic illustration of the CCDS process and (b) the preparation method for gradient materials.

and the size of molten pool can be controlled by the pulling velocity and input power [20,21]. In this study, Ti-44Al-6Nb-1Cr-2V-BY/Ti-44Al-6Nb-1Cr-2V and Ti-44Al-6Nb-1Cr/Ti-44Al gradient materials were successfully fabricated by the CCDS technique. The effects of precipitated phases and grain size on creep behavior and fracture toughness were studied. A particular attention was paid on the crack propagation performance.

2. Experimental procedures

2.1. Materials and CCDS ingots preparation

Ti-44Al, Ti-44Al-6Nb-1Cr-2V and Ti-44Al-6Nb-1Cr-2V-BY (Ti-44Al-6Nb-1Cr-2V-0.15Y-0.1B) ingots were fabricated by the vacuum consumable melting technology. The ingots were cut into a set of cylinder bars with 25 mm in diameter and 250 mm in length for the following CCDS experiments. The CCDS experiments were prepared on the basis of a multi-functional electromagnetic solidification apparatus equipment by the use of a square cold crucible (36 mm × 36 mm), as shown in Fig. 1. The experimental details have been described in Ref. [22].

2.2. TiAl-based gradient material ingots preparation

Ti-44Al-6Nb-1Cr-2V/Ti-44Al and Ti-44Al-6Nb-1Cr-2V-BY/Ti-44Al-6Nb-1Cr-2V gradient materials were prepared by the CCDS technique, as shown in Fig. 1. The adding alloys are Ti-44Al-6Nb-1Cr-2V in Ti-44Al-6Nb-1Cr-2V/Ti-44Al and Ti-44Al-6Nb-1Cr-2V-BY in Ti-44Al-6Nb-1Cr-2V-BY/Ti-44Al-6Nb-1Cr-2V. The composition of initial feeder bar with 50 mm is same to the composition of primer bar, and they are basic alloys, as shown in Fig. 1(b), which ensures that the gradient region can form in the well directionally solidified region. Therefore, the gradient region begins to form at 20 mm from the initial solidification interface (the velocity ratio between feeder bar and primer bar is 2.5:1). The solidification parameters are shown in Table 1.

Table 1

The compositions and solidification parameters of gradient materials.

No.	Compositions (at%)	Solidification parameters
X1	Ti-44Al-6Nb-1Cr-2V/Ti-44Al	45 kW and 8.33 μm/s
X2	Ti-44Al-6Nb-1Cr-2V-BY/Ti-44Al-6Nb-1Cr-2V	45 kW and 16.67 μm/s

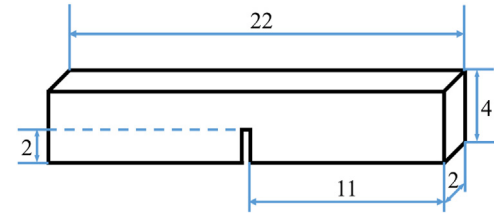


Fig. 2. The size (mm) of the specimen for fracture toughness.

2.3. Fracture toughness and creep tests

Fracture toughness tests were performed on the single edge notched bend (SENB) specimens with the size of 22 mm × 4 mm × 2 mm at room temperature, as shown in Fig. 2. The 2.0 mm deep slit notches in specimens were cut by the electrode discharge machine. The fracture toughness was tested in the Instron-5500 testing machine and the rate of crosshead displacement was 3 μm/s. At least 5 qualified samples of each CCDS ingot were tested. Based on these tests, the statistical results of the K_{IC} values for each CCDS ingot were obtained. The K_{IC} values can be expressed as:

$$K_{IC} = (P \cdot S / B \cdot W^{3/2}) \cdot f(a/w) \quad (1)$$

$$f(a/w)$$

$$= 3(a/w)^{1/2} \cdot \frac{1.99 - (a/w)(1-a/w)[2.15 - 3.93(a/w) + 2.7(a/w)^2]}{2(1 + 2a/w)(1-a/w)^{3/2}} \quad (2)$$

where, P is the load determined at the 95% slope of the linear elastic part of the load-displacement curves, W is the width of specimen, B is the thickness of specimen; a is the precrack length including the slit notch; S is the span of loading ($S = 4W$).

The creep specimens with cross-section of 4.5 mm × 2.5 mm and gauge length of 20 mm were cut from CCDS ingots. The samples for creep tests and fracture toughness tests were cut at transverse direction in CCDS ingot, as shown in Fig. 3, since these gradient materials have the same solute content at transverse section. The creep specimens were tested in air under constant load in a GWT504-model creep testing machine and the creep tests were performed at 850 °C under constant tensile loading of 200 MPa.

The CCDS ingots were cut into isometric two halves longitudinally. Nikon D800 Digital Single Lens Reflex recorded the macrostructure and the microstructure was investigated by scanning electron microscope in backscattered electron (SEM-BSE) mode. The chemical composition was

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