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Effects of lamellar spacing on microstructural stability and creep properties in β-solidifying γ-TiAl alloy by directional solidification

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ABSTRACT

Ti44Al6Nb1Cr (at%) alloys with different lamellar spacing were prepared by cold crucible directional solidification. Creep tests were conducted at 750 °C under 260 and 300 MPa, and the microstructure before and after creep testing were observed and analyzed. The results show that the prepared TiAl alloys have similar macro/microstructure except for lamellar spacing, which are different from the heat-treated TiAl alloys with obviously changed macro/microstructure. The refinement of lamellar spacing can improve creep properties, especially the steady-state of fine lamellar alloy lasted for more than 600 h with creep rate at $7.3 \times 10^{-9}\,S^{-1}$. The improvement of creep properties by refined lamellar spacing are revealed as following two reasons. (1) Fine lamellar spacing improves the stability of γ lamellae and increases the resistance for dislocation slip in γ lamellae. (2) It disperses stress concentration and delays the formation of globular structure at colony boundary. Moreover, the alternating β and γ laths in α-segregation zone can improve microstructural stability during creep. In β-solidifying γ-TiAl alloy, the local stress concentration on β-segregation at colony boundary promotes colony boundary sliding and the formation of void with globular structure, which further accelerates the creep failure.

1. Introduction

Titanium aluminide (TiAl) based alloys are promising structural materials at high-temperature applications between 600 and 900 °C, due to their low density in combination with good creep resistance, high-temperature corrosion resistance, good oxidation and burn resistance [1–3]. However, the major drawbacks for the structural applications of these materials are their inadequate fracture resistance at low temperatures [4–6]. In this context, the recent developments of the materials have focused on β-solidifying γ-TiAl alloys, and the room-temperature mechanical properties of β-solidifying γ-TiAl alloys could be improved through thermo-mechanical treatment (TMT) [7,8]. However, the high-temperature microstructure stability obviously decreases after TMT processing due to the formation of duplex microstructure, which decreases the high-temperature creep resistance and limites the application of TiAl alloys [9,10]. Therefore, researchers began to study the precision casting of β-solidifying γ-TiAl alloys in recent years [4,11,12]. Cold crucible directional solidification (CCDS) technique is a good method to solve the contradiction above, it can realize less or no contamination, continuous casting function, composition homogenization and so on [13–15].

Previous research results showed that the room-temperature and high-temperature strength of γ-TiAl alloys could be significantly improved by refining lamellar spacing [7,9,16]. γ-TiAl alloys with lamellar microstructure demonstrate the most balanced mechanical properties and the average lamellar spacing in the α_2/γ lamellar colony has a significant influence on mechanical properties [17–19]. However, previous studies about the effect of lamellar spacing on creep properties in TiAl alloys were mostly through heat treatment, which significantly changed the ratio of α_2 and γ lamellae, the size of lamellar colony, the perfection of the colony boundaries, the nature of the lamellar boundaries and so on [4,16,20]. Therefore, it is difficult to identify the effect of lamellar spacing on creep properties through heat treatment. CCDS technique can solve the contradiction above, it can obtain different lamellar spacing by controlling input power or pulling velocity (cooling rate) [13,15]. Moreover, the interactions between lamellar terminations and colony boundaries during creep need to be further studied, especially the β-solidifying γ-TiAl alloy with the presence of β-segregation at colony boundary and α-segregation in lamellar colony [21]. The decreasing of lamellar spacing will affect microstructural stability; the effect of lamellar spacing on creep properties and microstructural stability of β-solidifying γ-TiAl alloy need to be investigated.

In this paper, the Ti44Al6Nb1.0Cr (at% similarly hereinafter except the special illustration) alloys with different lamellar spacing were

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prepared by CCDS technique, the influences of α_2 and γ lamellar spacing on creep properties and microstructural stability will be compared and analyzed, respectively. The grain (colony) boundary sliding (GBS) mechanism and the interactions between lamellar terminations and colony boundary will be discussed.

2. Experimental procedure

The as-cast master ingot was fabricated by vacuum consumable melting technology; the ingot size was Ø 225 mm × 320 mm. The actual composition was Ti-44.55Al-6.03Nb-0.99Cr measured by inductive coupling plasma emission spectrometer (Optima 2100DV). Some bars with diameter of Ø25 mm were wire-electrode cut from master ingot and they were used for CCDS experiment. The experimental details have been described in Ref [15]. In this study, the Ti44Al6Nb1Cr alloys were well directionally solidified by cold crucible at the pulling velocity of 8.33, 11.67 and 16.67 μm/s under input power of 45 kW. The CCDS TiAl alloys with pulling velocity at 8.33 μm/s and 16.67 μm/s were selected, for studying the effects of lamellar spacing on microstructural stability and creep properties.

The samples were ground and polished following standard procedures. The etched liquid was the modified Kroll's reagent composed of 28 vol% HF, 2 vol% HNO_3 and 70 vol% H_2O. For transmission electron microscopy (TEM), discs of 3 mm in diameter and 0.4 mm in thickness were wire cut from specimens and ground to about 80 μm thick. The discs were twin-jet electro-polished in a solution of 60% methanol, 35% butyl alcohol and 5% perchloric acid at 15 V and −35 °C. The microstructure was examined by scanning electron microscopy (SEM) in back-scattered electron mode (BSE), transmission electron microscopy (TEM) was employed to identify different phase and investigate microstructure. The macrostructure of CCDS ingots were recorded by Nikon D800 Digital Single Lens Reflex. The thicknesses of the α_2 and γ lamellae and the lamellar spacing were measured when the lamellae were viewed in the edge-on position by the line interception method.

