Numerical simulation of multi-mini-pot pouring process of a 13-ton steel ingot

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Abstract. Heavy ingots up to several hundred tons for power plant forgings exhibit large scale grain size and morphology differences, which are harmful to the design of forging parameters, and severe macrosegregation, which could not be eliminated during the subsequent forging and heat treatment processing. To cast these ingots with more homogeneity, a multi-mini-pot (MMP) pouring technique is proposed, in which liquid metal is poured by multi-mini-pot (MMP) with intermission between each pot and solidification occurs step by step. In this paper, we are focus on the prediction of macrosegregation in MMP pouring process. A three-phase model is employed to study the MMP pouring process for a 13-ton heavy ingot. The main features of this three-phases model in such a heavy ingot can be quantitatively modelled: growth of columnar dendrite trunks; nucleation, growth and sedimentation of equiaxed crystals; thermosolutal convection of the melt; solute transport by both convection and crystal sedimentation; and the columnar-to-equiaxed transition (CET). The results shown that the MMP pouring technique tend to decrease the macrosegregation significantly by compared with the conventional method.

1. Introduction
Ingot casting is a common process in foundry. More alloyed metallic materials are now cast in ingot for further processing with increased quality to meet with the higher service windows, such as machine tools, forgings for power plant, etc [1]. Unfortunately, it seems that foundry man could not cast satisfactory ingot to meet the need of increasing desire from final products. Heavy ingots up to several hundred tons for power plant forgings exhibit large scale grain size and morphology differences, which are harmful to the design of forging parameters, and severe macrosegregation, which could not be eliminated during the subsequent forging and heat treatment processing. Therefore, to suppress macrosegregation during casting process has always been the focus of casting research [2-3]. Flemings [4] investigated the effect of the hot top on macrosegregation. He proposed that an ingot with ideal hot top can significantly reduce the macrosegregation by (1) eliminating formation and settling of equiaxed grains from the hot top and (2) promoting a positive temperature gradient from the ingot and hot top region. He also proposed a new method that rotated the ingot during solidification [4]. Sang et al. [5] present a new technique for reducing macrosegregation in steel ingots. They added
solid steel balls to the melt during the pouring process. With this technique the macrosegregation was reduced, the formation of A-type segregation was prevented. However, this technique is difficult to control, and some other defects will happen. Tanaka presented a multi concentration pouring technique to restrain the formation of macrosegregation during casting process [6-7]. The serious macrosegregation defects which were unavoidable for conventional casting were improved significantly. However, when the ingot size is larger than 180-ton the improvement is unapparent. Authors proposed a novel technique: multi-mini-pot (MMP) pouring for the casting of heavy ingot [1]. The liquid metal is poured by multi-mini-pot with intermission between each pot and solidification occurs step by step. The composition and amount of each pot are designated depending on the controls grain differences and segregation level of the target ingot. The model for multi-mini-pot pouring process is in consistent with the classical solidification theory, where the segregation will tend to the minimum as the amount of each pot goes to the minimal.

The principal intention for this paper is to validate the probability of MMP technique by numerical simulation. Therefore, a three-phase model [8-10] is employed to simulate MMP pouring process and to predict the formation of macrosegregation.

2. Process model of multi-mini-pot pouring

Generally, in the production of ingots, alloy, as large amount as needed, is melt in one (for small ingot) or more (for heavy ingot) furnaces, and then poured by one or more pots into a mould continuously. Solidification occurs after and progress freely to the end. Pouring time is only a little part compared with solidification time, during which intensive melt flow results in untraceable solute profile and cooling rate decreases gradually as solidification proceeds. As foundryman can cast small ingots with a quality as needed in heavy ingot, heavy ingot casting can be divided into several small ingots. As schematically shown in figure 1, an ingot with weight $W$ is divided into $N$ parts, each time $t_i$, $W_i=\frac{W}{N}$ melt is poured into the mould. Next $W_i$ melt is then added at the time when $(t_i-1)'s$ pouring become solid with 20%-30% left. We choose this value based on numerical parameters study and also the earlier laboratorial experiment study [1]. New pouring melt will mix with the former 20%-30% left and next solidification begins. This process repeats till the mould is full.

3. General description of the model

With MMP pouring technique the solidification process of a 13-ton big-end-up steel ingot (Fe-0.2 wt.% C) was simulated. Here a 2-D axis-symmetrical simulation was performed to approximate the solidification behaviour of this ingot. The configuration of this ingot, labelled with the necessary boundary and initial conditions, is described in figure 2. All the thermodynamic and physical properties used in this study are the same as reference [8,11], as shown in table 1.

