Numerical study of macrosegregation in a large steel ingot with multiple pouring process

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Abstract: Multiple pouring (MP) process with a higher concentration in the beginning and a lower concentration at the last is generally utilized to reduce macrosegregation in the large steel ingot production. However, it is insufficient to demonstrate the practical efficiency of MP process from the point view of theory. In this paper, the whole filling and solidification processes were investigated to analyze the formation of macrosegregation in a large steel ingot. Firstly, a filling transportation model considering the entire MP process was presented. The carbon concentration variation through the outlet of the tundish at different times was predicted and provided as the boundary conditions for the mold filling and the solidification processes simulation. Secondly, the macrosegregation model was integrated into the filling transportation model to investigate the influence of the MP on the macrosegregation in the ingot through the comparison of the MP and the single pouring process (SP). Finally, the top section of a 438-t steel ingot was cut off and the carbon concentration was measured to validate the numerical results. The results indicated that the MP process has a certain favorable effect on reducing the positive segregation in the top region of the ingot.

1. Introduction

Large steel ingots weighing more than 100 tons are widely used in the heavy equipment for power, shipbuilding, petrochemical, metallurgy and other industries, such as steam turbine rotor, hydraulic turbine shaft, pressure shell of atomic reactors, and roller for large mill housing [1]. For a long time, many steel plant workers and researchers have been devoted to improve the quality of these products through the casting practice and laboratory investigation. The defect of macrosegregation encountered in the large steel ingots has become a great concern in recent years. Some special technologies have been come up to reduce the macrosegregation in castings [2-3]. At the same time, great efforts have already been made in the last few decades in the modelling of macrosegregation [4-8]. However, the industrial application of these models is still limited to the steel ingots less than 100 tons regardless of pouring process. As the large steel ingots of 300~600 tons concerned, few researchers have attempted to take both the filling and solidification processes into account because of the large size of the calculation domain and the limitation of the hardware resource. The numerical simulation in a 360 tons steel ingot was carried out by Liu et al. Whereas the filling in the tundish and mold should be introduced in detail [9]. A marked reduction of macrosegregation was obtained in the ingot body for 570 tons steel ingot produced by MP process [10]. The MP process of a 292 tons steel ingot was simulated by Tu et al. And the favorable initial carbon distribution in the mold was found after MP process, however, the formation of the macrosegregation after filling was not presented [11].
The objective of the present research is to analyze the macrosegregation with the carbon concentration variation during the filling process. The influence of the MP process on the final macrosegregation in a large ingot is numerically simulated with validation of an industrial experiment.

2. Process description
The whole MP process with three stages of the filling, holding and draining is shown in figure 1. In the first stage (figure 1a), the refined molten steel is poured into the tundish from the first ladle with higher concentration until the liquid steel reaches the highest critical height in the tundish, then the tundish is closed and keeps standstill for a while. In the second stage (figure 1b), the outlet and inlet of the tundish are opened at the same time, the molten steel from sequential ladles with lower concentrations comes into the mold, and the level of the melt in the tundish remains certain height by controlling the flow rates through the inlet and outlet of the tundish. In the third stage (figure 1c), when the total molten steel are poured into the tundish completely, the bath level reduces to the lowest critical height, then the inlet and outlet of the tundish is closed, and the whole pouring process is over. After filling, molten steel solidifies in the mold and macrosegregation may form during solidification.

Figure 1. Schematic of MP process for a large steel ingot: (a) the filling stage, (b) the holding stage, (c) the draining stage.

3. Mathematical model
A turbulence model and a continuum model were integrated to investigate the macrosegregation in steel ingot with MP process. Table 1 shows the CFD turbulence transportation model based on the multi-phases and VOF methods for unsteady, turbulent and gas-liquid two phase flow in the tundish. The Realizable k-ε model was employed in the far-wall field zones, which has superior performance for flows involving rotation, boundary layers under strong adverse pressure gradients, separation, and recirculation. The commercial software Fluent was applied to simulate the solute mixing behavior in the tundish. The mass continuity, momentum, energy as well as the chemical species conservation equations were solved, and the carbon distribution in the tundish and the carbon variation through the outlet of the tundish during the MP process at different times were simulated.

