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Effects of the location of a cast in the furnace on flatness of the solidification front in directional solidification

Yuanyuan Lian [a,b,*], Dichen Li [c,d], Kai Zhang [e]

[a] School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an 710049, PR China
[c] State Key Laboratory for Manufacturing System Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China
[d] School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China
[e] School of Mathematics and Statistics, Xi'an Jiaotong University, Xi'an 710049, PR China

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ABSTRACT

Many defects of single crystals are caused by the nonplanar solidification front. The transverse temperature gradient at melt–crystal interface results in nonplanar solidification fronts. The location of a cast in the directional solidification furnace affects heat dissipation and thus influences the transverse temperature gradient. This paper presents a criterion and a searching algorithm to find the optimal location of the cast for flattening the solidification front. A numerical simulation was employed for the verification of our method. Additionally, the effects of the size of the cooling device of the furnace on the optimal location, the transverse temperature gradient and the solidification time were discussed. The transverse temperature gradient is reduced about 50% without increasing much solidification time when setting the cast with a varying thickness mould at the optimal location. In addition, the optimal location is mainly influenced by the radius of the cooling ring.

1. Introduction

The quality of directional solidified columnar crystals and single crystals is influenced strongly by the shape of the solidification front in the directional solidification technique. Chang and Wilcox [1] stated that thermal stresses, which lead to dislocations, are the minimum for a planar solidification front. Schadt et al. [2] indicated that nonplanar solidification fronts can cause freckles. Elliott et al. [3] pointed out that the grain orientation is directly related to the curvature of the solidification front. The primary dendrites grow toward the centerline of the cast for a concave solidification front. Miller et al. [4] studied the lateral growth of dendrites caused by curved solidification fronts during directional solidification. They stated that the lateral growth gives rise to misoriented grains. Derby and Yeckel [5] summarized that the propagation of deleterious interactions between crystals and moulds results from nonplanar solidification fronts. In principle, a planar solidification front is desired during directional solidification.

The solidification front coincides with the melting point isotherm of the cast [5,6]. The isotherms are determined by heat transfer. The transverse temperature gradient generates curved isotherms and thus causes the nonplanar solidification front. Volz et al. [7] presented two factors leading to transverse temperature gradients near the melt–crystal interface. The one is the penetration of transverse temperature variations from the hot zone and the cold zone into the mushy zone of the cast. The other is the so-called "interface effect", i.e., the transverse temperature gradient can be caused by the differences in thermal conductivities between the cast and the mould. Additionally, the latent heat releases along the transverse direction due to the interface effect. Lun et al. [8] also indicated that the solidification front deflects if axial heat flow is insufficient and the latent heat dissipates along the transverse direction. The flatness of the solidification front is also related to the following three aspects: the thermal field generated by the furnace, the microstructure of the melt–crystal interface and the size and structure of the cast. Yeckel et al. [9] discovered that the flatness of the solidification front can be affected by asymmetric heating by the furnace. Trivedi et al. [10] demonstrated that the solidification front with cellular structures is more planar than that with dendritic structures. Pfeiffer and Mühlberg [11] stated that the solidification front is more planar with a small aspect ratio for a bar. Lian et al. [12] pointed out that

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[*] Corresponding author at: School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, PR China.

E-mail addresses: lianyuanhk@stu.xjtu.edu.cn (Y. Lian), dcli@mail.xjtu.edu.cn (D. Li), zkzkzk@stu.xjtu.edu.cn (K. Zhang).

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the cross section of a cast with irregular shape causes the transverse temperature gradient at the melt–crystal interface. Thus, the shape of the solidification front is influenced by the structure of the cast.

Many studies have been carried out for flattening the solidification front by decreasing the penetration of transverse temperature variations near the melt–crystal interface. Jasinski and Witt [13] presented a finite-element thermal model of the Bridgman process and proposed a method employing localized heating at the melt–crystal interface to flatten the solidification front. Volz et al. [7] also demonstrated that the flatness of the solidification front can be improved by using localized heating and the solidification front can be flattened by increasing the melt flow (i.e., larger Grashof number). Hofmann et al. [14] provided a dynamical vertical gradient freeze technique to control the shape of the solidification front. Moreover, the penetration of the transverse temperature variations is influenced by the interface position. Chang and Wilcox [1] demonstrated that the solidification front is planar when the melt–crystal interface position is at the border between the hot zone and the cold zone. Fu et al. [15] stated that the melt–crystal interface position is determined by the axial temperature gradient and the withdrawal rate. Szofran and Lehoczky [16] provided a method for flattening the solidification front by choosing a proper growth rate. Monastyrskiy [17] presented a numerical optimization method on withdrawal rates in directional solidification processes for obtaining planar solidification fronts.

Additionally, some research has been performed for the relationship between the flatness of the solidification front and the interface effect. El-Mahallawy and Farag [18] found that the planar solidification front can be obtained with a large ratio of the thermal conductivity between the alloy and the mould. Adornato and Brown [19] indicated that a small thermal conductivity of the mould leads to a uniform convection of the melt at the melt–crystal interface and thus the solidification front is more planar. Brandon and Derby [20] pointed out that the solidification front can be flattened by reducing the thermal conductivity of the mould.

