EFFECT OF SHELL TEMPERATURE ON SOLIDIFICATION ORGANIZATION OF EQUIAXED CRYSTAL BLADE

Guoqiang Cao[1], Bo Zhang[1], Gang Li[2], Wenya Peng[2]
[1]School of Mechanical and Electrical Engineering, Shenyang Aerospace University, P.R. China;
[2]AECC Hunan Aviation Powerplant Research Institute, P.R. China
sycgq@126.com

Abstract. The investigation was conducted into the effects of different shell preheating temperatures (1100 °C, 1150 °C, and 1180 °C) on the organization of solidification of isometric crystalline blades made for an aero-engine. The experimental results show that with the increase of shell temperature, the dendrite spacing and dendrite robustness gradually increase, while the area between dendrites gradually increases. The size of the eutectic gradually increases as the shell temperature rises, and there is no obvious regularity in the eutectic content. The size and content of carbide show a trend of decreasing first and then becoming larger, and the size relationship was 1180 ºC > 1110 ºC > 1150 ºC. There is no obvious difference in the composition of carbides at different shell temperatures, all of them are MC-type carbides, and none of them decompose. At 1150 ºC, γ′ phase has a smaller size, the best cubical and most regular arrangement, while the largest size, worst cubicization and most irregular phase at 1180 ºC.

Keywords: equiaxial crystal superalloy; shell temperature; microstructure.

Introduction

Equiaxial crystal casting of high-temperature alloy blades is a key component of the hot end of advanced aero-engines, and the casting quality of the blades directly affects the engine life and reliability. The investment casting technology is the main molding method [1]. Melt casting of high temperature alloys is a process in which a vacuum induction melting alloy is poured into a preheated shell shape and cooled to obtain an equiaxed crystal casting with a certain shape [2]. This process is prone to coarse grain size, shrinkage and other solidification defects when forming complex structural castings of slender and thin-walled types [3]. In order to eliminate or reduce solidification defects and improve the mechanical properties of castings, researchers have developed optimization processes such as the thermal control method, kinetic method and chemical method. The thermal control method is mainly used to control the cooling rate and temperature gradient of the alloy by lowering the pouring and shell temperature to form a uniform temperature field over the entire casting section in order to increase the nucleation rate and thus obtain fine equiaxed crystals [4]. In the 1990s, a new thermal control solidification (TCS) technology was developed by PCC in USA [5], which is based on the principle of directional solidification, where the shell is held just below the solid-phase line temperature and the melt is drawn to the cold zone at a certain rate after pouring to complete solidification. By controlling the temperature gradient and solidification rate during solidification of high temperature alloys, sequential solidification conditions are formed that are not limited by the geometry and location distribution of the casting, which improves the complementary shrinkage during solidification and thus eliminates the shrinkage defects inside the casting. Zheng [6; 7] set the shell temperature in the solid-liquid phase line temperature interval and improved the thermally controlled solidification process to reduce the shrinkage defects. Recently, Jie [8] used this technique to achieve a composite control of casting densities and grain size as a way to improve the performance of castings.

In the casting process of high temperature alloy equiaxial crystal blade, the casting of slender crowned blade is the most difficult, often due to casting defects and fatigue performance failure and leads to a large number of cast blade scrap [9-10]. Among them, in the blade casting production practice is found that the shell preheating temperature has a great influence on the solidification of the blade organization and performance, but its specific influence law and mechanism of action to be further clarified. For this reason, this paper carried out a study on the effect of different shell preheating temperature on solidification organization of a certain type of aero-engine equiaxial crystal blade.

Materials and methods

The alloy composition of equiaxed crystal blades used in this study is shown in Table 1. The blades are slender blades with crowns, with the dimensions of 200mm × 50mm in length and width, the thinnest exhaust blade is 1mm and the intake side is as thin as 3mm.

Table 1

Chemical composition of the alloy (mass fraction/%)

C	Cr	Mo	W	Co	Nb	Al	Ti	Ni
0.13-0.20	8.0-9.5	1.2-2.4	9.5-11.0	9.0-10.5	0.8-1.2	5.1-6.0	2.0-2.9	Bal.

