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Static solid cooling: A new directional solidification technique

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ABSTRACT

A new directional solidification technique has been presented. This technique employs the pyrolytic graphite for heat dissipation by conduction and does not withdraw the cast. The furnace design was presented for this static solid cooling (SSC) method. A heat dissipation model was put forward for evaluating the cooling efficiency by calculating the total thermal resistance in directional solidification. The total thermal resistance in the SSC method is the minimum compared with other methods. The solidification process is simulated and the results show that the axial temperature gradient increases to 130 °C/cm from 52 °C/cm (Bridgman method) and the growth rate is improved to 10.84 mm/min from 3.86 mm/min (Bridgman method). The solidification time is reduced by 64.4%. The cooling rate increases dramatically as well. Additionally, the heat insulation of the hot and cool zones is improved substantially in the SSC method. The thermal resistance of the mould is reduced as well due to the thin mould. Besides, the SSC method employs the electrical network to control the growth rate. The solidification condition is much uniform due to the position control by the electrical network.

1. Introduction

Single crystals possess many unique properties, particularly mechanical properties [1] and thus the single crystal growth techniques are widely applied in the manufacturing of blades and vanes. Much research has been devoted to producing defects-free single crystals of desired shapes and sizes since Bridgman [2] put forward the directional solidification method. Uniform and stable unidirectional heat flow and large temperature gradients in axial direction are the keys to obtain large complex single crystals. The Bridgman method involves melting the metal and slowly cooling the molten metal from one end with a seed crystal. Stockbarger [3] improved the axial temperature gradient by employing a baffle to separate the heating chamber and cooling chamber. Versnyder and Shank [4] developed the high rate solidification (HRS) technique based on the Bridgman-Stockbarger method and constructed the furnace accordingly for manufacturing gas turbine components. The HRS technique employs more cooling devices such as the cooling ring and the chill plate and is applied widely to industrial production due to the relatively stable temperature field and simple devices.

However, the Bridgman (HRS) method has some drawbacks that limit the development of large defects-free gas turbine components. The cooling efficiency is low due to the radiative heat dissipation. The mould is made of refractory ceramic whose thermal resistance is large and hence results in low cooling rates. Low cooling rates lead to a high propensity for formation of defects such as freckles [5]. Besides, the hot zone is poorly insulated with the cool zone because the cast contour is complex and doesn't match the annular baffle and the cast needs to be withdrawn from the hot zone to the cool zone. The solidification condition is nonuniform for different parts of the casts on account of the shelter effect of the components in the radiative heat dissipation. Distributed microstructural features are thus caused [5].

Many efforts have been made to solve the above-mentioned problems. Giamei and Tschinkel [6] presented the liquid metal cooling (LMC) method to improve the cooling efficiency and the insulation of the hot and cool zones. The cooling efficiency is improved due to the stirring liquid metal [6]. The heat insulation

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performance is improved because of the floating baffle. In addition, the solidification condition for the complex parts of the cast is more uniform. The axial temperature gradient increases notably and the microstructure of the cast is refined accordingly [7]. Nevertheless, an increase in the curvature of the solidification front and the deviations in dendrite morphology are observed in the LMC method [8]. The grain nucleation thus appears [9]. Besides, the devices in the LMC method are complex and cost high because of the liquid coolant. Additionally, the liquid metal comes inadvertently into the solidified superalloy and the partial dissolution appears because of the reactions between the solidified superalloy and the liquid metal [7].

Konter et al. [10] installed a gas cooling system under the baffle in the directional solidification furnace for increasing the cooling efficiency, which is called the gas cooling casting (GCC) method. The cooling efficiency is increased by employing the gas cooling technique [10]. However, the heating chamber is also affected by the cooling gas because of the unsatisfactory insulation of the hot and cool zones. Additionally, the increase of the thermal conductivity of the ceramic mould is limited by the surface roughness. Nakagawa et al. [11] employed the fluidized bed quenching (FBQ) method to improve the cooling efficiency. This method uses the fluidized ceramic powder to improve the cooling efficiency. However, the process control is difficult because of the impact of the solid particles on the mould.

Ma et al. [12] invented the thin shell casting (TSC) method for directional solidification and some related researches have been conducted [13–15]. The heat dissipation of this method combines the radiation with the gas cooling technique. Additionally, the thermal resistance of ceramic moulds is reduced due to the small thickness. The cooling efficiency increases accordingly. The heat insulation of the hot and cool zones is improved on account of the flexible baffle. In addition, the defects such as freckles are reduced in consequence of the solidification direction from the top down. Nevertheless, the surface finish of the external surface of the mould is required as that of the internal surface because the mould is immersed in the molten metal. Thus, the fabrication of the mould is more complex. In addition, the solidification condition for a complex cast is also nonuniform due to the radiative heat dissipation.

