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# Shrinkage porosity criteria and optimized design of a 100-ton 30Cr<sub>2</sub>Ni<sub>4</sub>MoV forging ingot

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# ABSTRACT

The heavy  $30Cr_2Ni_4MoV$  forging ingots have been extensively used to fabricate the low-pressure rotors, which play a crucial role in the large nuclear power plant. However, the quality of the heavy ingots has been commonly affected by various inner defects. One of the most typical defects is the centerline shrinkage porosity, which has been found to be always accompanied by inclusions and macrosegregation. Within this context, a 100-ton  $30Cr_2Ni_4MoV$  ingot was cut and the axle plane of it was analyzed to observe the distribution and size of the shrinkage porosity in the sectioned surface. On basis of these experimental results, through the FEM (Finite Element Method) simulation several criteria of the centerline shrinkage porosity have been clarified. Of them, the best criterion has been found to be the condition under  $G/R_s^{0.5} < 2.5 \text{ °C s}^{0.5} \text{ mm}^{-1.5}$  (*G* and  $R_s$  are the temperature gradient and solidification rate, respectively). With this criterion, the distribution and size of the simulated centerline shrinkage porosity agree well with the experimental results observed by the sectioning and ultrasonic testing. Subsequently, by utilizing the optimized design, the simulated results uncovered that the centerline shrinkage porosity could be nearly eliminated. Thereby, offering a possibility by significantly improving the performance for the nuclear power low-pressure rotors.

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# 1. Introduction

The ability to manufacture high-quality heavy castings and forgings is not only a symbol of a developed heavy industry but also has a fundamental influence upon the further development of the country because of their wide applications in aerospace, shipbuilding, electric power, petrochemical and machinery manufacturing industries. As a raw material of heavy forgings, the heavy steel ingots determine the quality of products. Of all the factors that deteriorate the properties of the heavy steel ingots, inclusions, macrosegregation and shrinkage porosity are the most significant ones since it is highly difficult to reduce those defects by subsequent thermo-mechanical treatments [1]. As the computational technology develops rapidly, solidification, segregation and even microstructure evolution in the casting process can be now simulated successfully. In such a way, the casting has already advanced from a non-visible to a visible process. Therefore, the design based on the computational simulation and the real-time radiography technology is highly attractive because it would have many advantages, i.e., to improve quality, to reduce cost and to shorten preproduction time, etc. [2–4].

From the traditional point of view, one often ignored the influence of some defects (i.e., the centerline shrinkage porosity) in heavy steel ingots. The reason is that the forward forging process was thought to have the capability of closing up the entire shrinkage porosity defects. However, if the porosities in the heavy steel ingot are "too big", it is difficult to "healing" all the porosity just by the forward forging process. Indeed, it turns out to be that the shrinkage porosity affects surely the quality of the product, especially, for the ingot used in high-level request products, such as nuclear power low-pressure rotors. As a result, it is significant to theoretically simulate shrinkage porosity accurately for heavy steel ingots and also to find the effective ways to eliminate shrinkage porosity in real practices.

Although shrinkage formation involves heat flow, mass flow and some other complicated phenomena, a generally accepted practice to simulate shrinkage porosity is purely from thermal calculations [5]. Through this simplest way, shrinkage can be recognized in terms of solidification patterns. It is defined that shrinkage appears in a spot within the closed loops formed by the isochronal contours of solidification time. This means a complete separation of the casting from the riser, simultaneously, accompanied by the disappearance of the feeding path [6]. More specifically, there are many shrinkage porosity criteria for castings, such as the temperature gradient criterion (*G*), critical solid fraction criterion and famous Niyama criterion (*G*/ $L^{0.5}$  < constant, where *L* is cooling rate) [7,8]. In 1988, Hanson also proposed a shrinkage criterion  $GL^{-0.25}U^{-0.5}$ , where *U* is the feeding flow velocity [9]. In addition, Minakawa's research demonstrated that the





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parameter  $G/R_s$  (where  $R_s$  is the solidification rate) can serve as the best criterion to indicate the onset of porosity in plate castings [10]. Jia and Liu further discussed the theoretical derivation of Niyama's criterion  $G/L^{0.5}$  < constant [11]. However, for heavy steel ingots there is still not a precise criterion to predict the occurrence, distribution and size of the centerline shrinkage porosity.

