A Numerical Study of the Effect of Multiple Pouring on Macrosegregation in a 438-Ton Steel Ingot

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Abstract In present paper, a ladle–tundish–mold CFD model and a macrosegregation model were utilized to investigate the effects of the multiple pouring (MP) process on the macrosegregation in a 438-ton steel ingot. Firstly, the model was partially proved as compared to the measured carbon distributions along the transverse sections in the riser of ingot. Then, the comparison between the single pouring (SP) and MP process has been carried out to study their influences on the macrosegregation in ingot. Besides, the predicted macrosegregation results in MP process which introduced the improved riser fixed with an insulating sleeve were compared with that in traditional MP process. The traditional MP process leads to certain favorable initial carbon distribution in the mold, which has some favorable influence on suppressing the positive segregation in ingot. The holding time of the low carbon in the riser is the main factor to suppress the positive segregation in ingot. Improved insulating sleeve can prolong the holding time of the low carbon in the riser and release the positive segregation in the riser of ingot. Improvement of the insulating effect of the riser is an efficient method to control macrosegregation in large steel ingot.

KEY WORDS: Multiple pouring process; Macrosegregation; Numerical simulation; Large steel ingot

List of symbols

c_p	Specific heat [J/(kg K)]
C	Concentration of carbon (wt%)
a_p	Volume fraction of the molten steel
a_q	Volume fraction of the air
u_{eff}	Equivalent viscosity
μ_l	Liquid viscosity
D_{eff}	Effective diffusivity (m^2/s)
k_p	Partition ratio
k	Thermal conductivity [W/(m K)]

L	Latent heat (J/kg)
m_l	Liquidus slope (K/wt%)
λ_2	Secondary dendrite arm spacing
g_l	Liquid volume fraction
g	The gravity
g_s	Solid volume fraction
p	Pressure (Pa)
ρ_b	Density in the buoyancy term
t	Time (s)
T	Temperature ($^{\circ}\text{C}$)
T_m	Melting point of pure iron ($^{\circ}\text{C}$)
$\mathbf{u}$	Velocity vector (m/s)
β_C	Solutal expansion coefficient ($\text{wt}\%^{-1}$)
β_T	Thermal expansion coefficient (K^{-1})
ρ	Density (kg/m^3)
ρ_m	Volume fraction averaged density

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Subscripts or superscripts

0 Initial
b Buoyancy

- l Liquid phase
- s Solid phase

1 Introduction

Macrosegregation refers to chemical inhomogeneity in cast metals at the scale of the product size, which is the main defect in steel ingots. It is difficult to be removed through subsequent processing, and it has certain impact on the final mechanical properties of the final products [1]. It is well known that the origin of this defect is due to different bulk and interdendritic flow phenomena caused by the feeding flow, thermosolutal convection, solid movement and deformation of the solid network [2]. Modeling macrosegregation is a multiphase and multiscale problem. With the enhanced computational power, many numerical models have been developed with great efforts to predict the macrosegregation quantitatively. Ni *et al.* [3] and Wang *et al.* [4] firstly presented the multiphase models that account for the melt convection and the solid movement. Ludwig *et al.* [5] and Wu *et al.* [6] developed a series of multiphase models, even the most sophisticated five-phase model which allows the prediction of macrostructure and macrosegregation [7, 8]. Combeau *et al.* [9] and Zaloznik *et al.* [10] presented a multiphase and solidification model which describes the morphology of the equiaxed grains and their motion. Li *et al.* [11] developed a two-phase macrosegregation model that incorporates heat transfer, melt convection, solute transport, equiaxed grain motion, and grain nucleation and growth. These models offer a better understanding of the mechanisms of the formation of macrosegregation. However, only a few of efforts has been made to predict industrial steel ingots weighing from 2.45 to 231 tons [12–14] regardless of considering the filling process. Modeling the whole process from the pouring to the solidification stage is crucial for studying the macrosegregation in large steel ingots.