Furthermore, the previous continuum macrosegregation model in reference [8] was incorporated into the filling transportation model to simulate the filling and solidification processes in the mold. The fluid flow in the mold was much weaker compared to that in the tundish, because the melt was sprayed into the mold during the filling with vacuum. The main assumptions and simplifications for the macrosegregation model were employed as follows: a) two dimension in the calculation; b) laminar and Newtonian fluid flow in the liquid phase; c) rigid and stationary in the solid; d) the Boussinesq assumption in the buoyancy term of the momentum equation. The conservation equations
are listed in table 2. The moving grid method with expanded calculation domain was applied during the mold filling process. 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 surface. Once the new added volume of the molten steel at a calculation time step was larger than one layer of elements in the mold, the free surface was set upwards by one layer until the end of the MP process. However, the detailed dripping process of the liquid steel from the output nozzle of the tundish to the free surface of molten steel in the mold was simplified during MP process.

According to the actual MP process, three ladles with different carbon concentrations were poured in succession from the tundish to the mold for the production of steel ingot with average Fe-0.44%Mn (C0 = 0.44) in order to counteract the negative segregation at the bottom and the positive segregation at the riser. The weight of the molten steel in each ladle was 150 tons and the carbon concentrations from the first to the third ladle were 0.51%, 0.44%, 0.37%, respectively. The weight of ingot was about 438 tons with the height of 5.1 m and the average width of 3.765 m. The teeming temperature was 1560°C, and the total pouring time was about 5200 s. The heat transfer coefficients for the interfaces at the mold/ingot and mold/ambient were assumed as constant values of 1000 W⋅m⁻²⋅K⁻¹ and 100 W⋅m⁻²⋅K⁻¹, respectively. A small heat transfer coefficient of 5 W⋅m⁻²⋅K⁻¹ was used at the interface between the casting and powder at the mold top. The time step was 0.01 s for the fluid flow simulation in the tundish. The time step was 1 s in the mold filling process and then 2 s at the later stage of the solidification simulation. The mesh size was 30 mm with a square and tetrahedron shape for the mold and tundish, respectively.

### Table 1: turbulence transportation model: the mathematical model for the flow in tundish

| Equation   | Description                                                                 |
|------------|-------------------------------------------------------------------------------|
| Mass       | \( \frac{\partial u}{\partial t} + \rho v \cdot \nabla u = \frac{1}{\rho} \nabla (p + \rho u) - \rho g \) |
| Momentum   | \( \frac{\partial u}{\partial t} + \rho v \cdot (u u) = -\nabla p + \rho \nabla^2 u + \rho g \) |
| Realizable k-\( \varepsilon \) | \( \frac{\partial k}{\partial t} + \rho v \cdot (u k) = \left( \frac{\rho}{\rho_U} \right) \left( \frac{\alpha}{\frac{\nabla^2}{\rho_U}} \right) \left( \frac{\nabla^2}{\rho_U} \right) + G_s - \rho \varepsilon \) |
| Energy     | \( \frac{\partial \varepsilon}{\partial t} + \rho v \cdot (u \varepsilon) = \frac{K}{\varepsilon_U} \frac{\nabla^2 \varepsilon}{\rho_U} \) |
| Species    | \( \frac{\partial C}{\partial t} + \rho v \cdot (u C) = \nabla \cdot (D \nabla C) \) |