In this work, through FEM simulation in combination with the experimental sectioning investigation of 100-ton ingot, a criterion which can be used to reproduce precisely the experimental size and distribution of the shrinkage porosity in heavy steel ingots has been successfully proposed. Based on this proposed criterion the techniques were further redesigned and optimized to fabricate the heavy ingots with an aim of improving the quality by eliminating the shrinkage porosity.

# 2. Design 1: A preliminary design

#### 2.1. Numerical simulation

# 2.1.1. FEM model

The mold filling and solidification processes of the 100-ton  $30Cr_2Ni_4MoV$  ingot were simulated using the commercial FEM casting simulation software ProCast package. Before calculation, some assumptions were made: (1) the incoming liquid metal was evenly distributed just below the whole free surface to simulate the smooth filling process; (2) the liquid metal was incompressible Newton fluid; (3) the convection was driven by thermal buoyancy; (4) the solutal convection was ignored; and (5) the heat transfer was coupled with the mold filling. In the present study, the simulation model adopts the mass, momentum and energy equations during the solidification process. The natural convection of the liquid metal has been described by the continuity and the Navier–Stokes equations as follows:

Continuity equation

$$\nabla \cdot (\vec{V}) = 0 \tag{1}$$

Navier-Stokes equation

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

Furthermore, based on the classical isotropic Fourier conduction laws the heat transfer has been governed by:

$$\rho c \frac{dT}{dt} = \nabla \cdot (k \nabla T) + \dot{Q}$$
<sup>(3)</sup>

where  $\rho$  is the density, *t* is the time,  $\mu$  is the dynamic viscosity, *P* is the pressure, *g* is the gravitational acceleration component,  $\vec{V}$  is the velocity vector,  $\Phi$  is the velocity component, *T* is the temperature, *k* is the thermal conductivity, *c* is the specific heat and  $\dot{Q}$  is an internal power source. The conservation equations are solved numerically using a fully implicit time-stepping scheme and a standard finite-element formulation [12]. Details of the numerical model are given in the user manual of ProCast [13].

The finite element mesh of the mold and ingot consist 151,360 nodes and 770,163 tetrahedral elements (as shown in Fig. 1). The mesh was selected based on several mesh refinements. Fig. 2 shows the geometry and boundary conditions of the model. As it can be seen, an insulation condition was assigned over the melt surface at the hot top as the melt was covered by the insulation materials and covering flux. A natural air cooling convection was set over the mold body. Initial values of the interfacial heat transfer coefficients between metal/insulation and metal/mold were set as 200 and 1000 W/m<sup>2</sup>/K respectively.

The composition and main thermophysical parameters of the ingot and mold are listed in Tables 1 and 2 (the thermophysical



Fig. 1. The finite element mesh of the mold and ingot.



Fig. 2. The geometry and boundary conditions of the model.

parameters of the ingot were calculated by ProCast). The initial processing parameters used in the simulation include that (1) the pouring temperature is 1565 °C, (2) the filling time is 29 min and (3) the pre-heated hot-top mold temperature is 80 °C.

#### 2.1.2. Shrinkage porosity models [13]

Based on ProCast User Manual, there have been three available options to analyze the shrinkage porosity in a casting. They are (1) Temperature field and solid fraction field, (2) Shrinkage porosity field and (3) Specific RGL criteria.

- (1) Temperature field and solid fraction field: Through looking at the temperature and solid fraction fields in the cut-off mode (which provides a convenient option to visualize the inside of the casting during the solidification), it is easy to observe the porosity which is primarily due to enclosed pockets of liquid.
- (2) Porosity: When POROS model is activated, it can visualize the contour called "Shrinkage porosity". Values corresponding to a level below 0.01 shall be considered as microporosity and those above 0.01 are considered as macroporosity.

#### Table 1

Chemical compositions of the ingot and mold (wt.%).

Material	С	Si	Р	S	Mn	Cr	Ni	Мо	V
Ingot (30Cr2Ni4MoV) Mold (Eutectic Grav Iron)	≼0.35 3.47	≼0.1 2.5	≪0.006 -	≪0.006 -	≼0.15 -	1.5–2.0 –	3.25-3.75	0.25-0.6	0.07-0.15

#### Table 2

Thermophysical parameters of the ingot and mold used in simulation.