In the large steel ingots weighing 300–600 tons, there exist the typical types of the segregation including the positive segregation at the top and negative segregation at the bottom. In order to counteract macrosegregation in large steel ingot, the MP technology, *i.e.*, sequential pouring of molten steel from multiple ladles with different carbon concentrations was developed in Japan. And the large steel ingots weighing more than 600 tons were poured through careful control of each ladle content, temperature and weight at optimum condition to minimize the segregation [15, 16]. It has been argued that the MP process is effective to suppress macrosegregation in large steel ingots by reversing the initial concentration distribution in the top and the bottom sections of steel ingot before starting

solidification. Some experiments and preliminary simulations with numerical models support this issue. Kang *et al.* [17] proposed a water model to describe species diffusion behavior in the tundish and the mold. The methylene blue dye was used as solute to simulate the alloy element in the melt steel and the concentration variation curves at the tundish outlet, and the typical positions in the mold were obtained and analyzed. The numerical simulation for 360-ton steel ingot was carried out by Liu *et al.* [18], whereas the filling of the tundish and mold was simplified. The MP process of a large steel ingot was simulated by Tu *et al.* [19], and the initial carbon distribution in the mold was obtained after the MP process while the solidification process was not considered. Although the MP process has been adopted by many heavy industrial plants, the design of the casting parameters is still based on the experiences.

The objective of this work is to study the influence of the MP process on the macrosegregation of the large steel ingots through numerical simulation combined with the ladle–tundish–mold CFD model and the macrosegregation model. And an improved riser technique was given to observe the mechanism of reduction of macrosegregation in large steel ingot during the MP process.

2 MP Process and Mathematical Model

2.1 MP Process

Figure 1 shows the MP process from the ladles to the tundish and then the mold. This process includes three stages in the tundish, *i.e.*, the filling stage, the holding stage and the draining stage. At the first stage, the inlet of the tundish is opened, and the refined molten steel is poured into the tundish from the first ladle until the liquid steel reaches at the critical bath height in the tundish; then, the tundish is closed and kept standstill for a while. Secondly, the outlet and inlet of the tundish are opened at the same time in the holding stage; the level of the molten steel in the tundish is remained at certain height by controlling the flow rate through the inlet and outlet of the tundish. In the final draining stage, when the total molten steel is poured into the tundish completely, the bath level reduces to the critical height; then, the inlet and outlet of the tundish are closed and the whole pouring process is over.

The filling process in the mold starts from the holding stage in the tundish (Fig. 1b, c). Molten steel from the tundish goes into the mold when the outlet of the tundish is opened, the melt level in the mold rises, and the carbon mixing proceeds continuously until the end of the MP process. It should be mentioned that the effect of introducing the top pouring process into the solidification was simulated using moving grid method and that the liquid

Fig. 1 Schematic of MP process: **a** the filling stage; **b** the holding stage; **c** the draining stage

steel dripping process from the output nozzle of the tundish to the free surface of molten steel in the mold was ignored during MP process in this simulation. The basic concept is that the volume of liquid steel through the output nozzle of the tundish at each time step was calculated and equivalently added to the free surface of the molten steel in the mold with boundary conditions of the velocity and the carbon distribution on the affected area. During MP process, once the total volume of the molten steel is larger than the volume of one layer of elements, the free surface moves upward at a distance of one-layer element until the end of the MP process.

2.2 Governing Equations of MP Process and Macrosegregation

The mathematical model contains two parts: One is the turbulence model for the carbon mixing in the tundish and another is the macrosegregation model for the filling and solidification process in the mold. The two models were used in sequences to numerically study the effect of the MP processes on the final macrosegregation in the large steel ingot.

The turbulence model based on the multiphase and the volume of fluid (VOF) has been established, as shown in Table 1, which is characterized with the unsteady, turbulent and gas–liquid two-phase flow. The realizable k - ε model was employed in the far-wall field zones, and the standard wall function approach was adopted in the near-wall field zones. The ANSYS-FLUENT 15.0 [20] was applied to resolve the turbulent model. The mass continuity, momentum, energy and species equations were solved to investigate the carbon distribution evolution in the

tundish and the carbon variation at the tundish outlet during the MP process. The pressure–velocity correction was performed with the PISO procedure, and the PRESTO scheme was applied for the pressure discretization. The following assumptions were used in the model: (1) The liquid phase and gas phase are the two defined phases; (2) the motion of the molten steel by the blowing argon was not considered; and (3) the slag layer on the melt top in tundish was not included.