### Table 2: continuum model: the mathematical model for the macrosegregation in mold

| Equation   | Description                                                                 |
|------------|-------------------------------------------------------------------------------|
| Mass       | \( \nabla \cdot u = 0 \)                                                   |
| Momentum   | \( \frac{\partial u}{\partial t} + \rho v \cdot (u u) = -\nabla p + \rho \nabla^2 u - \rho K \nabla^2 u + \rho g \) |
| Density in buoyancy term | \( \rho_b = \rho [1 - \beta_f (T - T_i) - \beta_s (C_s - C_i)] \) |
| Energy     | \( \frac{\partial T}{\partial t} + \rho v \cdot (u T) = \frac{K}{c_p} \nabla^2 T + \rho \frac{1}{c_p} \frac{\partial T}{\partial \tau} \) |
| Species    | \( \frac{\partial C}{\partial t} + \nabla \cdot (u C) = \nabla \cdot (D \nabla C) + \nabla \cdot [g_i (D \nabla C_i - C_i)] - \nabla \cdot [u (C_i - C)] \) |
| Permeability | \( K = \frac{\alpha^2}{180 (1 - g_i)^2} \) |
| Temperature and liquid concentration | \( T = T_n + m c_i \) |
| Solid volume fraction and temperature | \( g_s = \frac{1}{k_s} \frac{T - T_n}{T - T_m} \) |
In above equations, \(a_p\) is the volume fraction of the molten steel, \(m_{pq}\) the mass fraction of the molten steel, \(m_{sp}\) the mass fraction of the air; \(u\) denotes the velocity, \(\rho\) the density, \(t\) the time, \(p\) the pressure, \(\mu\) the liquid viscosity, \(g\) the gravity, \(T\) the temperature, \(K\) the thermal conductivity (equation (4) and (9)), \(c_p\) the specific heat, \(L\) the latent heat, \(g_t\) the solid volume fraction, \(g_l\) the liquid volume fraction, \(C\) the species concentration, \(k_p\) the partition coefficient, \(T_m\) the melting temperature of the pure iron, \(m\) the liquidus slope of the phase diagram. The Boussinesq approximation (equation (8)) was used to model the thermo-solutal convection, where \(\rho_b\) denotes the density in the buoyancy term, \(\beta_T\) and \(\beta_C\) are the thermal and the solutal expansion coefficients; \(T_0\) and \(C_0\) are the reference values for the temperature and concentration, respectively. The permeability of the mushy region, \(K\), is defined by the Carman-Kozeny relation (equation (11)), which depends on the liquid volume fraction \(g_l\) and the secondary dendrite arm spacing \(\lambda_2\).

4. Results and discussion

4.1. Carbon distribution in the tundish and mold during filling

Figure 2 shows the carbon distribution in the tundish at different times during the whole MP process. Before 1600 s, the carbon concentration in tundish is homogenous, i.e., 0.51% which is same as that in the first ladle melt. When the molten steel from the first ladle has completely been poured into the tundish, the molten steel with less species from the sequential ladles begins to mix with the original molten steel in the tundish. This mixing behavior is carried on mainly by the way of convection owing to the violent flow induced by the impinging of the plunging jet from the ladle. In the holding stage as indicated in figure 2 (a-f), the molten steel with lower carbon concentration is transferred to the corners of the tundish, and several swirls with higher carbon concentration form in the middle of the tundish. When it comes to the draining stage and all ladles of the molten steel are poured into the tundish completely, the bath level in the tundish decreases to the lowest critical height because the molten steel flows out through the tundish outlet without supplement as shown in figure 2 (g-h). The carbon distribution is almost the same and remains higher than that of molten steel in the third ladle.

Another aspect should be mentioned that the carbon concentration through the outlet of the tundish comes from the following two parts: the circumfluence flow from the middle of the tundish and the plunging jet flow directly to the outlet. This carbon concentration at different times through the outlet of the tundish has been calculated and used as the boundary conditions in the simulation of mold filling and solidification stage.

Figure 3 (a-d) shows both the filling and the solidification processes with different times in the mold. There is no carbon variation (0.51% C) in the mold before 1600 s during the filling stage. In the impact region of the upper mold, the carbon mixing behavior is carried on by the way of the forced convection; the carbon distribution pattern takes on a kind of V-shape with the deepest height of about 1 m. Another phenomenon can be found that the low carbon solute from the top region is transferred to the lower region along the solidified shell growing from the mold wall. At the same time, the low carbon dilutes with the high carbon in the inner region of the mold mainly by the way of the diffusion, and thus the carbon distribution gradually decreases from the center to the side in middle of the mold. During the third ladle filling at times of 3750 s and 4700 s as shown in figure 3 (c-d), the impact area of the fresh steel on the free surface becomes narrow and the impact depth increases with the molten steel level rising in the mold. Moreover, an intensive turbulence forms around the center region on the free surface. Finally, the initial carbon concentration in the mold after MP process presents obviously low in the hot top section and high in the solidified shell near the mold bottom.

