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Modeling of the Influence of Hot Top Design on Microporosity and Shrinkage Cavity in Large-Size Cast Steel Ingots

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ABSTRACT

The effect of the changes in the hot top design on the risk of microporosity and shrinkage cavity formation during solidification of a 12MT cast ingot made of a Cr-Mo-low alloy steel was investigated. Three-dimensional finite element modeling code THERCAST® was used to simulate the thermo-mechanical phenomena associated with the various phases of mold filling and cooling in and out of the mold in the solidification process. Prediction results were validated by comparison between the simulation results and experimental measurement of chemical composition in the total part of the ingot and evaluation of the depth of the shrinkage cavity. The influence of the increase in the hot top height, and increase in both the hot top height and sideboard height on the risk of microporosity formation in the centerline, shrinkage cavity in the hot top, and solidification time were determined. Results revealed that variation in the hot top geometry and hot top insulation increased the solidification time, increased liquid feeding, reduced the depth of the shrinkage cavity, and reduced the possibility of centerline microporosity. The simulation results also showed more effects of combination design, including an increase of hot top height and sideboard height, on the reduction of centerline shrinkage porosity, as well as shrinkage cavity.

INTRODUCTION

Heavy mono-block high-strength steel is the raw material for different industrial applications such as energy, automotive, and transportation. The common manufacturing process for heavy mono-block high-strength steel is ingot casting[1] which plays an important role in the final product's quality. Indeed, during casting solidification, shrinkage porosity, macrosegregation, and inclusion are the most important defects that could deteriorate the heavy high strength steel properties. Furthermore, it is very difficult to eliminate the above defects by subsequent thermo-mechanical operations.[2] Traditionally, the effect of some defects such as centerline shrinkage porosity in heavy steel ingots was ignored because the subsequent forging process was capable to close up the shrinkage porosities. However, the porosities are not removed if their size is too big. Therefore, it is significant to study the formation mechanisms of centerline porosity in large-size ingots in order to improve their quality.[1; 2] On the other hand, purely empirical investigations on casting defects are costly and complicated due to the important dimensions of the workpieces. Therefore, the technology of computation developed rapidly to analyze the solidification process and defect formation during solidification.[2-4] However, the formation mechanism of shrinkage includes heat flow, mass flow, and some other complicated phenomena, but also the pure thermal calculation is a commonly accepted practice to simulate shrinkage porosity [2]. Shrinkage porosity criteria for casting, such as the temperature gradient criterion, critical solid fraction criterion, and common Niyama criterion were used in the developed macrosegregation models to predict the possibility of microporosity and simplify the high times and costs while delivering realistic predictions.[2; 3]

The hot top is one of the most important cast ingot setups placed in the top part of the mold and lined by a refractory material. The hot top is responsible to supply the continuous feeding during casting and controlling the heat flow during solidification.[5] Thus, the variation in the hot top properties alters the liquid feeding from the hot top towards the ingot body and the possibility of centerline porosity.[2] For this, it is important to develop new hot top designs with the view to reducing the formation of casting defects and as a result the overall cost of the product.[6] Thus, the study of hot top properties has been considered numerically for years.

Tashiro et al.[7] studied the design conditions of the hot top and mold in large 0.25%C-3.5%Ni-Cr-Mo-V steel ingots 100 MT and 135 MT using the finite element method (FEM). They reported the importance of the geometric design of the mold and hot top on the ingot quality. They found that the reduction of slender ratio H/D (the ratio of the height of the ingot body relative to the average diameter of the ingot body) and increase of ingot taper result in the reduction of central porosity. Heidarzadeh et al.[8] reported the reduction of centerline porosity of a 4.4 MT steel ingot type X210Crl2 due to increasing taper of mold, decreasing H/D ratio, and incorporating extra insulation board between the body of mold and the hot top. Kermanpur et al.[9] reported that the lower mold slenderness ratio and circular shape of the insulating material in the hot top of a 6 MT Cr-Mo low alloy steel ingot improve the efficiency of the riser and decrease crack sensitivity during further hot forging. Balcar et al.[10] studied 8.9 MT tool steel ingot. They found that lower slenderness ratio H/D, higher taper, and increase in hot top volume reduce axial defects and macrosegregation. Wang et al.[2] studied the optimized design in 100 MT steel ingot to reduce shrinkage porosity and improve ingot quality. They proposed the increase of hot top mass ratio, a decrease in hot top taper, using better thermal insulation material, preheating the hot top mold, and optimizing the tail cone design of the ingot to eliminate the shrinkage porosity. However, it should be noted that in the above publications, the combination effect of mold and hot top geometry is mostly investigated on the shrinkage porosity.