These methods overcome parts of the drawbacks in the Bridgman method. In order to solve all problems mentioned above, this paper presents a new method, static solid cooling (SSC) method, which employs the heat conduction to dissipate heat and does not withdraw the cast. A heat transfer solid with a large thermal conductivity and a large thermal diffusivity is used for improving the cooling efficiency and the axial temperature gradient. This heat transfer solid is composed of heat transfer layers and insulation layers. And this heat transfer solid surrounds a thin mould. The heating and cooling are both through the heat transfer solid and controlled by an electrical network. Section 2 presents the furnace design for the SSC method. In Section 3, a heat dissipation model is built for evaluating the cooling efficiency. The simulation of directional solidification process is also provided for the analysis of heat transfer. Section 4 shows the simulation approach of the directional solidification. The analyses of the heat dissipation and the solidification process are presented and discussed in Section 5 and 6. And this paper is concluded in Section 7.

2. Furnace design

Fig. 1 shows the schematic illustration of the SSC method. The mould is surrounded by the heat transfer solid who consists of heat transfer layers and insulation layers. The alternate layers are designed to obtaining a high axial temperature gradient and well heat insulation. The mould is both heated and cooled through the heat transfer layers. Thus, the heat transfer layers are required high thermal shock resistances. In addition, the heat transfer layers are required a large thermal conductivity and a large thermal diffusivity for enhancing the cooling efficiency. A large thermal conductivity is suitable for transferring the heat from the cast-mould to the coolant. On the other hand, when a layer changes from heating to cooling, a large thermal diffusivity is needed to dissipate the heat carried by the layer itself quickly. The pyrolytic graphite is appropriate for the requirement due to its large thermal conductivity which leads to a large thermal diffusivity. Furthermore, the pyrolytic graphite possesses many other excellent properties such as easy accessibility, high melting point, small expansion coefficient, fine stability property and high thermal shock resistance etc. Some heat insulating ceramics such as nanostructured yttria-stabilized zirconia can be chosen for the insulation layers. The thicknesses l_1 and l_2 of a heat transfer layer and an insulation layer, as shown in Fig. 1, are designable by actual requirements.

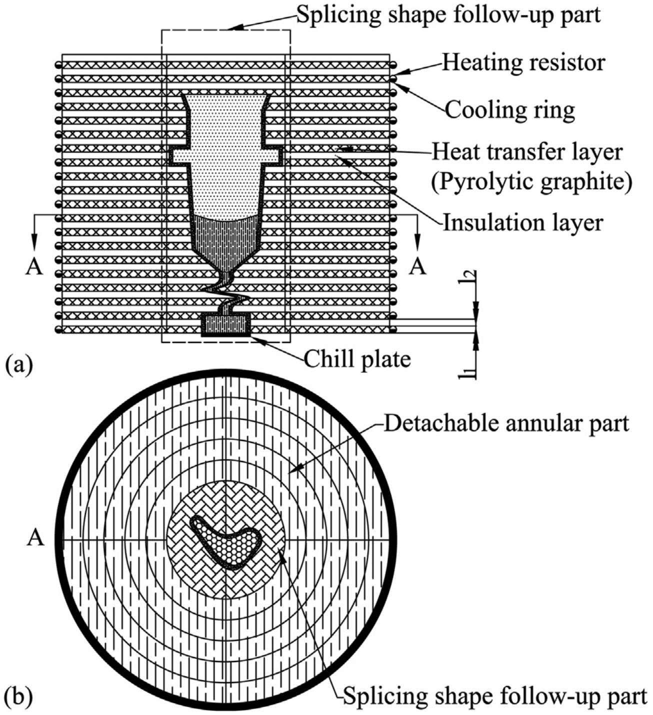

Fig. 1. Schematic illustration of the static solid cooling method.

We use resistors to heat the mould and employ water cooling rings near the resistors to dissipate the heat. In the directional solidification process, the heating resistor stops working and the water cooling ring starts working at the layer which is below the melt-crystal interface. The layers change from heating to cooling one by one along the solidification direction, which is controlled by the electrical network. Therefore, the crystal growth is controlled electrically instead of withdrawing mechanically from the hot zone to the cool zone. The rate similar to the withdrawal rate here is named control rate. During directional solidification, the growth rate and the flatness of the solidification front can be controlled by the control rate.

In our method, the heat transfer solid on one horizontal cross section can be designed as two parts: the detachable annular part and the splicing shape follow-up part. The detachable annular part consists of pyrolytic graphite layers and insulation ceramic layers. And these layers are arranged alternately by annular parts, as shown in Fig. 1 (b). This design aims at manufacturing casts in