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ARTICLE

Effects of Elevated Withdrawal Rate on the Microstructure and Segregation Behavior of a Nickel-base Single Crystal Superalloy

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Abstract: The effects of withdrawal rate on the microstructure and segregation behavior of a nickel-base single crystal superalloy were investigated. The results indicate that by increasing the withdrawal rate, the primary dendrite arm spacing (λ_1), the secondary dendrite arm spacing (λ_2) and the size of γ' precipitates decrease gradually. Moreover, the shape of γ' precipitates is more regular at higher withdraw rates. Also, the size of γ/γ' eutectic becomes small while the total volume fraction increases. Considering the composition segregation is determined by diffusion time of the constituent elements, when withdrawal rate is elevated, diffusion time of solutes decreases, and the effects of segregation are enhanced.

Key words: nickel-base single crystal superalloys; withdrawal rate; solidification microstructure; composition segregation

Due to the excellent high temperature creep performance, nickel-base single crystal superalloys are attractive preference of advanced aero-engine turbine blades[1-6]. As known, performance of nickel-base single crystal superalloys is determined by the alloy composition, the melting process of master alloy, the directional solidification (DS) technique and heat treatment schedule. Using seed or by a screw selecting method to prepare single crystals, temperature gradient of the liquid/solid interface and crystal growth rate are the two key parameters for the as-cast microstructure and the final performance[7-11]. Therefore, it is very important to investigate the effect of withdrawal rates on the microstructure of nickel-base single crystal superalloys. Moreover, the multi-alloying of single crystal superalloys can lead to severe segregation in the as-cast microstructure and ultimately influences the heat treatment process and the performance of alloy[12-14]. In the present paper, the relationships between growth rates of the nickel-base single crystal superalloys, dendrite arm spacings (λ_1, λ_2), γ' phase, γ/γ' eutectic and composition segregation were investigated. We tried to optimize the process parameters and found an appropriate way to control the as-cast microstructure under a constant temperature gradient.

1 Experiment

The nominal composition (wt%) of the experimental alloy is 7Cr-7.5Co-2Mo-5W-6.5Ta-3Re-6.2Al, and the balance is Ni. The master alloy ingots were prepared by water-cold crucible vacuum induction levitation melting. Rod-shaped samples from the ingots were cast into a copper mold by gravity casting. The single crystal bars with a diameter of 8 mm and a length of 100 mm were prepared by a seed method using a vacuum induction directional solidification furnace as shown in Fig.1. The DS was carried out for the samples with withdraw velocities (V) of 10, 20, 50, 80 μm/s at the holding temperature of 1823 K. And the deviation between the principal axes and [001] direction was less than 10°. The

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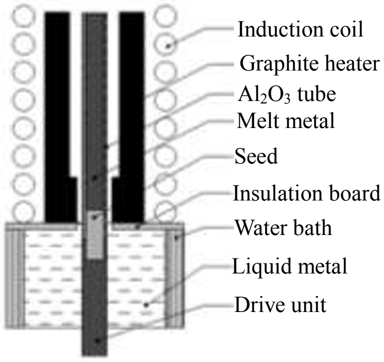

Fig.1 Schematic diagram of directional solidification

resulting samples were polished, and then were etched by a solution of 5 g $CuSO_4$ +20 mL HCl+80 mL H_2O. The as-cast microstructure was observed by Olympus GX41 optical microscope (OM) and ULTRA 55 scanning electron microscope (SEM). The composition segregation coefficient was calculated according to Energy Dispersive X-ray Spectroscopy (EDX). The dendrite arm spacing was calculated by a unit area method and the content of γ/γ' eutectic was measured by a specific area method.

2 Results and Discussion

2.1 Effect of withdrawal rate on the dendrite morphology

The as-cast microstructure at different withdrawal rates is shown in Fig.2a~2d. All the alloys were solidified in a dendrite way and many γ/γ' eutectics were distributed among the interdendritic region. By increasing the withdrawal rates, the size of dendrite spacing decreased. The relationships between withdrawal rates and the dendrite arm spacing (λ_1 and λ_2) are shown in Fig.2e and 2f. They exhibit a linear relationship between λ_1, λ_2 and $v^{-1/4}$, $v^{-1/2}$ respectively, consistent with the Hunt fore- casting model[15,16]. During the solidification process, fresh grains nucleate and grow in the form of dendrite due to the constitutional supercooling because of the solute enrichment. By increasing the withdrawal rate, the degree of constitutional supercooling of the solid/liquid interface becomes larger, and the radius of the dendrite tip is smaller and sharper. Therefore, the solute atoms shift more easily per unit time which is conducive to diffuse atoms. Moreover, with the enhanced radiating capability of solid solution and the effect of the solidification heat on the each branch, λ_1, and λ_2 gradually become weak.

