Effect of Low angle Grain Boundary on the Microstructure and Mechanical Properties in a Fourth Generation Nickel Based Single Crystal Superalloy

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Abstract: The effect of different low angle grain boundaries (LAGBs) on the microstructure and mechanical properties in a fourth generation Nickel-based single crystal superalloy was studied. Double seed crystals techniques were used to obtain the specimens with LAGBs. After thermal exposure at 1100 °C for 100 h, the microstructure stability deteriorated when the angle exceeded 12.6°, where the discontinuous precipitation (DP) colonies region occurred along the grain boundary because of high interfacial energy and mobility at LAGBs. With the grain boundary angle increasing, the ultimate tensile strength of the sample rose slightly and then fell, while the elongation and creep rupture life decreased significantly exceeded 4.9°. Under 1100 °C service condition, the carbides and topological close-packed (TCP) phases were precipitated at LAGBs, which seriously impaired the grain boundary bonding strength. On the other hand, the misorientation at LAGBs led to the stress concentration, which increased the difficulty of grain boundary coordinated deformation. Finally, the damage tolerance of the LAGBs in this fourth generation Nickel-based single crystal superalloy was approximately estimated as about 7° at 1100 °C/150 MPa creep rupture condition based on a 70% creep rupture life standard.

Keywords: Nickle-based single crystal superalloy; Low angle grain boundaries; Microstructure; Mechanical properties; Damage tolerance

1 Introduction

In order to meet the need of the increasing thrust-to-weight ratio of aero-engines, the content of refractory elements in single crystal superalloys increased, the turbine blade shape and the internal air-cooled structure became increasingly complex, and the instability factors in the directional solidification process of single crystal turbine blades increased, inevitably resulting in the formation of LAGBs defects [1,2]. LAGBs could provide some preferential nucleation sites for precipitated phases as a high diffusion channel, which destroyed the γ/γ′ microstructure and deteriorated the properties of the alloy [3,4]. Therefore, it was significant to reveal the effects of LAGBs on the mechanical properties of nickel-based single crystal superalloys. The aim of the present work was to investigate the effects of LAGBs on the microstructure stability, tensile properties and creep rupture properties of a fourth generation Nickel-based single crystal superalloy. This research could also accelerate the application process of the fourth generation Nickel-based single crystal superalloy.

2 Experimental procedure

The nominal composition of the experimental Ni-based single crystal superalloy is as follows (wt.%): 21.5Co+Mo+W, 14.5Al+Ta, 3.5Cr, 0.1Hf, 5.4Re, 3.0Ru, 0.1C, and the balance Ni. The samples with different LAGBs (4°, 8° and 12°) could be prepared by a bi-crystals method, where the grain boundary angle was controlled by two seeds as shown in Fig. 1(a). The HCl + H_2O_2 etchant was used to slightly corrode the samples for the observation of the grain boundary as shown in Fig. 1(b)

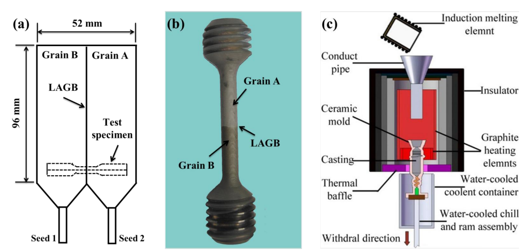

Fig. 1. The schematic diagram of the bi-crystal slab casting (a), the transverse test specimen after macro etching (b) and schematic illustration of the Bridgeman high rate solidification (HRS) furnace (c).

The bi-crystals samples were directionally solidified by high-rate solidification (HRS) process as shown in Fig. 1(c). The standard heat treatment process was adopted as follows: 1315 °C/16 h+1325 °C/16 h/air cooling (AC); 1150 °C /4 h/AC; 870 °C/24 h/AC.

3 Result and discussion

Effect of LAGBs on the microstructure stability

After the thermal exposure for different times at 1100 °C, the γ′ phase in matrix gradually coarsened and connected to form a labyrinthine microstructure, and the microstructure at LAGBs evolved differently ascribed to differences in grain boundary angles, as revealed in Fig. 2. A γ-phase film was formed along LAGBs when the grain boundary angle was small as shown in Fig. 2(a) and (b). With the extension of thermal exposure time, the thickness of the γ-phase film increased and was equivalent to the size of the channel in matrix, controlled by the element diffusion behavior. In Fig. 2(c), a DP colonies region occurred at LAGBs when the grain boundary angle was large, such as 12.6°. The regular and ordered γ/γ′ phase microstructure was transformed into a coarse (γ′+γ+TCP) microstructure. The DP colonies region altered the orientation of the single crystals within the zone to be consistent with the orientation of the other crystal and precipitated the TCP phases. Simultaneously, the boundary advance into the other crystal to become a new grain boundary. The width of the DP colonies region increased with the thermal exposure time extension, forming a diffusion-controlled solid phase transition. Moreover, the higher mobility at the grain boundary provided the potential for a DP colonies region.

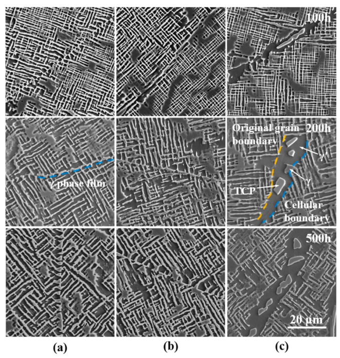

Fig. 2. SEM images of LAGBs microstructure of the alloy with (a) 4.9°; (b) 7.5° and (c) 12.6° after thermal exposure at 1100 °C for 100 h, 200 h and 500 h.

4 Effect of LAGBs on the mechanical properties

The variation of the tensile strength and elongation of the specimen with the grain angle was presented in Fig. 3(a). As the grain boundary angle increased, the strength of the alloy increased slightly at first and then decreased gradually, while the plasticity rapidly decreased. At 1100 °C/150 MPa creep rupture condition, the creep rupture life of specimens containing LAGBs significantly decreased as the grain boundary angle increased, as shown in Fig. 3(b). The effect of LAGBs on mechanical properties was primarily the deterioration of grain boundary microstructure and stress concentration at the grain boundary. The elastic modulus of crystals on both sides was inconsistent along load direction. Then, stress concentration occurred at the grain boundary, and the degree varied with the grain boundary angle, so as to assure the deformation coordination at the grain boundary. From another perspective, LAGBs, with a high energy and element diffusion rate, were easy to form γ phase file, DP colonies region and carbides, which deteriorated the microstructure and lowered the bonding strength of the grain boundary.

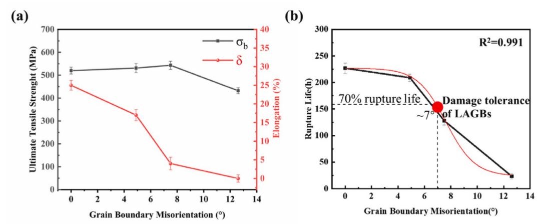

Fig. 3. Transverse tensile properties of the alloy with LAGBs specimens at 1100 °C (a) and transverse rupture properties at 1100 °C/150 MPa (b).

5 Conclusion

1. After thermal exposed at 1100 °C for different times, a γ phase film formed along LAGBs or a DP colonies region occurred, the width of which increased with the extension of the thermal exposure time.

2. Under 1100 °C/150 MPa creep rupture conditions, the alloy has a LAGBs damage tolerance of approximately 7° based on a 70% creep rupture life standard.

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