![](_page_2_Figure_7.jpeg)

The default shrinkage porosity model in ProCast accounts for coupled micro and macroporosity, as well as pile shrinkage. During the solidification of a casting, pockets of liquid are created, surrounded by a mushy zone and then a solid shell. Accordingly, the casting is divided into "regions" in which the solid fraction is lower than that in the regions that are bounded by walls (or symmetry planes). As solidification proceeds and the geometric shape of the casting becomes more complex, the number of "regions" may increase. A region can thus be split in more regions. A region can disappear when all nodes have completely solidified. When a "region" is cooling down, some shrinkage occurs under the condition that the density increases with decreasing temperature (the usual case for most alloys). The detailed scenarios of shrinkage and microporosity calculations are given in the user manual of ProCast [13].

(3) Specific RGL criteria: Per requirement, it has the choice to define a customized criterion function with the RGL option in ProCast. Function RGL is able to calculate the solidification rate " $R_s$ ", the temperature gradient "G" and the cooling rate "L".  $R_s$  corresponds to the velocity of a given isotherm whereas G is calculated at a given temperature which has to be the same temperature as the one used for the solidification rate. The definition of G reads:

$$G = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \tag{4}$$

As a linear interpolation between two temperatures, the cooling rate *L* is defined as:

$$L = \left| \frac{T_{\text{upper}} - T_{\text{lower}}}{t_{\text{upper}} - t_{\text{lower}}} \right|$$
(5)

where *T* is the temperature and *t* is the time.

In ProCast, there are ways to combine the  $R_s$ , G and L variables together so as to obtain a combined criterion function (called Mapping factor) as follows:

$$M = aR_s^b G^c L^d \tag{6}$$

where the coefficients a, b, c and d should be specified. When a = 1.0, b = 0, c = 1.0 and d = -0.5 are used, Niyama criterion can be obtained as:

$$M = G/L^{0.5} < \text{constant} \tag{7}$$

where the constant is dependent on the material and size of the castings [14].

# 2.2. Experiments

The 100-ton 30Cr<sub>2</sub>Ni<sub>4</sub>MoV steel ingot was pouring in vacuum condition (top filling). The ingot was cut along the axle plane and machined by milling. The milled surface was then prepared for metallurgical analysis by grinding and polishing processes. The surface was etched by the dilute nitric acid to display the microstructure of the ingot. The ultrasonic testing was used to detect the distribution and size of the shrinkage porosity. Fig. 3 compiles the photos of the 100-ton ingot (panel (a)), its sectioned surface (panel (b)), and the magnified centerline shrinkage porosity (panel (c)) as well as the macro-examination of the etched ingot (panel (d)), respectively.

# 2.3. Results and discussion

Fig. 4 compiles the filling and solidification sequences of the preliminary design of the 100-ton ingot with the melt flow rate

![](_page_3_Figure_1.jpeg)

**Fig. 3.** Photos of the 100-ton 30Cr<sub>2</sub>Ni<sub>4</sub>MoV ingot (a), its sectioned surface (b), the magnified centerline shrinkage porosity (c), and the macro-examination of the etched ingot (d). In (b) the red circle denotes the region of the typical centerline shrinkage porosity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

![](_page_3_Figure_3.jpeg)

Fig. 4. Distribution of simulated solid fraction during the filling and solidification of the preliminary design of the 100-ton ingot at: (a) 134 s, (b) 1124 s, (c) 1709 s, (d) 9800 s, (e) 32,750 s, (f) 61,100 s, (g) 74,600 s and (h) 89,450 s.

![](_page_4_Figure_2.jpeg)

**Fig. 5.** The simulated results of various criteria to predict shrinkage porosity of the ingot: (a) the default shrinkage porosity model in ProCast, (b) the default shrinkage porosity model in ProCast but viewed with slices, (c) the temperature gradient criterion, (d) Niyama criterion( $G/L^{0.5}$ ), (e)  $G/R_s^{0.5}$  < 2.5 °C s<sup>0.5</sup> mm<sup>-1.5</sup> criterion and (f) the experimentally sectioning and ultrasonic testing of the ingot.

