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Hot top design and its influence on feeder channel segregates in 100-ton steel ingots

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ABSTRACT

The influence of hot top design on feeder channel segregates (F-CS) and centerline shrinkage porosities (C-SP) were investigated both experimentally and numerically. Two 100-ton 30Cr2Ni4MoV steel ingots with different insulating hot tops were longitudinally sectioned. The experimental results showed few channel segregates but severe shrinkage porosities appeared in the ingot with poorly insulated hot top, while it was the opposite case after the improved hot topping practice. By employing the finite element numerical simulation, the critical condition for the formation of F-CS in 30Cr2Ni4MoV steel was verified to be $R^{2.1}G \leq 1.0 \times 10^{-5}$ °C $\text{mm}^{1.1}$ $\text{s}^{-2.1}$. Through coupling with the published C-SP criterion ($GR^{-0.5} \leq 2.5$ °C $\text{mm}^{-1.5}$ $\text{s}^{0.5}$), it was found out that the increase of hot-top height and preheating temperature would aggravate F-CS while alleviate C-SP contrarily. Hence, to comprehensively control those two defects, the optimum hot-top height and preheating temperature for 100-ton ingot were suggested to be 700 mm and 600 °C, respectively. Ultimately, the ratio of the solidification time for the whole ingot to the ingot body (t_f/t_b) was proposed as a novel criterion for hot top design. This practical criterion has been successfully utilized to optimize the hot top of a 5-ton steel ingot.

1. Introduction

As the extensively used raw materials for low-pressure rotors, the heavy 30Cr2Ni4MoV forging ingots assume tremendous importance in the nuclear power plant [1]. The defects, primarily macrosegregation and porosities, have been considered as the most detrimental factors impairing the soundness and application of these large castings. Along with the deepening cognitions of the formation mechanisms of macrosegregation and shrinkage porosities, a lot of efforts have been devoted to the models predicting the severity and location of those defects, as well as the approaches of controlling. After reviewing a succession of macrosegregation modeling that comprise complicated mathematical and physical treatments, Pickering [2] indicated the superiorities of simplified approaches in the practical application. Simplified models, such as the Niyama criterion [3] for shrinkage porosities and Suzuki criterion [4] for channel segregates, could produce instructive results and reduce computing time by purely thermal field computation.

All the approaches to alleviating macrosegregation and shrinkage porosities aim at controlling the mass and heat flow. Examples include adjustments to the alloy composition, alterations on the mold or hot top design, and applications of centrifugal forces or electromagnetic fields [5]. In addition, the optimization design is usually accomplished by means of numerical simulation [6–8]. Recently, Li and coworkers [9] have demonstrated that one of the typical types of macrosegregation in steel ingot, the channel segregation ("A" segregates) can be reduced or even eliminated through purifying the steel melt, in particular to decrease the oxygen concentration of steel. A series of dissected ingots and numerical simulations from atomic scale to process scale have revealed that the flotation of oxide-based inclusion is the primary driven force for the formation of channel segregates. However, in these dissected 100-ton ingots, even though the oxygen concentration is extremely low, the channel segregates occur in the hot top as it is sufficiently large and preheated. In contrast, as the hot top is small enough and avoids preheating, the channel segregates disappear but the shrinkage porosities become more serious. A perfect design of hot top that lowers the cost of ingot casting and simultaneously inhibits the growth of those two defects is urgent in the steel ingot production. Based on the heat and mass flow theory, Flemings [10] has conducted the pioneering work on hot top design. The proposed guidelines for ideal hot top design are concluded: (1) the ideal hot top should have the minimum volume that is enough to feed ingot; (2) the temperature gradients should be always negative downwards from the hot top to the ingot body; (3) thermal properties of the hot top should be identical throughout the entire hot top, including the top and the side wall; (4) the hot top should be as highly insulating as possible and be heated uniformly as high a temperature as convenient. Afterwards the design conditions of the hot top were experimentally studied by Tashiro et al. [11]. Compared with the geometric parameters, the thermal conditions of hot top turned out to have little impact on the solidification characteristics of the ingot body. The augmentation in the hot-top volume by increasing the hot-top diameter would contribute to the formation of feeder channel

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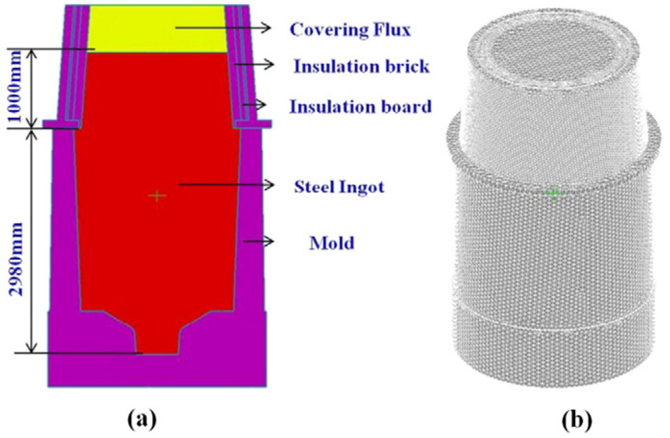

Fig. 1. The geometrical shape (a) and tet-mesh (b) of the simulated 100-ton steel ingot.

Table 1
Composition of 30Cr2Ni4MoV steel ingots (wt.%).