The test shells were made of a slurry of silica sol and Al_2O_3 powder, which were coated and hung by spreading Al_2O_3 sand in multiple layers. The tests were carried out in a large industrial production isometric furnace, and the preheating temperatures of the shells before casting were 1100 ºC, 1150 ºC and 1180 ºC. The preheating and holding time of the shells was greater than or equal to 4 hours. The pouring temperature of the alloy liquid was 1490 ºC.

The metallographic specimens were prepared by cutting the blade into different parts, and then corroded by $HF:HNO_3:CH_3COOH:H_2O$ = 1:33:33:33 corrosive solution after grinding and polishing treatment. Shrinkage of the alloy was observed using a DM4000M optical microscope. The microstructure of the alloy was characterized using a ZEISS SUPRA 55 field emission scanning electron microscope. The shrinkage content, carbide area and γ′ phase size and volume fraction were calculated using Image-pro Plus software.

Results and discussion

After the corrosion of the blades with three different shell preheating temperatures, the surface grain size analysis is shown in Fig. 1. It can be found that the blade surface grain degree of different casing preheating temperature is not significantly different, which indicates that the shell preheating temperature does not affect the grain size.

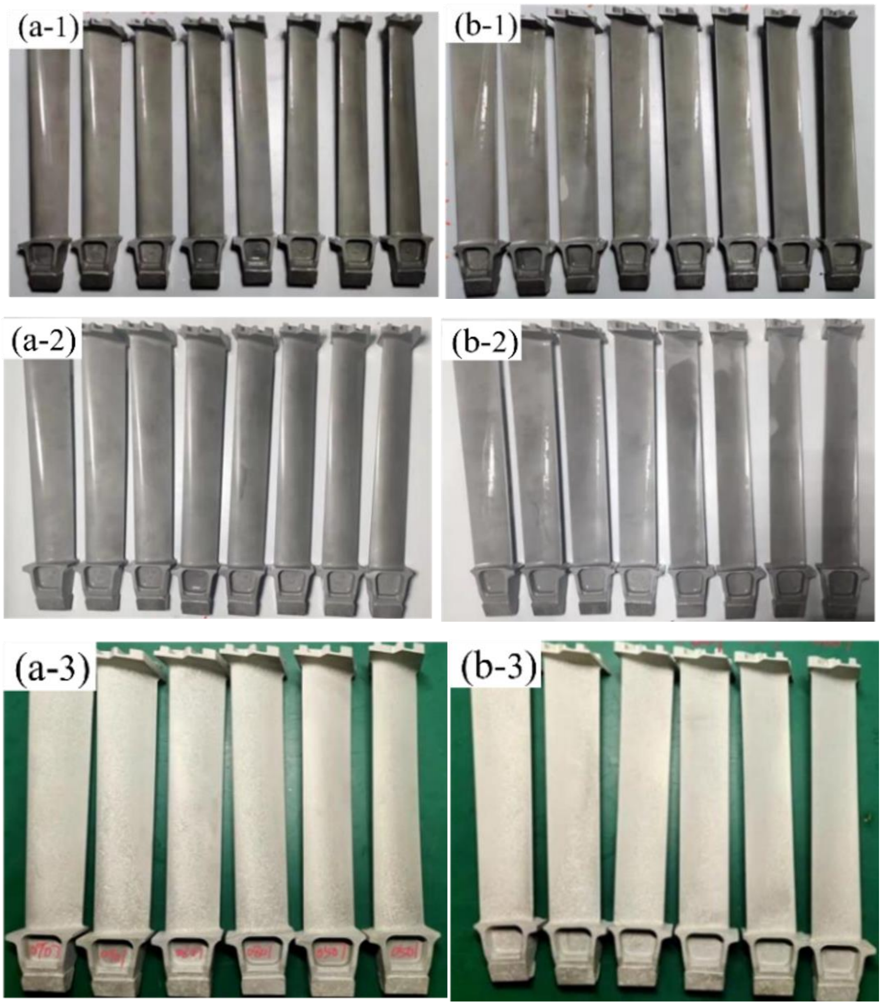

Fig. 1. **Surface grain size of blades after corrosion at three types of shell preheating temperature:** a – convex; b – concave; (1)1110 ºC; 2 – 1150 ºC; 3 – 1180 ºC

