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Effect of Solidification Parameters on the Microstructure and Creep Property of a Single Crystal Ni-base Superalloy

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A single crystal Ni-base superalloy was processed with withdrawal rates between 2 and 7 mm/min. The as-cast microstructures, heat treatment response and creep property have been characterized as a function of the withdrawal rate. As expected, the primary and secondary dendrite arm spacing decreased with increasing withdrawal rate; microsegregation degree and porosity distribution were also varied with different withdrawal rates. The withdrawal rate of 2 mm/min resulted in a noticeable residual microsegregation even after full heat treatment. The samples solidified at 7 mm/min exhibited a high density of cast porosities, and this led to a dramatical decline of the creep strain. 4 or 6 mm/min appeared to be the optimum withdrawal rate in the present study, which resulted in a uniform microstructure and an optimum density of cast porosity.

KEY WORDS: Single crystal superalloy; Withdrawal rate; Microstructure; Creep

1. Introduction

In recent years, Nickel-base single crystal (SC) superalloys have been widely used and resulted in dramatic improvements in the performance of gas turbines[1–3]. Single crystal superalloys which exhibit considerable improvement in the mechanical properties are usually attributed to the characteristics as below: (I) complete elimination of grain boundaries; (II) accurate control of growing crystal orientation; (III) elimination or reasonable reduction of the amount of the grain boundary minor element which leads to a rise in solution temperature[4]. With SC superalloys developing, it is gradually realized that there are some defects associated with the microstructures of SC superalloys which are detrimental to their performance and give rise to a limit to their potential use, such as: (I) serious dendritic segregation; (II) microporosity located in interdendritic region. Although these defects seem to be inevitable in the dendritic structure, adjusting solidification parameters during superalloy casting is still an effective method to optimize microstructures then to obtain improved mechanical properties eventually. Therefore, many researches have been concentrated on the influence of the solidification parameters (such as withdrawal rate and thermal gradient) on microstructures and mechanical properties[5–14]. It is found that, in general, the dendrite arm spacing decreases as the withdrawal rate increases. The solute segregation, microporosity and creep property are also affected by withdrawal rate. Some researches reported that there exists a peak value for creep properties with increasing the withdrawal rate[7]. While some researches showed that a complete homogenization heat treatment could eliminate any difference in segregation resulted from varying of withdrawal rate, and increasing withdrawal rate does not offer an improvement in properties of SC superalloys[11]. Up to now, there is still no consistent conclusion about the influence of withdrawal rate on the microstructure and property. In order to better understand the influence of the withdrawal rate, in the present paper, the effect of the varying solidification processing parameters (*i.e.*, withdrawal rate) on the microstructure and creep property of a single

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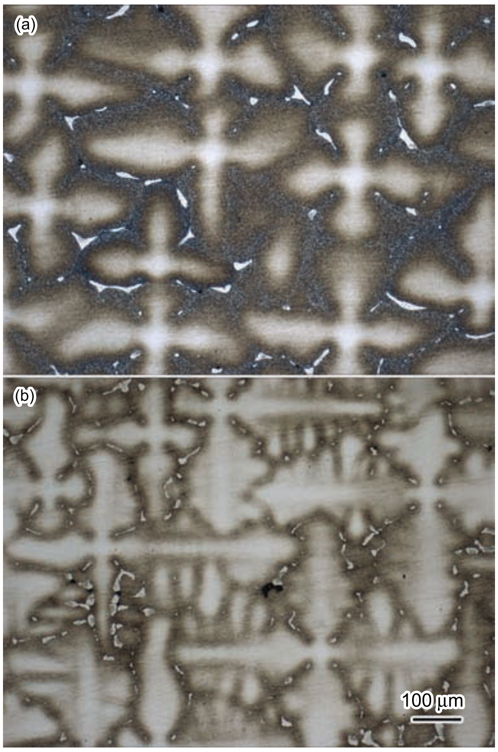

Fig. 1 The as-cast microstructure of experimental alloys at various withdrawal rates: (a) 2 mm/min, PDAS=356 μm; (b) 7 mm/min, PDAS=283 μm

Table 1 Nominal compositions of the experimental alloy (mass fraction, %)

Cr	Co	Mo	W	Al	Ta	Ti	Ni
8	5.5	2.2	5	6	3.5	2	Bal.

crystal Ni-base superalloy has been carried out. Based on this study, more guidance for choosing optimum withdrawal rate in directional solidification process will be provided.

2. Materials and Experimental Procedures

The alloy used for the present work is a first generation SC superalloy (for alloy composition see Table 1). All of the samples examined in this study were from the same master alloy. The single crystal bars (16 mm in diameter and 200 mm in length) were produced in [001] orientation by Bridgman high rate solidification technique at four withdrawal rates: 2, 4, 6 and 7 mm/min, and the temperature gradient at solidification front was approximately 60–80°C/cm. The orientation of each bar was determined by electron back-scatter diffraction technology (EBSD). Only samples with orientations within 10 deg. were used in the experiment. The alloys received a solution and homogenization heat treatment at 1280°C for 2 h and 1300°C for 4 h followed by a precipitation heat treatment at 1080°C for 6 h and 870°C for 24 h in air.

The microstructure of the samples was observed by optical microscopy (OM) and scanning electron microscopy (SEM) metallographic techniques. To characterize the porosity, a total of 50 OM images unetched samples were captured for each sample corresponding to 40% of the transverse section of each single crystal bar. Pores under 5 μm in diameter were rejected. Image analysis of porosity was performed by Sisc IAS image analysis system to determine the number, area fraction and diameter. Microprobe analysis was conducted on polished, but un-etched samples to analyze the compositions of various regions and the degree of segregation. Differential scanning calorimetry (DSC) was performed to determine the γ' solvus temperature, solidus, liquidus in the as-cast and heat-treated samples. Uni-axial constant load tensile creep testing was carried out in a FC-20 creep-testing machine on specimens with 25 mm in gauge length and 5 mm in diameter in ambient atmosphere at 980°C/260 MPa along the [001] direction.

3. Results and Discussion

3.1 Microstructure of as-cast samples

Figure 1 shows the typical transverse as-cast microstructures with different withdrawal rates, and all exhibited the dendritic segregation pattern with γ/γ' eutectic in the interdendritic areas. As expected, the primary dendrite arm spacing (PDAS) and the secondary dendrite arm spacing (SDAS) decreased with increasing withdrawal rate, as listed in Table 2. SEM observation showed that γ' precipitates became more refined with smaller dendrite arm spacing as the withdrawal rate was increased. The average volume fraction of γ/γ' eutectic in the as-cast microstructure did not appear to be a strong function of the withdrawal rate. The volume fraction of γ/γ' eutectic varied from 1.96% to 2.13%. It also can be found that with the decrease of DAS, γ/γ' eutectic regions tended to distribute more dispersedly and to be smaller in volume, as shown in Fig. 1.

The DSC testing of the as-cast samples indicated that the solidus and the liquidus temperatures did not strongly vary with the withdrawal rate (Table 3). Their changes were quite small and within typical experimental scatter for DSC testing. No evidence of the γ'-solvus temperature was observed in the DSC data for the as-cast samples.

The chemical compositions of the dendritic and interdendritic regions were determined by using an electron microprobe to investigate the difference in the extent of microsegregation which resulted from varying withdrawal rate. Comparing to the nominal composition, W segregated mainly in dendrite core for all samples, while Ta, Al and Ti segregated mainly in the interdendritic region. The eutectic γ/γ' regions were further enriched in Ta, Al and Ti, and depleted in W. The partition ratio k'=(dendritic composition/interdendritic composition) of these elements