Element	C	Si	Mn	P	S	Cr	Ni	Mo	V
Weight percent	0.30	0.08	0.25	0.008	0.006	2.0	3.5	0.4	0.1

segregates, which could also be found in the longitudinal section of 1.7 t [12] and 65 t [13] steel ingots. Likewise, Scepi et al. [14] put forward that to improve the quality of large ingots the mass ratio of hot top should be no less than 23%, which is also conflicting with the above ideal hot top design tips. Moreover, through taking into account the grain structure and mechanical workability of steel ingots, the proper height and shape of hot-top isolate were sought after by Kermanpur et al. [15] via numerical simulation. The specific implications of separate hot-top parameters, the thickness of exothermic powder and the height of hot top were respectively investigated by Dang [16] and Ma [17]. From the above, the hot top has been our predominant concern in pursuit of the improvement in material utilization and the clarification on neglected feeder channel segregates.

In this study, simplified models, based solely on thermal parameters, solidification rate (R), temperature gradient (G) and cooling rate (L), are adopted to predict the formation of segregation defects. The criteria of feeder channel segregates (F-CS) are validated against the experimental results of two 100-ton 30Cr2Ni4MoV steel ingots. After investigating the effects of different hot-top parameters both numerically and experimentally, a criterion of hot top design is put forward to minimize the channel segregates and shrinkage porosities comprehensively in practical engineering.

2. Numerical simulations and experiments

2.1. Numerical model

In the calculations of the temperature and flow fields for 100-ton steel ingot, some assumptions have to be made in the finite elements method as follows: (1) the free surface rises steadily with the top pouring liquid evenly distributed to simulate the smooth filling process; (2) the continuity, Navier–Stokes and heat transfer equations are included for the solidification of the casting, while only the heat transfer equation is considered for the mold; (3) the solutal effect is ignored and the convection is driven only by thermal buoyancy for an unified analysis of the effects of hot top on channel segregates and shrinkage porosities.

The conservation equations to simulate the natural convection and heat transfer during solidification of steel ingots are described as follows:

Continuity equation:

$$\nabla\cdot\left(\overrightarrow{V}\right) = 0. \tag{1}$$

Navier–Stokes equation:

$$\frac{\partial\rho\Phi}{\partial t} + \nabla\cdot\left(\rho\overrightarrow{V}\Phi\right) = \nabla\cdot(\mu\nabla\Phi) - \nabla P + \rho g. \tag{2}$$

Heat transfer equation:

$$\rho c\frac{dT}{dt} = \nabla\cdot(\lambda\nabla T) + \dot{Q}\ . \tag{3}$$

Here, $\overrightarrow{V}$ is the velocity vector and Φ is the velocity component; ρ is the density and P is the pressure; t is time and T is temperature; μ is the dynamic viscosity; g is gravity acceleration; λ is the thermal conductivity; c is the specific heat; $\dot{Q}$ is an internal power source. Details of the numerical implementation are available in the ProCAST manual [18].

The schematic drawing and finite element mesh of the 100-ton steel ingot are depicted in Fig. 1. The height–diameter ratio and taper of the ingot are 1.04 and 8.5% respectively, with 2.47% tail cone and 22.0% hot top accounting for the whole weight. The maximum element size of the ingot is 100 mm. The total number of tetrahedral elements in

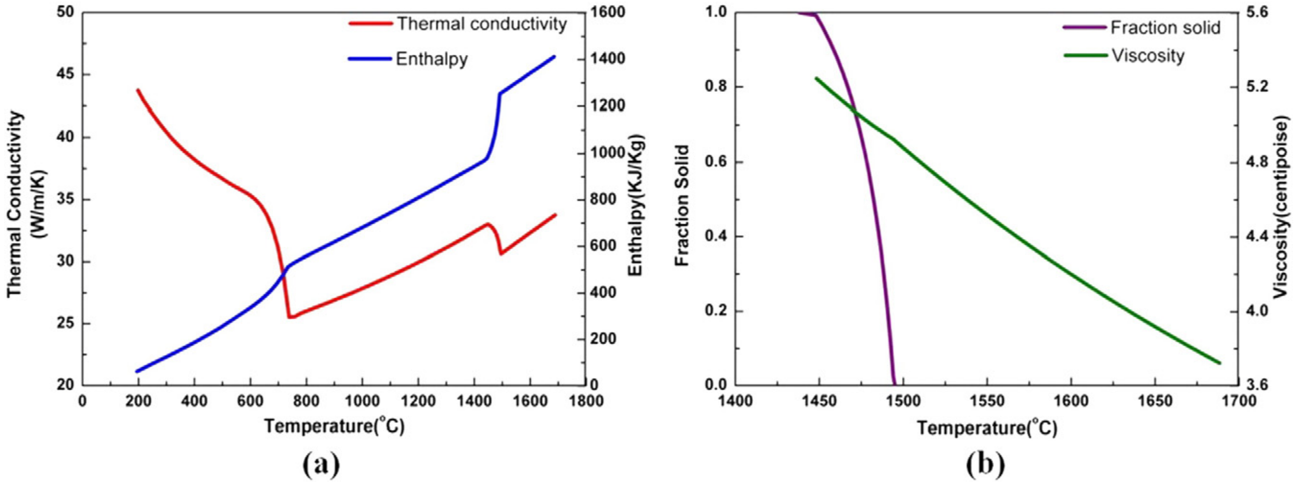

Fig. 2. Thermophysical properties used for solidification analysis: (a) thermal conductivity and enthalpy, (b) fraction solid and viscosity.