In the current work, the influence of two hot top designs including an increased in hot top height and both increase in hot top height and sideboard height on the centerline shrinkage porosity as well as the depth of shrinkage cavity in 12 MT high strength steel was investigated using 3D finite element (FE) modeling code THERCAST®. Niyama criteria was used to predict the possibility of centerline porosity formation in the solidification model.

MATERIALS AND METHODS

The molten metal with a chemical composition including 0.32 C, 1.08 Cr, 0.34 Mo, and 0.57 Mn was bottom poured into a polygonal cast-iron mold to produce a 12 MT ingot. The casting temperature was about 1580°C. A cast-iron hot top, lined by refractory (sideboard), was in the upper part of the mold. Two exothermic caps were covered on the molten metal after pouring. Figure 1 shows the assembly of the 12 MT ingot cast setup. After completion of solidification, the shrinkage cavity depth was measured experimentally.

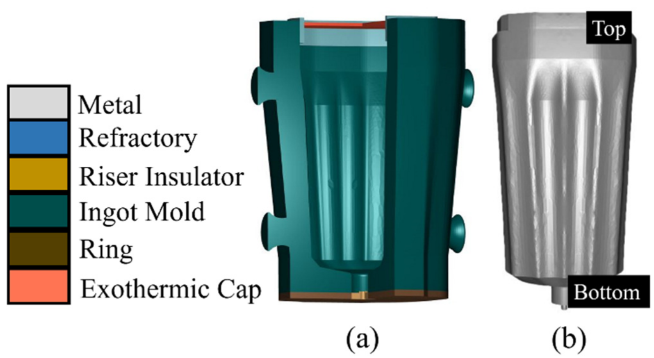

Figure 1. (a)Assemble of ingot 12MT (120° model), (b) Ingot 12 MT (360° model).

The casting simulation software THERCAST® was used to simulate the mold filling and thermal-mechanical behavior of molten metal during solidification for 12MT.[11] It contains a 3D finite element thermal-mechanical solver, based on an Arbitrary Lagrangian-Eulerian (ALE) to calculate the thermal convection in the liquid pool and mushy zone, and a Lagrangian to compute the deformation in solid regions.[12] Input parameters of simulation including thermophysical properties, thermomechanical properties, thermodiffusion computation, and initial condition of materials were obtained from JMatPro® version11.0 software,[13] THERCAST® material database,[14] and industry.[15] After simulation, the solidification model was validated by comparing the prediction and experimental results such as shrinkage cavity depth. A good agreement was observed between simulation and experiment results. Two different designs of the hot top were created in terms of an increase in mass ratio (weight of hot top melt to the total weight of the melt) than the original design with of 21.35% mass ratio and a decrease of slenderness ratio of 12 MT ingot. Then both new designs listed in Table 1 were simulated by considering the same input parameter as the original designs.

Table 1. Different Designs of the Hot Top

Type	Symbol	Increase in mass ratio
Original	OD	-
Increase of hot top height	ND1	10%
Increase of hot top height and sideboard height	ND2	8.15%

RESULTS AND DISCUSSION

1. Centerline Porosity

The solidification model available in THERCAST® code to predict centerline porosity is based on Niyama criteria[11; 16] which are associated with thermal gradient ahead of solidification front and cooling rate. During solidification, low thermal gradient and high cooling rate of molten metal in the solidification front result in freezing the solidifying metal before liquid feeding from the hot top reaches the solidification front. Therefore, the void forms ahead of the solidification front.[16] However, the precise size and shape of porosities are not computed by this model, although the risk, possibility, and zones of porosity formation could be predicted if the Niyama value is more than 1. Indeed, there is a potential to form shrinkage porosities.[17] The Niyama criterion is represented by the mentioned formula:

$$\mathrm{Ni}= \frac{\sqrt{\|\dot{T}\|}}{\|\Delta T\|} \quad \text{for} \quad f_l = f_{lNi} \qquad (1)$$

where $\dot{T}$ is the cooling rate and indicates the rate of the temperature variation of a spot in the material with time, ΔT is the temperature gradient that represents the temperature difference between a point and neighbours spots in the material, f_l indicates the liquid fraction and f_{lNi} is the threshold liquid fraction. The Niyama criterion is computed at a threshold liquid fraction that is considered $f_{lNi} = 0.3$ in THERCAST®. The criterion thus illustrates that, during cooling at a spot in the material, if the crossing to a solidification state given by f_{lNi} occurs with an extensive temperature fall or a small difference between its temperature and that of neighbouring spots or both at once, then these above indicate a risk of micropores formation at this point in the material. Indeed, the above Niyama equation is the inverse of the Niyama criterion expression as can be seen in the literature. The high risk of micropores formation is then represented by the low criterion values, where 0 is the minimum value. However, it is common to assume that high criterion values are critical. Thus, the result represented by THERCAST® accordance with the high criterion values, which is a high possibility for the micropore formation[11].

