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Microstructures and tensile properties of directionally solidified Ti-45Al-2Cr-2Nb alloy by electromagnetic cold crucible zone melting technology with Y_2O_3 moulds

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In this study, a Ti-45Al-2Cr-2Nb alloy was directionally solidified by electromagnetic cold crucible zone melting technology with Y_2O_3 moulds, and the effects of growth rate and heating power on microstructural evolution and tensile properties were investigated. In the directionally solidified regions, microstructures were mainly composed of well-aligned α_2/γ lamellae and B2 phases as well as Y_2O_3 particles. Higher growth rates and heating powers refined the lamellae. In addition, the angle of the lamella orientation to the growth direction increased with a higher growth rate and a lower heating power, but the amount of Y_2O_3 particles was reduced. Appreciable tensile properties, including an ultimate tensile strength of 576 MPa, a yield strength of 511 MPa, and an elongation of 1.1% were achieved at optimal solidification parameters. Moreover, Y_2O_3 particles significantly affected the tensile properties, because they were found to act as crack sources.

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1. Introduction

Lightweight TiAl-based alloys are usually recognized as optimal materials for high thrust-to-weight ratio turbine engines, where they are used as compressor blades or turbine blades. Unfortunately, the current blade materials need to be more resistant to high temperature creep and fatigue [1–4]. Therefore, processing of materials to create directionally solidified (DS) microstructures is essential for improving mechanical properties of blade materials because the grain boundaries normal to the working stress can be eliminated. TiAl blade-like components can be produced using the Bridgeman directional solidification process with a ceramic mould. This highly effective approach not only improves high temperature creep, fatigue, and strength, but also enables the processing of more geometrically complex parts [5,6]. Unfortunately, the interaction between the mould and the TiAl melt is inevitable, even when using a high stability mould material such as the Y_2O_3 ceramic.

External heating methods, including resistance heating [7] and inductive graphite heating [5,6,8], are typically used to heat the moulds and the TiAl alloy during the Bridgeman directional solidification process. Because this kind of heating method is indirect, long periods of heating are required, which is inherently inefficient and causes contamination. Recently, a novel process was developed that combined Y_2O_3 moulds with electromagnetic cold crucible (EMCC) zone melting technology. It is more practical to prepare TiAl-based alloys by this method, which effectively reduces the interaction between the mould and the TiAl melt during the casting of a component with a complex shape.

According to the previous research [9–11], the solidification parameters such as growth rate and heating power have a significant effect on microstructure evolution during the directional solidification process, which influences the mechanical properties. Unfortunately, there is a lack of relevant published research works on the microstructure evolution and mechanical performance as a function of solidification parameters using the EMCC process with Y_2O_3 moulds. Therefore, the aim of this paper is adopt different solidification parameters of electromagnetic cold crucible zone melting method to control microstructure as well as to examine the effect of microstructure on tensile properties of DS Ti-45Al-2Cr-2Nb samples.

2. Experimental procedure

A γ-TiAl based alloy master ingot with a nominal composition of Ti-45Al-2Cr-2Nb (at %) was prepared by inductive skull melting

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technology under a high purity argon atmosphere. Afterwards, the master ingot was cut into Φ15 mm × L100 mm bars using electrode discharge machining (EDM) for the following directional solidification experiments.

The experiments were performed in an EMCC directional solidification furnace as shown in Fig. 1(a), in which an inductive coil connected to a high frequency power supply unit was wrapped around a bottomless water-cooling copper crucible. The cold crucible has a cylindrical lumen that is φ33 mm and has 12 water-cooled individual segments. A ceramic mould, φ15 mm and Φ31 mm, was inserted into the cold crucible. In the beginning of this directional solidification experiment, the near bottom of the TiAl alloy bar was directly super-heated to 1825K, 1923K, 2030K and 2125K by EMCC inductive heating. Because of the Ga-In alloy coolant cooling at the bottom of the TiAl alloy bar, a vertical temperature gradient was spontaneously established and sustained during the directional solidification process, which enabled the columnar grains to align opposite to the thermal flow transfer direction. The temperature of melt and temperature gradient were measured by WRe26-WRe5. The temperature gradient was determined by the temperature difference between two different positions in DS ingots, as in Refer [10]. All directional solidification processes are at sub-atmosphere-pressure gas processing conditions (at 300Pa pressure of argon). The process achieving 300 Pa pressure of argon can be described as follows. The furnace chamber was evacuated to a pressure of less than 3 Pa, and then backfilled with argon at a pressure of 300 Pa. And these processes needed to be repeated three times. This vacuum-pumping process is much important to avoid the contamination of oxygen from air.