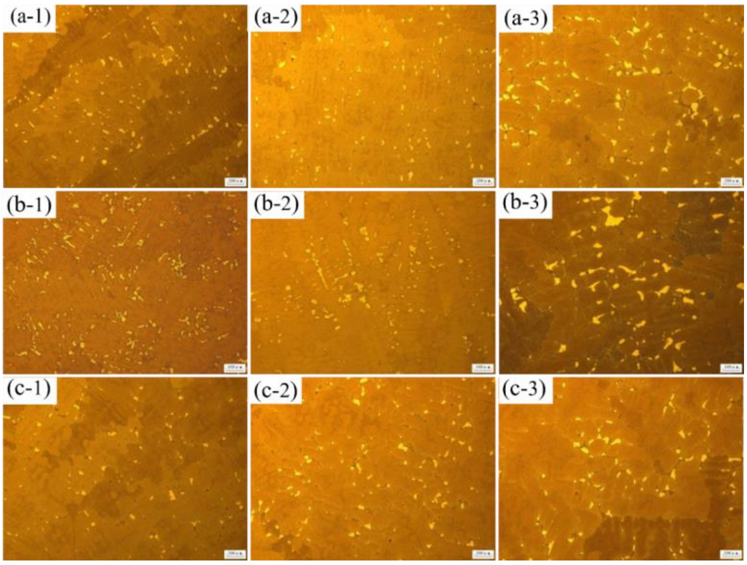

Fig. 2. **Dendrite morphologies of the blade typical sectional positions at three shell temperatures:** a – canopy; b – aerofoil; c – tenon; 1 – 1110 ºC; 2 – 1150 ºC; 3 – 1180 ºC

Further analysis of the dendrite morphology at different shell temperatures and different positions is shown in Fig. 2. With the increase of shell temperature, the spacing and sturdiness of dendrites gradually both increase, while the area between dendrites gradually increases. The difference of dendrite organization in the leaf body is the largest, and the difference of dendrite organization in the tenon part is the smallest. The size of eutectic gradually increases by increasing the shell preheating temperature. At the same time, the eutectic content of different positions was counted, and it was found that the highest eutectic content was found at 1150 °C and the lowest at 1110 °C in the tenon part. The lowest eutectic content was found at 1150 ºC in aerofoil part, and the eutectic content was close at 1110 ºC and 1180 ºC. The canopy part had the highest eutectic content at 1180 ºC, and the eutectic content at 1110 ºC and 1150 ºC was close.

In-depth characterization of the microstructure shows that there are some differences in the morphology and distribution of carbides as the shell temperature increases, as shown in Fig. 3.

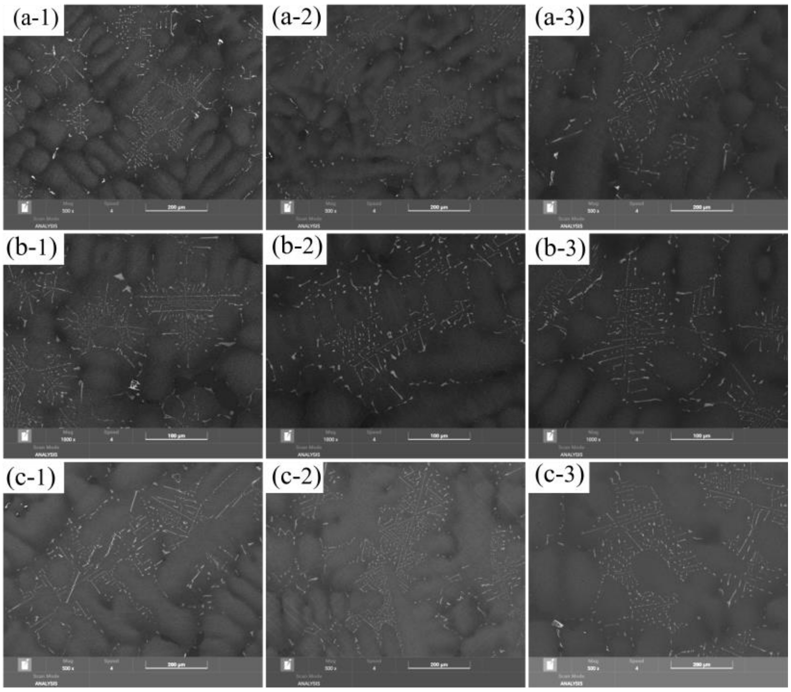

Fig. 3. **Carbide morphology of the blade typical sectional positions at three shell temperatures:** a – canopy; b – aerofoil; c – tenon; 1 –1110 ºC; 2 – 1150 ºC; 3 – 1180 ºC