Furthermore, a previously developed continuum macrosegregation model was applied to simulate the filling and solidification process in the mold. The conservation equations are listed in Table 2. The main assumptions are laminar-, Newtonian- and Darcy-type flow with isotropic permeability in the mush; stationary solid; equal and constant thermophysical properties for the solid and liquid but for the density in the buoyancy term in the momentum equation; and microsegregation governed by the lever rule.

2.3 Simulation Condition of MP Process

Three-dimensional simulation of the carbon mixing process in the tundish and two-dimensional simulation of the filling and solidification process in the mold were carried out. The ICEM-CFD software was utilized to mesh tundish with nodes of 196710 and hexahedron elements of 189317. The Courant number was set 0.25, and the convergence of all the variables was set as 0.001. The elements were non-uniform grids. The time step was constantly 0.01 s in the tundish simulation, and it costs about two weeks to fulfill the tundish filling process on a PC with a maximum of 48 parallel processes. The time step was 1.0 s during mold filling and then was set up to 2.0 s at the later stage of the

Table 1 Conservation equations used in mathematical model for the mixing in tundish

Mass	$\rho \frac{\partial a_q}{\partial t} + \rho \bar{\mathbf{u}} \cdot \nabla_0 \cdot a_p = 0$	(1)
Momentum	$\frac{\partial \rho_m \mathbf{u}}{\partial t} + \nabla \cdot (\rho_m \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot (\mu_{\text{eff}} \nabla \mathbf{u}) + \rho_m \mathbf{g}$	(2)
Realizable k - ε	$\frac{\partial \rho_m k}{\partial t} + \nabla \cdot (\rho_m \mathbf{u} k) = \nabla \cdot \left(u + \frac{u_{\text{eff}}}{\sigma_k} \right) \nabla k + G_k - \rho_m$	(3)
	$\frac{\partial \rho_m \varepsilon}{\partial t} + \nabla \cdot (\rho_m \mathbf{u} \varepsilon) = \nabla_0 \cdot \left(u + \frac{u_t}{\sigma_\varepsilon} \right) \nabla \varepsilon_0 + \rho_m C_1 E \varepsilon - \rho_m C_2 \frac{\varepsilon^2}{k + \sqrt{v \varepsilon}}$	
Energy	$\frac{\partial \rho_m T}{\partial t} + \nabla \cdot (\rho_m \mathbf{u} T) = \nabla \cdot \left(\frac{k_{\text{eff}}}{c_p} \nabla T \right)$	(4)
Species	$\frac{\partial \rho_m C}{\partial t} + \nabla \cdot (\rho_m \mathbf{u} C) = \nabla \cdot (D_{\text{eff}} \nabla C)$	(5)

Table 2 Conservation equations used in the mathematical model for the macrosegregation in the mold

Mass	$\nabla \cdot \mathbf{u}$	(6)
Momentum	$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \nabla \cdot (\mathbf{u} \mathbf{u}) = -\nabla p + \mu_1 \nabla^2 \mathbf{u} - \mu_1 K^{-1} \mathbf{u} + \rho_b \mathbf{g}$	(7)
Density in buoyancy term	$\rho_b = \rho [1 - \beta_T (T - T_0) - \beta_C (C_1 - C_0)]$	(8)
Energy	$\frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{u} T) = \frac{k}{\rho c_p} \nabla^2 T + \frac{L}{c_p} \frac{\partial g_s}{\partial t}$	(9)
Species	$\frac{\partial C}{\partial t} + \nabla \cdot (\mathbf{u} C) = \nabla \cdot (g_1 D_1 \nabla C) + \nabla \cdot [g_1 D_1 \nabla (C_1 - C)] - \nabla \cdot [\mathbf{u} (C_1 - C)]$	(10)
Permeability	$K = \frac{\lambda^2}{180} \frac{g_s^3}{(1 - g_s)^2}$	(11)
Temperature and liquid concentration	$T = T_m + m_1 C_1$	(12)
Solid volume fraction and temperature	$g_s = \frac{1}{1 - k_p} \frac{T - T_1}{T - T_m}$	(13)

solidification in the mold simulation and costs about 48 h to complete the mold filling and solidification stage with two parallel processes. The steel grade was assumed to be a Fe–C binary alloy. The thermophysical properties of the steel ingot and mold are listed in Table 3. The other parameters are listed in Table 4.