The results of the risk of centerline microporosity formation at the end of solidification for the original design (OD) and two new designs (ND1 and ND2) were obtained using Niyama criteria in this work. The maximum Niyama values in the ingot body were obtained at 1.53, 1.15, and 1.2 for OD, ND1, and ND2, respectively, which illustrate the reduction of the possibility of shrinkage microporosity in new designs.

According to the results, the total depth of centerline microporosity in the ingot body relative to a reference point (indicated in Figure 2) was 1300 mm, 1180 mm, and 1267 mm in OD, ND1, and ND2 respectively. The microporosity depth in the ingot body was reduced in ND1 and ND2. A direct relationship between depth of microporosity formation in the ingot body and mass ratio was obvious. The fewer depth of centerline microporosity in the ingot body was observed in ND1 with the highest mass ratio of 10% more than the original design. Therefore, an increase in mass ratio enhanced liquid feeding towards the ingot body, and result in a move upward the location of centerline microporosity in the ingot body.

In addition, Figure 2 reveals the difference in the dispersion line of centerline microporosity in OD, ND1, and ND2. The centerline shrinkage microporosity was formed in two separate zones in ND1 which were concentrated at 512 mm in length and 486 mm in length. According to the results, there was a 3.66% of zones with the Niyama criteria less than 1 in the dispersion line of shrinkage microporosity in ND1. Also, three separate zones were observed in ND2 which were concentrated at 63 mm in length, 146 mm in length, and 143 mm in length. The percentage of the zone with the Niyama criteria less than 1 in the dispersion line of shrinkage microporosity was 70% in ND2. Therefore, the concentration location of centerline microporosity was reduced by increasing the hot top height and increasing both hot top height and sideboard height. It could be found that the effect of the hot top geometry and heat capacity is greater than the geometry alone on the reduction of condensation of microporosity at the centerline. Thus, new designs could improve the ingot quality in terms of the elimination of microporosity. As Wang et al.[2] reported that the higher hot top height represents the larger heat capacity, higher liquid feeding into the center part of the ingot, and influence on the centerline shrinkage porosity.

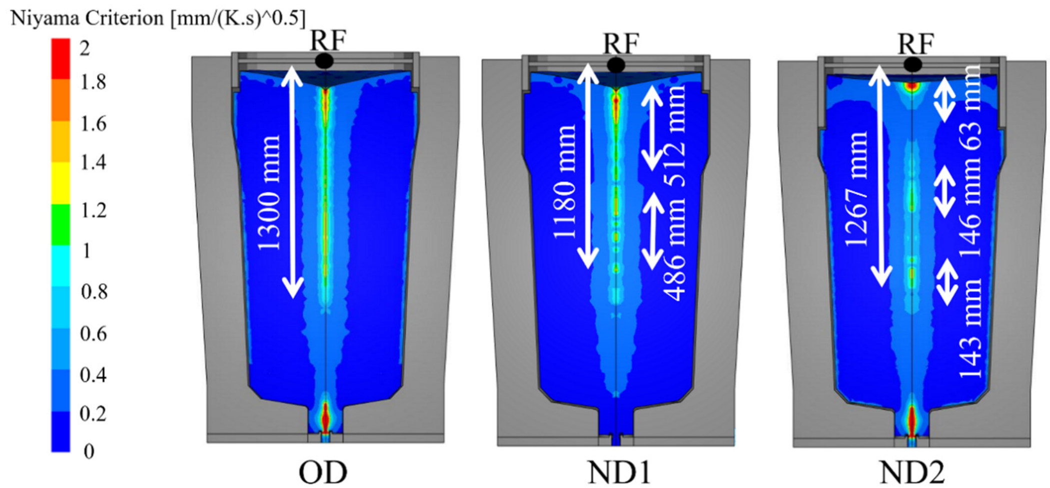

Figure 2. Possibility of centerline microporosity at the end of solidification, RF indicates the reference point for measurement of depth.

2. Shrinkage Cavity

The macroscopic shrinkage cavity forms in the hot top region due to thermal contraction and the change from liquid to solid. There is an estimation based on the change in the liquid fraction in the liquid and mushy zone in THERCAST®. The principle of calculation is based on the computation of the volume loss obtained in the liquid metal.[11] Figure 3 illustrates the displacement of the ingot due to contraction at the end of solidification in OD, ND1, and ND2. According to the results, vertical displacements of the metal relative to the top point of the mold component due to contraction were 158.2 mm, 144 mm, and 88.9 mm in OD, ND1, and ND2, respectively, at the end of solidification. The above results reveal that the top surface of liquid metal cooled slower by increasing the hot top height and increasing both the hot top height and the sideboard height. Thus, the drop of the metal surface in the hot top region was reduced by prolonging the solidification time and reducing the cooling rate of the metal. In terms of yield material, the fewer solid material was wasted in ND2, and ND1 respectively than in OD due to cropping the shrinkage cavity area to flatten the top surface of the ingot. Thus, the efficiency of material usage increases with the change in hot top designs.