Both reticular and massive carbides existed at different shell temperatures, with more massive carbides at 1110 °C and more scattered reticular carbides at 1150 °C and 1180 °C, and the reticular carbides were the most regular at 1150 °C. The size and content of carbides were counted, and it was found that with the increase of the shell temperature, the size of carbides showed a trend of decreasing first and then becoming larger, and the size relationship was 1180 ºC > 1110 ºC > 1150 ºC. The carbide content also showed the same trend in Fig. 4, with 4.9% at 1110 °C, 3.1% at 1150 °C and 5.8% at 1180 °C. The energy spectra of carbides at different shell preheating temperatures were analyzed. As it can be seen from Figure 5, with the increase of the shell temperature, there is no significant difference in the composition of carbides, which are all MC-type carbides, and none of them decomposed.

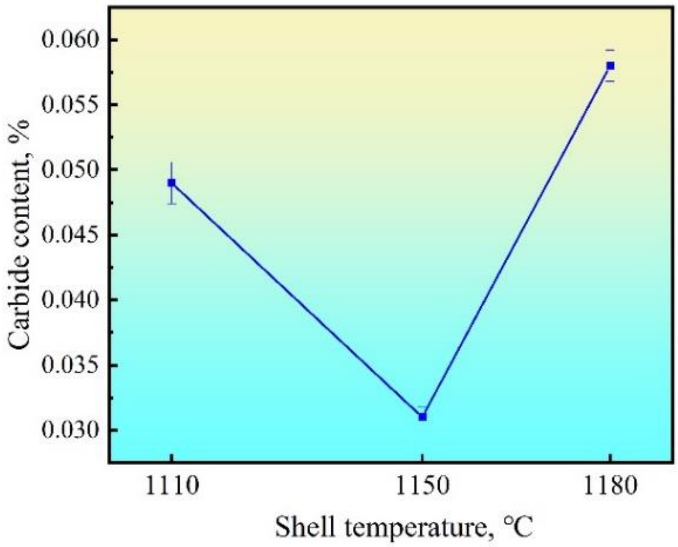

Fig. 4. **Carbide content of the blade at three shell temperatures**

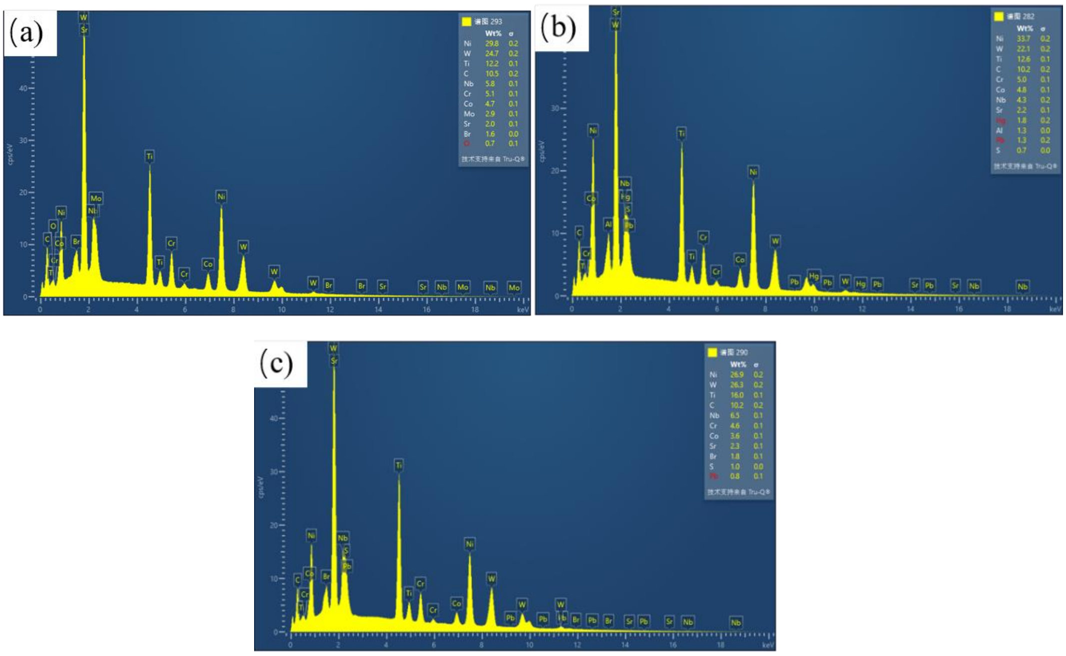

Fig. 5. **EDS of carbide at different shell preheating temperatures:**
a – 1110 ºC; b – 1150 ºC; c – 1180 ºC

