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Investigation on local cooling in reducing freckles for directionally solidified superalloy specimens with abruptly varying cross-sections

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ABSTRACT

In order to suppress the freckle formation in specimens with abruptly varying cross-sections, superalloy CMSX-4 was directionally solidified, and the local cooling method was investigated, in which a graphite block was inserted into the bottom of platform of specimen. The experimental and simulation results were coupled to evaluate this method in terms of freckling number, primary dendrite arm spacing (PDAS), dendrite morphology, and solidification interface shape. The results show that, with the application of local cooling method, freckles appearing in the specimens were absolutely removed. Dendrite microstructure was refined with reduced PDAS, and a dendritic to cellular transition was promoted. In addition, the concave solidification interface was flattened. Therefore, the local cooling method with the application of graphite block can be employed to reduce the freckling tendency in directionally solidified CMSX-4 superalloy specimens with abruptly varying cross-sections.

1. Introduction

With the increase in demand for electrical energy, efficient power generation based on industrial gas turbine (IGT) is favored. It means that larger directional solidification (DS) and single crystal (SC) blades need to be produced. At present, the process of IGT blades primarily depends on the well-developed technology for aero engines. However, the mass and size of IGT blades are several larger than that of aero engines, thus casting defects, such as freckles, stray grains and shrinkage, increase.

For the DS/SC superalloy castings, freckles, chain-like macrosegregation, are generally found on the surfaces of castings [1–6]. It is widely accepted that freckles arise for the reason that thermosolutal convection induced by the density inversion leads to the remelting and fracture of dendrite arms in the mushy zone [4,7–9], deteriorating high temperature mechanical properties, and cannot be removed by post-process and heat treatment. Thus, the formation of freckles should be prevented during solidification.

So far, several methods of reducing freckling tendency during solidification have been reported in the literatures. In the study of Lu et al. [10], freckles appearing on DZ411 superalloy blade were removed by the Liquid Metal Cooling process using liquid metal as coolant, because thermosolutal convection was depressed by the refined microstructure obtained. However, the coolant used may contaminate the castings. For the Downward Directional Solidification process proposed by Ma et al. [11], the density inversion leading to thermosolutal convection is absent owing to the downward dendrites growth, then the occurrence of freckles can be suppressed as demonstrated by Wang et al. [8]. In the patent of Ebisu [12], when the high static magnetic field is applied onto the whole mushy zone, thermosolutal convection can be suppressed, thus freckles will be eliminated. However, it needs to spend much time on the preparation of new equipment. According to the study on Autonomous Directional Solidification technique demonstrated by Ludwig et al. [13], it is believed that the interdendritic liquid flow will not be initiated for the shortened solidification time, therefore freckles may be removed. However, the rigid temperature control and the application of a nucleation-inhibiting amorphous coating complicate the practical operation.

In addition, in the study of Sample and Hellawell [14], the mould rotation, about axes inclined to the vertical by some degrees, led to the translation of bulk liquid across the solidification interface, disturbing convection, thus freckle formation was prevented. The investigation of Tan [15] revealed that thicker mushy zone containing more interdendritic liquid can support freckle formation, and also concluded that the application of vibration can reduce the mushy zone thickness, then causes the freckling tendency to be reduced. A study by Shih et al. [16] showed that the periodic lid-driven flow applied onto the free surface during solidification can reduce the concentration gradient near the front of solidification interface and within the mushy zone, leading to the weakened thermosolutal convection, and then depresses the freckle formation. These methods above do well in aqueous ammonium chloride (NH_4Cl-H_2O) solution, but the applications of them in the

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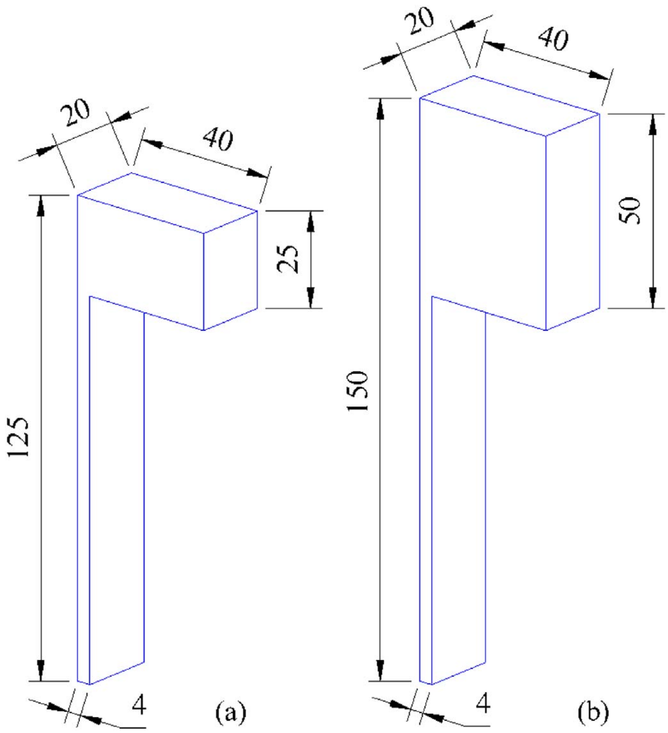

Fig. 1. Specimens used in the experiments. (a) with a height of 125 mm; (b) with a height of 150 mm.