Figure 3 (e-h) shows the carbon distribution evolution and the fluid flow during the later solidification stage after pouring process. High carbon distribution is presented at the lowest bottom of the ingot because the high carbon species with 0.51 wt. % C from the first ladle melt has been captured by the solidified metal at the beginning of solidification. With the solidification proceeding, the carbon distribution in the center of the liquid steel increases, and finally the serious positive segregation is presented in the hot top region of the ingot. It should be mentioned that if the carbon mixing in the
tundish was ignored, the carbon concentration of ingot is different compared with that considering the tundish filling especially during the pouring process and finally may be little different according to [9].

Figure 2. Evolution of carbon distribution in the tundish at different times. (a-h) at 1700 s, 2000 s, 2500 s, 3000 s, 3500 s, 4300 s, 4900 s and 5200 s.

Figure 3. Fluid flow and carbon distribution at different times in the mold. (a) 1750 s, (b) 2250 s, (c) 3750 s, (d) 4700 s, (e) 15000 s, (f) 36000 s, (g) 108000 s, (h) final solidification stage.

In order to validate the present numerical model, a trial steel ingot weighting 438 tons was produced in the steel plant of the CITIC Heavy Industries Co., Ltd. as illustrated in figure 4 (a). After the steel ingot had been cooled and stripped out from the mold, the riser part of the steel ingot was cut off and the specimens were taken along these transverse sections. The concentration of these samples was measured using spectral analysis.

Figure 4 (b-d) shows the comparison between the predicted and measured result of the carbon concentration along the transverse sections (A-C) in the hot top of ingot. The distance of these sections (A-C) from bottom of the riser is about 0.7 m, 0.6 m, 0.5 m, respectively. In general, the agreement between the predicted concentration and the measured tendencies can be considered good. The
predicted positive segregation around the riser center region is underestimated as compared to the experimental results. However, the difference between them can be accepted in industrial applications. Besides, negative segregation in the bottom of ingot was not simulated successfully due to the fact that the motion of equiaxed grains is not considered in current continuum model.

![Figure 4](image)

Figure 4. (a) Schematic showing 438 tons ingot mold and carbon measurement positions. Measured and predicted carbon concentration at (b) section A, (c) section B and (d) section C.

4.2. Comparison of the macrosegregation between the MP and SP

In order to investigate the effect of MP technique on the final macrosegregation in ingot, two cases with the MP and the SP (single pouring) process were simulated and compared. The SP process is referred to the MP process with the uniform carbon concentration of the molten steel in the sequential ladles.

![Figure 5](image)

Figure 5. Comparison of the macrosegregation between the SP (a) and the MP (b).

![Figure 6](image)

Figure 6. Comparison of the carbon concentration along the ingot center line.
Figure 5 shows the comparison of the final macrosegregation in ingot between the case 1 (SP) and case 2 (MP). The overall patterns of macrosegregation are nearly similar for two cases, namely, the strongly positive segregation in the riser. It can be seen from the width and the depth of the positive segregation zone as illustrated in figure 5 that the positive segregation in the top center region of the ingot for the case 1 is more serious than the case 2. It can be explained simply by the reason that the low carbon species from the last ladle remains for a longer time in the riser with MP. Figure 6 shows the comparison of the carbon distribution profile along the ingot center line between the two cases. It can be illustrated that the carbon concentration at the same center line’s position with SP is higher than that with MP except for the tail section of the ingot. The highest carbon is shifted upper into the hot top riser of the ingot with MP, that is to say, the macrosegregation degree in the steel ingot body is released to some extent with MP. Therefore, the comparison of the simulation results between the two cases demonstrates that the MP technique has some certain favorable effects on suppressing the positive segregation in ingot. However, the macrosegregation is still severe in the ingot body and the optimized MP process should be adapted in the future research work.

5. Conclusions
A filling transportation model has been realized to describe the carbon mixing behavior and distribution in the tundish during the multiple pouring (MP) process. The macrosegregation model was integrated into the filling transportation model, and the numerical results of the macrosegregation with MP process have been validated with the carbon measurements in a 438 ton steel ingot. Comparison results show that the multiple pouring process has some certain favorable effect on reducing the final macrosegregation as compared to the conventional constant concentration pouring process.

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