Figure 2 shows the 438-ton steel ingot system used in the MP process. During the actual MP process, three ladles with different carbon concentrations were arranged for the production (average carbon concentration is 0.44 wt%). The weight of the molten steel in each ladle was about 150 tons, and the carbon concentrations from the first to the third ladle are 0.51, 0.44 and 0.37 wt%, respectively. The teeming temperatures were 1560 °C, and the total pouring time was about 5200 s. Figure 3 shows carbon

concentration variation of the molten steel through the outlet of tundish, which was simulated and obtained by the turbulence model listed in Table 1. This carbon concentration variation was used as the boundary condition on the impacted region of the filling steel in the mold. The heat transfer coefficients at the interfaces of the ingot/mold and mold/ambient were 1000 and 100 W/(m²K), respectively. The powder layer at the ingot top was not considered, and a small heat transfer coefficient with value of 5 W/(m²K) was utilized in the simulation. Because the main focus of this work is to make the assessment of the effect of MP processes on the final macrosegregation in large steel ingot, the detailed analysis of the carbon mixing behavior in tundish is not presented here.

3 Results and Discussion

3.1 Macrosegregation with Multiple Pouring and Validation

A trial steel ingot was cast in the steel plant of CITIC Heavy Industries Co., Ltd. After the steel ingot had been cooled and stripped out from the mold, the riser part of

Table 3 Thermophysical properties of the steel ingot and mold materials

Material	ρ (kg m ⁻³)	k (W m ⁻¹ K ⁻¹)	c_p (J kg ⁻¹ K ⁻¹)
Steel ingot	6990	38.3	520
Mold	7100	26.3	540
Insulation sleeve	180	1.2	1020

Table 4 Steel properties used in the simulation

k_p	m_l (K wt% ⁻¹)	β_C (wt% ⁻¹)	β_T (K ⁻¹)	L (kJ·kg ⁻¹)	μ_l (Pa·s)	λ_2 (μ m)	D_1 (m ² ·s ⁻¹)
0.314	-80.45	1.4164×10^{-2}	1.07×10^{-4}	271	0.0042	500	2×10^{-8}

Fig. 2 Sketch of 438-ton steel ingot system **Fig. 3** Carbon concentration variation through the outlet of the tundish

ingot was cut off and the analytic specimens were taken from different transverse sections in the riser of ingot as illustrated in Fig. 2. The carbon concentrations of these samples were measured using spectral analysis.

Figure 4 shows the evolution of the fluid flow and carbon distribution at different time (count the time from the

beginning of the pouring) after the MP process. It can be seen that the strong positive segregation forms in the riser at the end of solidification stage. The as-known cone-shape negative segregation was not predicted in the bottom of ingot due to the settlement of equiaxed grains since it was not considered in the present model. And the most negative segregation forms at the bottom of ingot located a little off the centerline as well as at the side and the bottom of the hot top part.

Figure 5 shows the comparison of the predicted and measured carbon concentration along the transverse sections from A to D with different heights of 4.6, 4.5, 4.4 and 4.3 m from the ingot bottom, respectively. The simulated results can reproduce generally well with the measured tendencies. However, in the center region, there exhibits some large discrepancy between the measured and predicted results. It should be noted that the cone-shape negative segregation has not been presented at the bottom because there is no consideration equiaxed grains' movement in the model. If the negative segregation at the bottom can be accurately predicted, the positive segregation region will become more serious based on the species balance in ingot and the comparisons in the center region of hot top riser of ingot will become closer. The other possible reasons contributing to the discrepancies are two-dimensional geometry, the simplification of the boundary conditions, the thermal physical properties, the uncertainties of actual process, the model discretization, calculation and measurement errors.

It should be noted that the present macrosegregation model with a semi-implicit scheme for the thermal–solutal coupling and solving was numerically and experimentally validated through classical benchmark test in Ref. [21]. Generally, the numerical results of the present model are in good agreement with the measurements by Hebditch and Hunt [22].