2.2 Effect of withdrawal rate on γ' phase

Fig.3 shows the morphology of γ' phase in dendrite and interdendrite at different withdrawal rates. As shown, the size of γ' phase in dendrite core is smaller. Moreover, by increasing the withdrawal rates, the sizes of γ' phase both indendrite core and interdendritic region decrease, as shown in Fig.4. However, the morphology of γ' phase is also more regular and the volume fraction of γ' phase in dendrite core and interdendrite region is larger at the higher withdrawal rate.

The microstructure of the nickel-base superalloys primarily consists of γ matrix and γ' phase precipitated from the continuous γ phase. According to the phase formation rule, γ' phase is divided into primary γ' phase and the secondary γ' phase. The primary γ' phase nucleates and grows from residual liquid through the eutectic reaction ($L\rightarrow\gamma+\gamma'$), and the secondary γ' phase is precipitated by the eutectoid reaction ($\gamma_1\rightarrow\gamma_2+\gamma'$). In the early time of eutectoid reaction, the γ' phase is precipitated

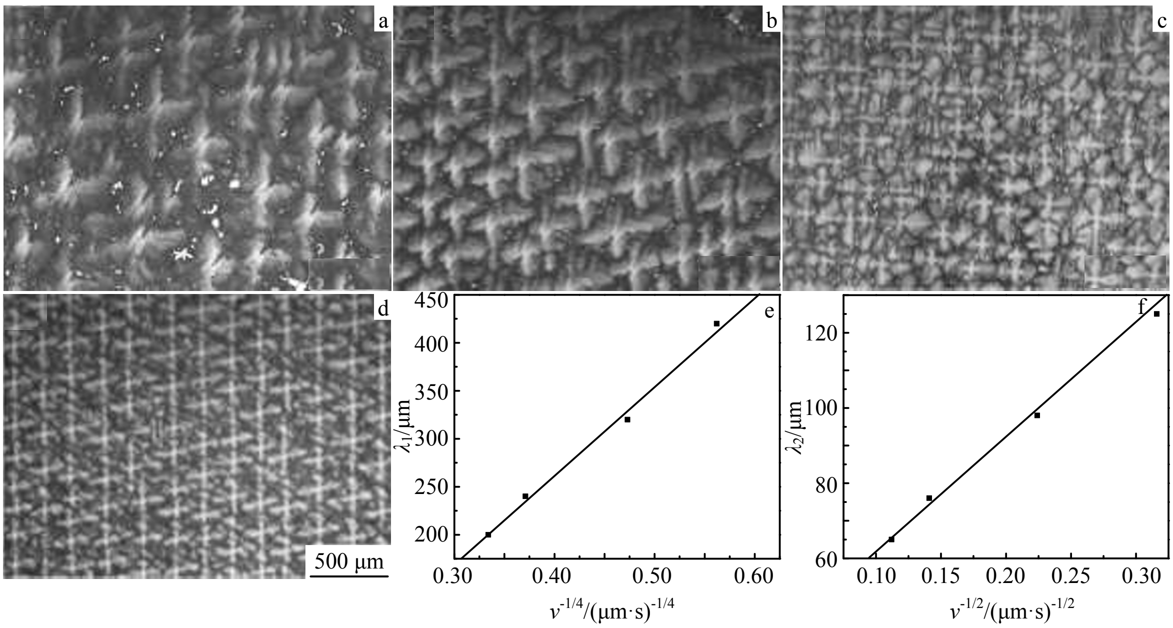

Fig.2 Dendrite morphology at different withdrawal rates: (a) 10 μm/s, (b) 20 μm/s, (c) 50 μm/s, and (d) 80 μm/s and relationship between dendrite spacing λ_1 (e), λ_2 (f) and the withdrawal rates