The columnar-equiaxed mixed three-phase model [8, 12-13] was employed to simulation the solidification process. Details of the numerical model are described elsewhere [8, 12-13]. A brief outline of the model and simulation settings are given below:

- Mould filling for each pot is ignored. Solidification starts with an initial concentration Fe-0.2 wt.%C and an initial temperature of 1840 K.
- Three phases are defined: the primary liquid phase ($\ell$), the equiaxed phase ($e$), and the columnar phase ($c$). The corresponding phase fraction is $f_\ell$, $f_e$ and $f_c$, with $f_\ell + f_e + f_c = 1$. Both the liquid and equiaxed phases are moving phases, for which the corresponding Navier-Stokes equations are solved. The columnar phase is assumed to stick to the wall, and solidifies from the wall towards the bulk melt. Thus, no momentum equation for the columnar phase is considered.
- Columnar dendrites are approximated by growing cylinders starting from the mold wall towards the casting centre. The advance of the columnar tip front was tracked during the solidification.
Table 1. Thermodynamic & physical properties

| Property                        | Symbol | Units          | Quantity  |
|---------------------------------|--------|----------------|-----------|
| Melting of pure iron            | $T_f$  | K              | 1805 [8]  |
| Liquidus slope                  | $m$    | K (wt.%)$^{-1}$| -8000 [11]| |
| Equilibrium partition coefficient| $k$    | -              | 0.18 [11] |
| Reference density               | $\rho_l$, $\rho_e$, $\rho_c$ | kg·m$^{-3}$ | 7060 [11] |
| Solid-liquid density difference  | $\Delta \rho$ | kg·m$^{-3}$ | 150 [8]   |
| Specific heat                   | $c_p^l$, $c_p^e$, $c_p^c$ | J·kg$^{-1}$·K$^{-1}$ | 500 [8] |
| Thermal conductivity            | $k_l$, $k_e$, $k_c$ | W·m$^{-1}$·K$^{-1}$ | 34.0 [8] |
| Latent heat                     | $L$    | J·kg$^{-1}$    | $2.71 \times 10^5$ [8] |
| Viscosity                       | $\mu$  | Kg·m$^{-1}$·s$^{-1}$ | $4.2 \times 10^{-3}$ [8] |
| Thermal expansion coefficient   | $\beta_l$ | K$^{-1}$    | $8.9 \times 10^{-5}$ [11] |
| Solutal expansion coefficient   | $\beta_c$ | wt.%$^{-1}$ | $1.416 \times 10^2$ [11] |
| Dendritic arm spacing           | $\lambda_i$ | m         | $5 \times 10^4$ [8] |
| Diffusion coefficient (liquid)  | $D_l$  | m$^2$·s$^{-1}$ | $2.0 \times 10^{-8}$ [8] |
| Diffusion coefficient (solid)   | $D_e$, $D_c$ | m$^2$·s$^{-1}$ | $1.0 \times 10^{-9}$ [8] |

- For equiaxed grain a simple method is employed to handle the dendritic morphology [10].
- A three-parameter heterogeneous nucleation law is used for the nucleation of equiaxed grains. No fragmentation and grain attachment are currently considered. Growth of the columnar trunk and equiaxed grain is governed by diffusion.
- The permeability in the columnar mush zone is modelled according to Blake-Kozeny, while the drag law between the melt and equiaxed phase is modelled according to Wang’s approach [14].
- Growth of columnar primary tips is stopped when the volume fraction of equiaxed phase in front of them reaches 0.49 (hard blocking criterion) [15].
- Packing limit for the equiaxed phase is set as $f_e + f_c = 0.637$ [16], and the equiaxed crystals are trapped when the trapping limit of $f_e$ 0.2 is reached [17].
4. Simulation result and discussion
The solidification sequence of MMP pouring process was presented in figure 3. As for MMP pouring technique, the ingot was divided into 10 mini-ingot (each pot can be considered as one mini-ingot), each mini-ingot solidified step by step. The current pot be poured into the model when the previous pot has only 20-30% liquid melt remained, therefore, the solidification of each mini-ingot behaved approximately individually. For the solidification process of each pot the melt was in a shallow-broad domain. The molten steel can only flow and develop within this small domain. Therefore the melt velocity is quite small, as seen from figure 3, after 15 minutes of pouring the maximum melt velocity for each pot is around 0.002 m s\(^{-1}\). The solidification front, as well as the mush zone, behave as a shallow U-type other than deep V-type as in the conventional pouring technique [8]. With shallow flow domain, the sedimentary equiaxed grain did not have sufficient time to accumulate in the bottom of the ingot which result in the significant cone shape negative segregation for the conventional casting [8].