The CCDS ingots were cut into the specimens with cross-section of 4.5 mm × 2.5 mm and gauge length of 20 mm. The uni-axial tensile creep tests were performed under constant load in a GWT504-model creep testing machine. Creep tests were carried out in air under constant tensile loading at 750 °C under 260 and 300 MPa. Creep tests were generally terminated either at fracture (tensile) or creep life over 800 h.

3. Results

3.1. Macro/microstructure before creep testing

Fig. 1 shows the longitudinal and transverse macrostructure of CCDS ingots under the same power of 45 kW at different pulling velocities: (a) 8.33 μm/s; (b) 11.67 μm/s; (c) 16.67 μm/s, which exhibit the well directional-solidification macrostructure. The macrostructure of three ingots consist of two parts, as shown in Fig. 1(a), the "solid–liquid interface" is marked by the white line, the upper part "liquid region" formed by the power failure suddenly, "stable solidification region" located at lower part formed by the relative equilibrium of heat and mass transfer [13]. The selected areas for creep tests are marked by white rectangle frames, as shown in Fig. 1(a) and (c), they are mainly composed of vertical columnar crystals. Table 1 lists the basic data of three ingots. In this paper, the CCDS alloy at pulling velocity of 8.33 μm/s is named CL-alloy (coarse lamellar alloy); at pulling velocity of 16.67 μm/s is named FL-alloy (fine lamellar alloy).

Fig. 2 shows the SEM-BSE microstructure of FL-alloy and CL-alloy. The microstructure of FL-alloy is shown in Fig. 2(a), many micro-segregation with blocky β(B2) + γ phases can be observed in the matrix, which is induced by the relatively low Al-containing and the high content of β-stabilizers. The blocky γ phase with dark contrast formerly interspersed with β phase, the magnified microstructure of β-segregation is shown in the inset of Fig. 2(a). The similar microstructure can be observed in CL-alloy, as shown in Fig. 2(b), the magnified microstructure of colony boundary is shown in the inset of Fig. 2(b).

3.2. Lamellar spacing

Table 1 lists the lamellar spacing of CCDS specimens. The lamellar spacing decreases with the increasing of pulling velocities. These relevant experiment results meet the Eq. (1) indeed from the related Ref [14,15]:

$$d = k_1 V^a \tag{1}$$

where, V is pulling velocity, d is lamellar spacing, k_1 is proportional constant and a is velocity exponent respectively. Regression analysis of experimental data yields an equation can be expressed as:

$$d = 1811V^{-0.51} \tag{2}$$

$$r_1^2 = 0.97 \tag{3}$$

where, r_1^2 corresponds to the regression coefficient. The relationship of

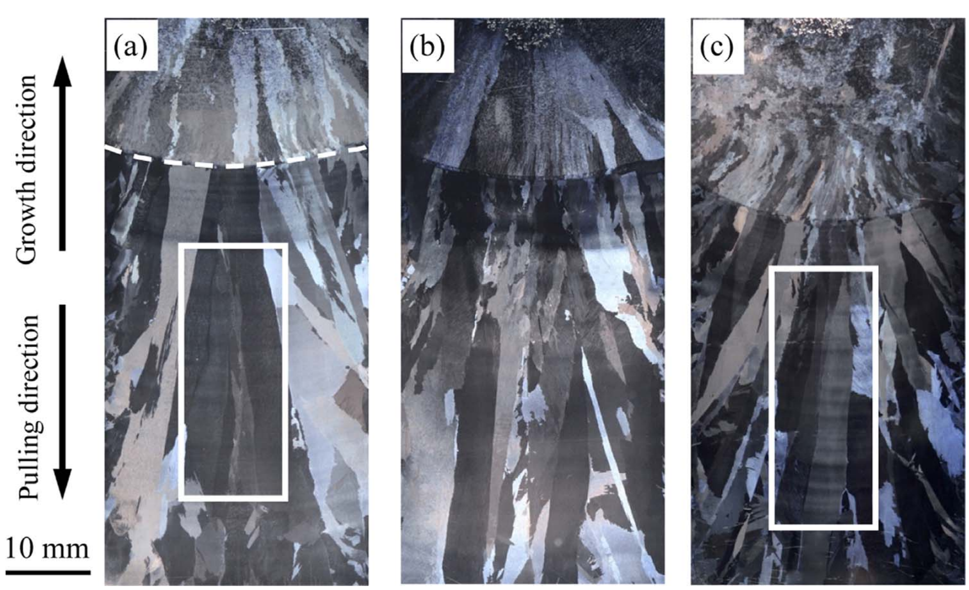

Fig. 1. Macrostructure of CCDS ingots under the same power of 45 kW at different pulling velocities: (a) 8.33 μm/s, (c) 11.67 μm/s and (d) 16.67 μm/s.