3.2 Comparison Between MP and SP Processes

In order to investigate the effects of the initial concentration of the molten steel in the mold on the macrosegregation of ingot, the MP process and the single pouring process (SP, i.e., with constant initial concentration) were simulated and compared.

As shown in Figs. 4 and 6, the similar segregation pattern in solidified shell during MP and SP is presented at

Fig. 4 Fluid flow and carbon distribution in the mold during MP process: **a** at 1.3 h; **b** at 4.2 h; **c** at 20 h; **d** at final solidification

Fig. 5 Comparison of carbon concentration between the predicted and experimental results: **a** section A; **b** section B; **c** section C; **d** section D

different times of solidification. From Figs. 4d and 6d, it can be seen that the total segregated area with carbon concentration higher than 0.50 wt% occupied about 25% of the whole steel ingot for MP and about 35% for SP. Therefore, the MP technique is proven to have certain favorable effect on suppressing the positive segregation in the large steel ingot. Figure 7 shows the comparison of

carbon distribution along the ingot centerline between the SP and MP processes. It should be noted that the vertical dash line represents the average carbon concentration of steel, and the horizontal black line is located at the riser neck.

When the whole filling process is nearly over, the flow pattern of both the MP and SP is characterized by an

Fig. 6 Fluid flow and carbon distribution with SP process at different times: **a** 1.3 h; **b** 4.2 h; **c** 20 h; **d** final solidification

Fig. 7 Comparison of the carbon distribution along the ingot centerline between the SP and MP processes: **a** at 1.3 h; **b** at 4.2 h; **c** at 20 h; **d** at final solidification

impact region with the deepest depth of about 1 m in the top part of the melt at 1.3 h (Figs. 4a, 6a). Meanwhile, an intensive turbulent flow forms around the center impact region in the mold. Notably, the impinging force induced by the plunging steel from the tundish acts as the main driving force for the melt flow and the species dilution in the upper mold during the pouring stage, while the thermal–solutal convection becomes the primary driving force in the lower mold. However, there are great differences of the carbon distribution between the MP and SP at different times. Firstly, the carbon distribution is nearly the same with the averaged value of 0.44 wt% in the liquid steel during SP process (Fig. 6a), while the carbon concentration is lower in the riser and the stratification forms in the ingot body region during MP process (Fig. 4a). Secondly, the liquid steel with the lower carbon concentration from the impact region descends along the mold side and solidifies

fast, which causes the carbon distribution near the surface of the ingot body lower than the normal value of 0.44 wt% in MP process. Figure 7a shows the comparison of the carbon distribution along the ingot centerline, which presents higher carbon concentration at ingot bottom and lower carbon concentration at ingot top with a certain fluctuation during the MP process, while the concentration is almost constant (average value of 0.44 wt%) during the SP process.

At 4.2 h as shown in Figs. 4b and 6b, the molten steel flows downwards along the solidified shell in the mold. After reaching the ingot bottom, it changes the flow direction to move inward and then upward in the middle region of ingot. Meanwhile, a few strong recirculation loops in clockwise or counterclockwise form in the lower part of ingot with thanks to the competition between the thermal buoyance and the solutal buoyance forces.

Fig. 8 Comparison of final macrosegregation with different riser insulating times: **a** 0 h (traditional mold riser); **b** insulating 10 h; **c** insulating 20 h; **d** insulating 30 h

However, the flow field in the riser appears more peaceful than that in the ingot body. Figure 7b shows that the carbon concentration gradually varies from the value of 0.44–0.38 wt% from the bottom to the top during the MP process, while it remains nearly constant value of 0.44 wt% during the SP process. The carbon distribution along the ingot centerline (between 0.8 and 4.0 m) remains nearly constant with higher carbon concentration in SP as compared with MP except for the ingot tail section.

At 20 h, the flow pattern is nearly identical for both MP and SP, and the solute-enriched liquid is advected away from the mushy region and moves up and inwards, which results in the carbon concentration increasing greatly in the center of ingot (Figs. 4c, 6c). As illustrated in Fig. 7c, the carbon variation profile along the centerline is nearly similar between the MP and SP processes, with higher carbon distribution in SP except for the tail section of the ingot.