Figure 4 shows the comparison between conventional and MMP casting after 15 minute of pouring. The left part shown the melt velocity vector and the right part indicated the liquid volume fraction. As for conventional casting, since at the early stage of solidification the molten steel domain is very large, due to the thermalsolutal convection and the sedimentation of equiaxed crystal the liquid flow can develop to a big value, as large as 0.018 m s\(^{-1}\), in this large domain as seen in figure 4(a). For MMP solidification the ingot was divided into 10 mini-ingots, and they solidified gradually approximately one by one. During the solidification process of each pot the melt domain is about one tenth of the
conventional solidification. Which determined that the melt flow did not have sufficient space to get full developing. Subsequently, the liquid velocity was significantly decreased by compared with the conventional casting, which is about one eighteenth smaller than the conventional one.

Figure 3. Solidification sequence of MMP pouring processing. All the figures were selected after 15 minutes after the pouring of each pot. The left part shown the melt velocity vector. The right part shown the macrosegregation index \( \left( \frac{c_{\text{mix}} - c_0}{c_0} \right) \). The liquid volume fraction iso-lines were also shown as the red line.

Figure 5 shows the final macro segregation pattern. As for conventional casting, the core of negative segregation in the ingot bottom and positive segregation in the top region were predicted which is correspond to the classic solidification theory and other researches [8, 12]. The reason for the core of negative segregation in the bottom region could be in two aspect: on one hand, the sedimentation of equiaxed crystal from upper region to the bottom; on the other hand, the equiaxed crystal moved from the side mushy zone to the bottom region by sedimentation and molten steel flow. Since the molten steel flow is very unstable and chaos in the domain (see figure 4(a)), the macrosegregation distribution is also uneven. There is some small positive or negative segregation patches near the ingot edge.

For MMP technique, by contrast, there is neither core of negative segregation zone in the bottom nor obvious positive segregation zone in the hot top region, however, a periodic distribution of negative-positive segregation layer is easily be found in the central of the ingot. Since the melt domain for MMP is small and shallow there is fewer equiaxed crystal settling from the upper to the bottom. Moreover, since the liquid velocity in this case is very small it is difficult to drive the equiaxed crystal
from the side mushy zone to the centre bottom region. The equiaxed crystal become more scatter than the conventional casting. Therefore, although there is a negative segregation region in the bottom of each mini-ingot, the severity of negative segregation was significantly decreased.

**Figure 4.** The comparison between conventional and MMP solidification after 15 minute of pouring: (a) conventional with one pot; (b) MMP with 10 pots. The left part shows the melt velocity vector. The right part indicates the liquid volume fraction.

**Figure 5.** The predicted final macrosegregation pattern: (a) conventional with one pot; (b) MMP with 10 pots.

In addition, there are some positive segregation patches which are periodic distribution near the ingot wall. The formation of this positive segregation can be understand as following: under the melt-air interface about two or three cells distance there are horizontal melt flow from the solidification front (melt-rich region) to the centre of the ingot (relative melt deplete region), as seen from figure 3; this flow bring more solute into the volume and bring out less solute out of the volume; subsequently, result in a positive segregation patch. Figure 6 elaborates this mechanism more distinct. As discussed by Wu [18], in the mush zone in the region where the melt velocity is in the opposite direction with the concentration gradient may tend to form a positive segregation zone. The formation of this positive segregation patch in coincide with their opinion. This kind of positive segregation, to some extent,
indicated the shortcoming of the current processing parameter for the MMP technique. Therefore, more effort should be implement to overcome this defect, and increasing the final homogeneity more effectively.

**Figure 6.** The relationship between positive segregation patch and the melt velocity and concentration gradient. The color map indicate the concentration field. The blue vectors show the melt velocity. The black vectors indicate the concentration gradient. The result was zoom in from Z1, as shown in figure 3(b).

**Figure 7.** The comparison of central line macrosegregation distribution between conventional and MMP pouring techniques.

In order to obtain more detail information about the macrosegregation, the centreline segregation were compared and shown in figure 7. As we can see, the severity of macrosegregation was significantly decreased by MMP casting. The maximum (magnitude) negative segregations were predicted as one third of the conventional casting.

5. **Summary**

A novel technique, Multi-Mini-Pot (MMP) pouring, for cast heavy ingot was present to diminish the macrosegregation. In order to validate this novel technique, a mixed columnar-equiaxed three-phase model was employed to simulate both the MMP pouring solidification and conventional solidification process. The result shown, for the solidification of a 13-ton heavy ingot, that by compare with the conventional technique the MMP pouring technique: 1) decreased the melt velocity dramatically, the maximum melt velocity was decreased from 0.018 m s\(^{-1}\) to 0.001 m s\(^{-1}\); the core of negative segregation in the bottom region was eliminated; the intensity of negative segregation was decreased significantly which is from -0.3 to -0.1. In brief the solidification of heavy ingots may be divided into
several steps by a multi-mini-pot pouring to increase homogeneity. However, there are some positive patch in near the ingot wall which was the shortcoming of the current casting parameters for MMP pouring technique. Further parameter optimum and technology improvement should be implement to overcome this shortcoming.

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