The effect of the casing preheating temperature parameter on the morphology of γ′ phase at different locations of the equiaxed crystal blade is shown in Fig. 6. With the increase of the casing preheating temperature, the size of γ′ phase at the canopy part shows a gradual increase, and the size relationship of γ′ phase at aerofoil and tenon is 1180 ºC > 1110 ºC > 1150 ºC. Meanwhile the cubicization of γ′ phase at 1150 ºC is the best and the arrangement is the most regular, but at 1180 °C the cubicization of γ′ phase is the worst and the arrangement is the most irregular.

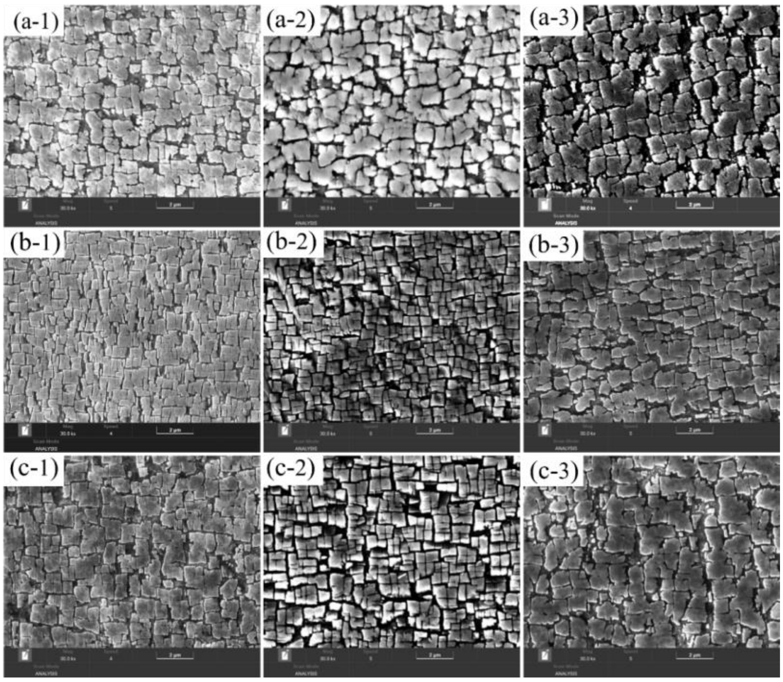

Fig. 6. **Microstructures of γ′ precipitates of the blade typical sectional positions at three shell temperatures:** a – canopy; b – aerofoil; c – tenon; 1 –1110 ºC; 2 – 1150 ºC; 3 – 1180 ºC

Conclusions

1. There was no significant difference in the grain size of this equiaxed blade due to shell preheating temperature.
2. As the preheating temperature of the shell increases, the dendrite spacing and robustness gradually increase, while the area between dendrites gradually increases. For eutectic, the size gradually increases with no obvious regularity of content.
3. With the increase of the shell temperature, the size and content of carbide showed a trend of decreasing first and then becoming larger, and the size relationship was 1180 ºC > 1110 ºC > 1150 ºC. However, there is no obvious difference in the composition of carbides at different shell temperatures, all of them are MC-type carbides, and none of them decompose.
4. The size of γ′ phase is smaller, best cubed and most regularly arranged when the insulation temperature of the shell is 1150 °C, and the opposite at 1180 °C.

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Author contributions

Conceptualization, G.C.; methodology, G.C.; validation, G.C. and Y.S.; formal analysis, G.C. and G.L.; investigation, G.C. and W.P.; data curation, G.C.; writing – original draft preparation, G.C.; writing – review and editing, Y.S. and G.C.; visualization, G.L.; project administration, G.C.; funding acquisition, G.C. All authors have read and agreed to the published version of the manuscript.

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