Based on the above comparison and analysis, it indicates that the lower carbon concentration remains in the mold riser in the MP process until the moment of 10 h, while this phenomenon never comes up in the SP process. On the other hand, it can be found that the dwell time of the low carbon in the riser from the last ladle is crucial for MP to release the positive segregation in ingot. Obviously, how to obtain more dwell time of the low carbon concentration in the riser is a key technology to control macrosegregation in large steel ingot. Therefore, the following method to improve the riser is provided.

3.3 Comparison Between Improved and Traditional Mold Risers

The mold riser was improved by the addition of an insulating sleeve in place of traditional sleeve, with the purpose of prevention from the heat transfer between the ingot and

the sleeve. Four cases with the different insulating times were simulated and compared: case 1 (0 h), case 2 (10 h), case 3 (20 h) and case 4 (30 h). The other parameters are similar to those used above.

Figure 8 shows the comparison of final macrosegregation pattern among the four cases. It can be seen that the improved sleeve has some favorable effects on suppressing the macrosegregation defect in large steel ingot. With the increasing insulating time, the positive segregation in ingot becomes more lessened.

Figure 9 shows the solidification sequences of the 438-ton steel ingot with the fluid field, the solid volume fraction and the carbon distribution at different times in case 4. At 1.7 h, the intensive flow induced by the competition of the thermal and solutal buoyance forces is formed in the ingot body. The lower carbon concentration can be seen in the riser, and solidified shell forms along the mold wall as shown in Fig. 9a. At 10 h, several fluid circumfluences occur in the liquid metal and a nearly homogeneous carbon distribution is presented in the ingot body as illustrated in Fig. 9b. At 30 h, it can be seen in Fig. 9c that although the molten steel has been solidified a lot in the mold, the steel in the riser still keeps liquid with the lower carbon concentration. In addition, the flow field in the center of the ingot body is obviously more intensive than that in the riser. It can be explained by the reasons that there is a narrow space in the center region of the ingot body for the liquid steel to transport and that there is intensive heat transfer in the ingot body with a strong thermal–solutal convection, while there are inverse conditions in the riser of ingot without any solidification. The carbon concentration in the riser increases much more with the solidification proceeding, and all steel keeps liquidus in the riser until 30 h due to its good insulation.

Figure 10 shows comparison of the carbon distribution along the ingot centerline between case 1 and case 4. It

Fig. 9 Predicted solidification sequence of 438-ton steel ingot with riser insulating time of 30 h, the left part shows the solid volume fraction (g_s), while the right shows the macrosegregation and liquid velocity: **a** at 1.7 h; **b** at 10 h; **c** at 30 h; **d** at 60 h

Fig. 10 Comparison of the carbon distribution along the ingot centerline: **a** at 1.7 h; **b** at 10 h; **c** at 30 h; **d** at final moment

should be noted that there must exist different thermal gradients and thus the different thermal–solutal convections in the riser of ingot for two cases because of the different insulating conditions, which can be the reason for their difference of the carbon distribution along the centerline as illustrated in Fig. 10. At 1.7 h, the two cases generally present similar profile of the carbon distribution except for the riser section with a little lower carbon concentration in case 4 than in case 1. At 10 h, the profile of the carbon distribution along the centerline (above 0.8 m from the ingot bottom) presents nearly constant for case 1, while the carbon concentration remains lower in the riser and constant in the ingot body for case 4. It means that the dwelling time of the low carbon concentration in the riser is less than 10 h in case 1. The reason is that case 1 with insulating time of 0 h has more intensive convection and

thus the fast carbon mixing behavior in the riser than case 4. At 30 h, the molten steel with the lower carbon concentration in the riser is gradually mixed with that from the ingot body, which causes the solute concentration enriched in the liquid within the riser for two cases as shown in Fig. 10c. Finally, it can be illustrated from Fig. 10d that the positive segregation was released and almost shifted into the riser with the improved insulating sleeve.

In order to gain better insight into the effect of the improved riser sleeve on the formation of macrosegregation in ingot, a position of P located in the riser (Fig. 2a) was selected to investigate and compare its variation of the carbon concentration and fluid velocity for case 1 (the traditional case) and case 4 (the improved case) as illustrated in Fig. 11. The position P is in the hot top part and remains in the liquid until the final solidification moment.