Besides, some studies have been conducted to flatten the solidification front by the furnace design, the control of the microstructure of the melt–crystal interface and the structure design of the mould. Lun et al. [8] showed that increasing the axial temperature gradient flattens the solidification front and invented a multiple-zone electrodynamic gradient furnace to increase the axial temperature gradient. Zhang et al. [21] employed a bell-curve furnace profile to improve the flatness of the solidification front and obtain high crystallinity. Liu et al. [22] indicated that the superfine cellular structure can be obtained by the high axial temperature gradient and the large withdrawal rate. Hence, the solidification front is flattened due to the superfine cellular structure. Ebrahimi et al. [23] put forward a method for optimizing the investment casting by combining finite element solidification heat transfer analysis and design sensitivity analysis. They applied this method to improve the design of mold wrap to control the solidification pattern. Lian et al. [12] provided a method by varying the wall thickness of the mould for flattening the solidification front.

Moreover, the heat transfer at the melt–crystal interface is also influenced by the location of the cast in the furnace, especially for the cast with irregular shapes. In the directional solidification process, the radiant heat transfer from the mould to the cooling ring is determined by the configuration factors on the external surface of the mould and the configuration factors are affected directly by the location of the cast in the furnace. Thus, it can be expected that the transverse temperature gradient at the melt–crystal interface can be reduced by setting the cast at an appropriate location. And the solidification front can thus be flattened. Here, we provide a study of the effects of the location on the flatness of the solidification front and put forward a method for searching the optimal location. In Section 2, a criterion and a searching method for the optimal location are presented. Section 3 provides numerical simulations to verify our method. A parametric analysis is also discussed in Section 3. Section 4 presents the conclusions.

2. Modeling methods

In this section, we first build a heat transfer analysis model and then provide the criterion and the searching method for the optimal location of a cast. The flatness of the solidification front is mainly affected by the heat dissipation near the melt–crystal interface. Thus, the heat transfer at the cross section near the melt–crystal interface is analyzed for obtaining the optimal location of the cross section. Then, the optimal location of the cast at any time is just the optimal location of the cross section near the melt–crystal interface at that time. Hence, we choose a cross section C of the cast to analyze the heat transfer. We use γ to represent the cast contour, i.e., $\gamma = \partial C$. In the directional solidification process, the heat radiates from the mould to the furnace. It is an ideal circumstance that radiant heat fluxes are the same for all points on γ. Then we call the heat dissipation uniform on γ. For a cast with irregular shape, the heat dissipation on γ is nonuniform in directional solidification. Especially, for a cast with a concave part on γ, the radiation of the concave part is sheltered from the cast itself. This nonuniformity causes the circumferential temperature gradient (DT_c) and the transverse temperature gradient (DT_t) on C. The circumferential temperature gradient (DT_c) and the transverse temperature gradient (DT_t) are defined as follows: $DT_c = \max_t(\max_{P\in\gamma} T_2(P) - \min_{P\in\gamma} T_2(P))$ and $DT_t = \max_t(\max_{P\in C} T_2(P) - \min_{P\in C} T_2(P))$, where t is the time and $T_2(P)$ is the temperature of the cast at point P. We want to find an optimal location of the cast in the furnace with the purpose of minimum circumferential temperature gradient. The transverse temperature gradient is positively related to the circumferential temperature gradient. Hence, the transverse temperature gradient is thus reduced and the solidification front is flattened.

In the Bridgman process, the radiation from the external surface of the mould to the furnace is the main way of heat dissipation as the solidification is proceeded. During the directional solidification, the melt–crystal interface position is near the cooling ring. Here we assume that the heat on the mould surface near the melt–crystal interface all radiates to the cooling ring. On the basis of [12], the radiant heat flux from the external surface of the mould to the cooling ring can be expressed as

$$q_r(P) = \frac{C_b(T_1^4(P) - T_0^4)}{\dfrac{1-\varepsilon_1}{\varepsilon_1} + \dfrac{1}{X(P)}}, \tag{1}$$

where $(C_b = 5.67 \times 10^{-8}\mathrm{W}/(\mathrm{m}^2\,\mathrm{K}^4))$ is the black body radiation coefficient. $T_1(P)$ is the absolute temperature of point P on the external surface of the mould. T_0 is the absolute temperature of the cooling ring. ε_1 is the emissivity of the external surface of the mould that is determined by the material of the mould. $X(P)$ is the configuration factor of point P and it can be calculated as

$$X(P) = \int_{A_2} \frac{\cos\varphi_1 \cos\varphi_2}{\pi\rho^2} dA_2, \tag{2}$$

where dA_2 expresses the differential area element of the heat receiving surface of the cooling ring, and φ_1 [resp. φ_2] is the angle between the outer normal of the external surface of the cast at point P [resp. dA_2] and the vector $\overrightarrow{PdA_2}$ [resp. $\overrightarrow{dA_2P}$], and ρ