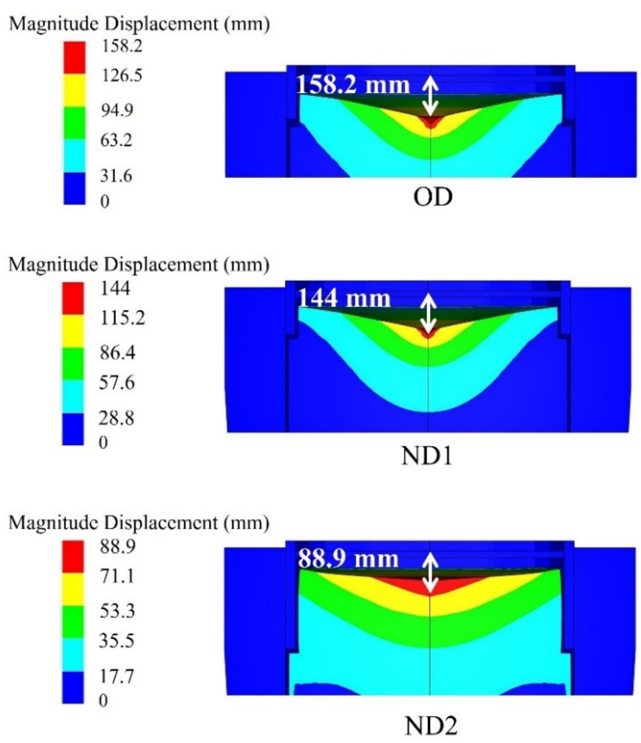

Figure 3. Magnitude view of hot top and shrinkage displacement in different designs.

3. Solidification time

The 3D FEM simulation results showed that the variations in hot top design affect significantly solidification time. According to Figure 4, an increase in the solidification time of about 2.56% and 34% were obtained by an increase in the hot top height (ND1) and both the hot top height and sideboard height (ND2) compared to the original design (OD). It was observed that the increase in both refractory height and hot top height extended solidification time more than only an increase in the hot top height. The variations of the hot top in ND1 and ND2 raised the molten metal volume in the hot top and enhanced the feeding pressure of liquid metal which is located within the hot top upon the ingot body center. On the other hand, the solidification of liquid metal within the hot top was delayed, and feeding time for lower layers of the ingot body and the last solidified zones was increased. The cooling rate of molten metal was reduced by increasing the solidification time. Thus, the hot top variations, especially in ND2, declined the centerline shrinkage porosity formation along the ingot center. Shengwen et al. [6] found that solidification time is an important parameter influence significantly the shrinkage porosity, and it highly depends on the mold and hot top designs. They showed that an increase in solidification time, by putting preheating temperature in a hot top, reduces shrinkage porosity defects.

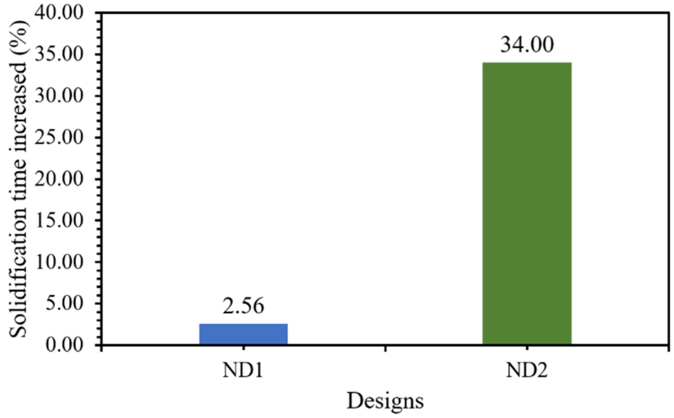

Figure 4. The percentage of solidification time increased comparing original designs.

CONCLUSIONS

3D finite element simulation was used by THERCAST® code to investigate the effect of hot top change on the possibility of shrinkage microporosity and shrinkage cavity in a 12MT high-strength steel ingot. In the present work, one new design including an increase of hot top height and another one containing both increased hot top height and sideboard height was investigated. The following results are obtained as below:

1. The change of hot top designs improved the ingot quality in terms of reduction of centerline shrinkage microporosity.
2. The concentration line of microporosity was affected by the change of hot top geometry and hot top heat capacity. The effect of the combination of both of them was more than only one to alleviate the centerline microporosity.
3. New designs especially ND2, increased the material yield of ingot in terms of cropping in the hot top zone, due to an increase in solidification time and a decrease in depth of shrinkage cavity in the hot top area.

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