Fig. 11 Time evolution of the carbon concentration and liquid velocity at the position P in case 1 and case 4: **a** carbon concentration, **b** velocity in horizontal; **c** velocity in vertical

Figure 11a shows the predicted evolution of the carbon concentration at position P for both case 1 and case 4. Obviously, the trend of the carbon variation at position P is nearly the same. At initial solidification stage, the solute concentration is about 0.37 wt% and then increases continuously as the carbon species redistribution and mixing behavior proceeding. It can be found that it takes only about 5 h for the carbon concentration to increase from the value of 0.37 to 0.44 wt% at position P in case 1 and at about 24 h in case 4. This means that the carbon mixing at the position P or in the riser develops much more intensively in case 1 as compared to case 4, which can be explained through the comparison of the variation of the liquid velocity at position P. Figure 11b, c shows the vertical and horizontal liquid velocities during the solidification process. As analyzed above, the liquid movement is affected by the thermosolutal convection, which is related to the heat transfer condition in ingot system. It can be seen that the velocity variation presents fluctuations for both cases with thanks to the competition between the thermal buoyance and the solutal buoyance forces. However, difference between the two cases is also found: Firstly, the horizontal velocity variation shows the similar fluctuation but with smaller amplitude in case 4 than in case 1 before 35 h as illustrated in Fig. 11b. Secondly, the vertical liquid velocity at position P stays nearly constant in Fig. 11c before 35 h in case 4 and then follows the similar trend as that in case 1. The reason for the above differences of the liquid velocity variation is due to heat transfer conditions in the two cases. The improved sleeve in the riser with the insulating time of 30 h reduces the strength of the

thermosolutal convection and carbon mixing in the riser. It also prolongs the holding time of the lower carbon concentration in the riser, which can be regarded as the key factor in suppressing the positive segregation in the steel ingot.

Based on the simulation and analysis above, it can be concluded that the key point of the improved riser is to prolong the critical time of holding the low carbon concentration in the riser. With increasing insulating ability of sleeve, the hotter melt tends stable in riser with longer holding time, and the light melt at the top overcomes more segregated carbon floating from the lower part of ingot. Therefore, insulating materials should be properly selected in order to control the macrosegregation, especially for the positive segregation in the large steel ingot.

4 Conclusions

The whole ladle–tundish–mold model containing the CFD model in tundish filling and the mixture continuum macrosegregation model in the mold filling and solidification was developed to study the influence of MP process on the final macrosegregation in the large steel ingot. The main conclusions are summarized as following:

1. The predicted macrosegregation was generally in an agreement with the industrial experimental tendencies in the riser of ingot except for the center region because of the model simplicity, actual conditions and measurement error.

2. Comparison of flow field and carbon distribution between the MP and SP (constant initial concentration) processes indicated that the low carbon distribution in the riser remains for a longer time in the MP process, while this phenomenon never comes up in the SP process. The holding time of the low carbon concentration in the riser is a major factor to release the positive segregation in the large steel ingot. The MP process has certain positive effect on the prevention of final macrosegregation as compared to the single pouring process.
3. Improved riser with the addition of insulating sleeve was suggested to further control macrosegregation, and the results indicated that the more positive segregation is released with the increasing insulating time of the riser sleeve. The dwell time of the low carbon concentration in the riser is crucial to suppress the positive segregation in the large steel ingot, increasing with the insulating time.
4. The velocity fluctuation of the melt is much weaker in the improved sleeve as compared with the traditional case. With increasing insulating ability of sleeve, the light melt at the top overcomes more segregated carbon floating from the lower part of ingot, and the positive segregation could be decreased.

The continuum macrosegregation model in present study was selected to predict the large industrial ingots, especially for the 300- to 600-ton steel ingots, due to the convenience and its low calculation cost. The simulation results in present report should be viewed as the preliminary results losing some detailed features of macrosegregation and in need of improvement of the model considering more physical mechanisms. Nonetheless, it can provide a better insight into the formation of the macrosegregation during the MP process, meanwhile offer a guidance to optimize the MP process and control the

macrosegregation in large ingots through careful selection of processing parameters such as pouring temperatures, species content, pouring time and the molten steel's weight in each ladle and other special technologies.

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