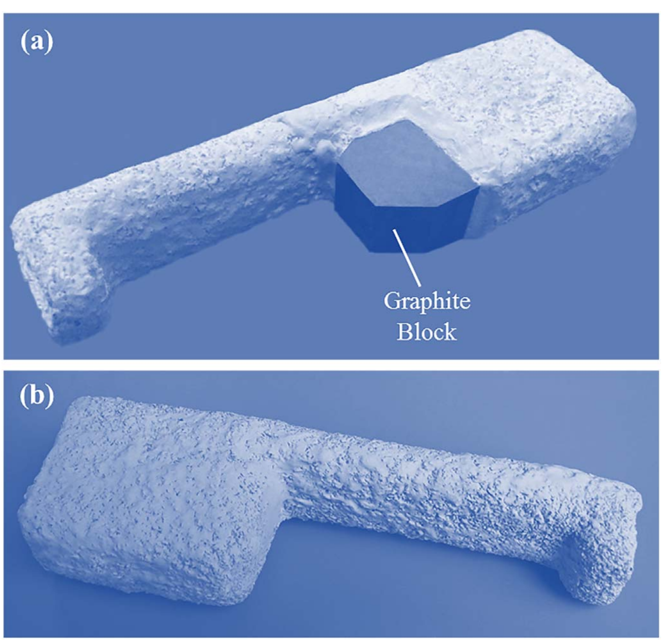

Fig. 2. Shell moulds (a) produced by modified investment casting procedure with graphite block and (b) used in previous work.

superalloys have not been reported and the poor operability also limits its application in the practical conditions.

In terms of IGT blade, the actual shape is characterized with non-uniform cross section, especially for the platform zone with an abruptly varying cross-section where the transition from blade body to tenon occurs, and in which freckles are usually found as reported by Tin and Pollock [17] and Hobbs et al. [18]. As is known to all, the primary component of ceramic shell material for the production of blades is Al_2O_3 with a low thermal conductivity and low emission coefficient. It means that, during solidification, the cooling rate and thermal gradient in the platform are low due to the large thermal resistance, and then a coarsened microstructure with large dendrite arm spacing will be obtained as reported by Pollock et al. [19] and Trivedi [20]. At the same time, the simulation results of Miller et al. [21] and experiments conducted by Pollock and Murphy [22] indicated that the large dendrite arm spacing and/or low cooling rate will lead to an increase of freckling tendency. Thus, based on analyses above, it is not difficult to conclude that the inefficient heat dissipation in the platform of blade induces the formation of freckles, and that the improvement of local cooling condition may suppress the freckles appearing in the platform.

In the previous study [23], the specimens with abrupt cross section variation were solidified directionally, and they found that freckles exclusively appeared on the surfaces within a range of 2–15 mm above the platforms. It can better simulate the situation in the platforms of blades. Therefore, in this paper, the specimens with abrupt cross section variation was chosen. More importantly, in order to improve the local cooling condition in the platform of specimen, a graphite block with a higher thermal conductivity and larger radiation area was inserted into the bottom of platform. Then, combining experiments and simulations, the effect of local cooling on freckle formation was investigated in terms of the microstructures and macroscopic solidification interface shapes.

2. Experimental Procedure

2.1. Directional Solidification Experiments

In order to model the practical processing procedure and freckle formation as accurately as possible in the laboratory, the rectangular specimens with abruptly varying cross-sections (Fig. 1) which were same as that in previous study [23] were employed. The specimen consists of two sections, of which the small and large section represent the blade body and tenon, respectively. The specimen shown in Fig. 1 (a) has a height of 25 mm above the platform, while it is 50 mm for that in Fig. 1(b).

According to previous study [23], freckle formation on the specimens with abruptly varying cross-sections is influenced by the platform. Thus, in this work, the shell mould shown in Fig. 2(a) produced with the modified investment casting procedure was designed, where a graphite block was inserted into the bottom of platform. To keep graphite block from reacting with melt, a thin ceramic layer (shown in Fig. 3) with a thickness of about 0.5 mm was located at the interface between graphite block and superalloy. In addition, the shell mould with no insertion of graphite block used in previous work is also shown in Fig. 2(b) for comparison.

Superalloy CMSX-4 (Cr 6.5, Co 9.0, Mo 0.6, W 6.0, Al 5.6, Ta 6.5, Ti 1.0, Re 3.0, and Hf 0.1, and Ni Bal. in wt pct) was chosen for the freckle-prone feature as reported by Schadt et al. [24] and Ma and Bührig-Polaczek [6]. All the specimens were directionally solidified in the conventional Bridgman furnace as shown in Fig. 3. The heater temperature was measured with the thermal thermocouple of type D (W-3% Re/W-25% Re). During solidification, CMSX-4 superalloy was overheated and soaked in shell mould for 20 min, and then pulled down from the heater through the baffle into the cooling chamber. The experimental conditions can be found in Table 1. The shell mould shown in Fig. 2(b) was used for case 1 and 2, while the one with graphite block shown in Fig. 2(a) was used for case 1# and 2#. The case 2 and 2# were designed so as to confirm the effect of local cooling on freckling tendency.

After directional solidification, the specimens were knocked out from shell moulds. The residual ceramic particles attached to the surfaces of specimens were removed with a sandblaster. The number (Table 1), distributions (Fig. 4) of freckles in the directionally solidified specimens were revealed with macro-etching agent (a solution of 50 pct H_2O_2 and 50 pct HCl). After that, specimens were sectioned transversely (perpendicular to the growth direction) at the position about