In this research, due to the heat being only derived from the electric TiAl melt through internally induction heating, the nonconducting ceramic mould had to be with much lower temperature than the TiAl melt. On the contrary, the ceramic mould attained a temperature close to TiAl melt through externally heating as it had been studied by ourselves and reported by Ref. [12], where graphite heater or resistance heater were used. In the next, things became so favorable that the mould could further decrease its temperature on basis of the chilling effect of cold crucible contacted with outer wall of the ceramic mould. Therefore, the temperature difference between the TiAl melt and mould was enhanced. In kinetics aspect, the holding time of interaction can be effectively shortened because of the rapid inductive heating and cooling as the molten zone moving out off the coil. Hence, the

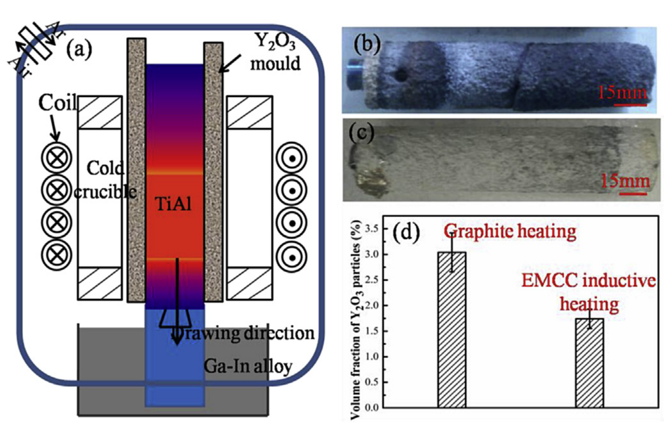

Fig. 1. (a) schematic diagram of directional solidification process by an Y_2O_3 mould with EMCC zone melting, (b)–(c) differences in Y_2O_3 mould appearances between (b) this novel heating mode and (c) traditional graphite heating mode at same growth rate (0.6 mm/min) and heating temperature (1923 K), (d) volume fraction of Y_2O_3 particles in lamellar matrix with different heating modes.

interaction will be greatly reduced, compared with previous processes with externally heating. As shown in Fig. 1b–d, the above conclusions can be verified by comparing with each other in two aspects, including appearances of moulds and volume fraction of Y_2O_3 particles in DS samples through EMCC internal inductive heating and graphite heater external heating at same heating temperature (1923 K) and growth rate (0.6 mm/min), respectively.

The DS samples were cut into two halves symmetrically along their longitudinal directions. After grinding, polishing and etching, the macrostructure was recorded by the Digital Single Lens Reflex. The etching agent consisted of 90 ml H_2O, 5 ml HNO_3 and 5 ml HF. The microstructures about lamellae orientation were investigated by the optical microscope (OM, Olympus GX71). Microstructure details were examined by scanning electron microscope (SEM, Quanta 200FEG) and transmission electron microscopy (TEM, Tecnai F30). The areas of the Y_2O_3 particles in the SEM image were measured by Image-Pro Plus software. More than10 micrographs were analyzed to obtain statistically averaged values. TEM was used to measure the inter-lamellar spacing at higher magnification and analyze the structure of Y_2O_3 particle.

The tensile properties were measured by an Instron-5569 tester with a loading rate of 0.5 mm/min at room temperature (RT). Flat dog-bone-like tensile samples were EDM with the tensile axis parallel to the growth direction, and samples had a 20 mm gauge length with a 6 mm × 2 mm cross-section. In order to eliminate the stress and cutting marks caused by EDM and observe the side-view of the tensile specimen, all tensile samples were polished with 2000 grit emery papers and electro-polished in a solution of 5% $HClO_4$, 35% butanol and 60% methanol at −25 °C.

3. Results

3.1. Structures

3.1.1. Typical structure of DS Ti-45Al-2Cr-2Nb alloy

The typical structure of DS Ti-45Al-2Cr-2Nb alloy is displayed in Fig. 2. As shown in Fig. 2a, columnar grains are aligned nearly parallel to the growth direction at a length of about 100 mm, covering approximately the full length of the directionally solidified sample. The microstructure of the selected "A1" zone is shown in Fig. 2b; the orientations of lamellae are primarily concentrated 0–60° to the growth direction. Fig. 2c shows the typical microstructure of a DS region selected in the "A" zone. The microstructure consisted of α_2/γ lamellae. A small volume fraction of elongated B2 phase was formed at α_2/γ lamellae or along the grain boundaries. In addition, the DS samples contained Y_2O_3 particles that were formed due to the reaction between the mould and the TiAl melt. Fig. 2d indicates that the Y_2O_3 particles were preferentially distributed in the interdendritic (β dendrite) region, which is similar to results reported in previous studies [12–15]. For these reasons, we believe that the Y_2O_3 segregation is a result of the rejection of the particles by the growing β dendrites during solidification. A higher magnification image (Fig. 2e) further reveals their near-equiaxed morphology (diameter about 1 μm).

3.1.2. Effect of solidification parameters on lamellar structure

Statistics results of lamellae orientation of DS samples prepared at varied solidification parameters are shown in Fig. 3. In general, the lower growth rates and higher heating powers yield increasing percentage of small angle lamellae [10,16,17]. Here, the angle is the intersection angle between the lamella orientation and the columnar grain growth direction. In this research, almost all DS samples obeyed this rule except the sample prepared at a solidification parameter with a heating power of 25 kW and growth rate of 1.0 mm/min, which produced lamellae perpendicular to the growth

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