![](_page_4_Figure_4.jpeg)

**Fig. 6.** Schemes of the preliminary and optimized design of the ingot: (a) preliminary design and (b) optimized design.

of 3200 kg/min. The panels (a–c) demonstrate the filling process. In order to better fit to our experimental process as discussed above, here a top filling process was activated. The advantage for such a design is to guarantee that incoming mass can be evenly distributed just below the whole free surface, thereby simulating the smooth filling process of the large ingot. On the other hand, Panels (d–h) in Fig. 4 show that the solidification process from which the shrinkage porosity mechanism that Koichi TASHIRO proposed can be simulated. During the initial period of solidification (namely, 15 h after pouring time), the shrinkage porosity hardly forms.

# Table 3

The parameters of the preliminary and optimized designs of the ingot.

Improved methods	Preliminary design	Optimized design
Quality of the insulation material	General	Good
Hollow insulation bricks in the hot top mold	No	Yes
Preheat temperature of the hot top mold	80 °C	Much higher
Hot top taper	42%	15.8%
Mass ratio of the hot top of the ingot	15.6%	22.0%
Mass ratio of the tail cone of the ingot	3.96%	2.47%

The reason can be attributed to the fact that in the initial period the "U-shaped" contour of the solidification front, induced by the obvious cooling effect from the bottom of the mold, provides sufficient feeding channels from the hot top, as illustrated by Fig. 4d and e. However, in the middle of the solidification period, the cooling effect from the bottom of the mold decreases rapidly and vertical solidification progresses due to the effect of lateral solidification. This situation results in the signally accelerated vertical solidification velocity. The contour of the solidification front is a sharp "Vshaped" framework, as shown in Fig. 4f. Therefore, many shrinkage porosities occur during this period. The reason is probably due to that, as the "V-shaped" contour becomes sharper, the formation of the dendritic crystal becomes easier and the feeding melt from the hot top into the dendritic space becomes more difficult. In addition, the formation of the shrinkage porosity in the solidification acceleration areas is related with the distance of range where feeding from the hot top is difficult. When solidification proceeds near the hot top, the contour of the solidification front appears a "V shape" with a wider angle (as shown in Fig. 4g). This fact makes the melt feeding from the hot top easier, and thereby the formation of shrinkage porosities decreases [15]. The completed solidification time is about 24.8 h (as shown in Fig. 4h)), which is in good agreement with the experiment result (24 h).

Fig. 5 shows the simulated results through the applications of some criteria for the prediction of shrinkage porosity in the ingot. Fig. 5b and f confirmed that the simulated position of shrinkage pipes in the hot top of the ingot is in good agreement with the experimental results, which also indicated the accuracy of our FEM model. It has been concluded that the criterion  $G/R_s^{0.5}$  < 2.5  $^{\circ}$ C s<sup>0.5</sup> mm<sup>-1.5</sup>, where *G* and *R*<sub>s</sub> are the temperature gradient and solidification rate, respectively, can serve as the best criterion to predict the centerline shrinkage porosity for the heavy steel ingots (as shown in Fig. 5e). As  $R_s$  represents the feeding requirement and G the feeding ease, their ratio indeed demonstrates a reversed likelihood of shrinkage formation: the larger  $G/R_s^{0.5}$  is, the smaller the likelihood is and vice versa [5]. Furthermore, the distribution and size of the shrinkage porosity agree well with the experimental results obtained by the sectioning and ultrasonic testing detection, as shown in Fig. 5f.

Within the context, both the simulated and experimental results reveal consistently serious centerline shrinkage porosity defects in the 100-ton  $30Cr_2Ni_4MoV$  steel ingot. Therefore, it would be reasonable to expect that the corresponding forging process could not compensate all those defects. That is the reason as to why the optimized design is further discussed in the following chapter.

![](_page_5_Figure_4.jpeg)

**Fig. 7.** Comparison of the shrinkage porosity simulations through improving various techniques in the optimized design under the same  $G/R_s^{0.5} < 2.5 \text{ °C s}^{0.5} \text{ mm}^{-1.5}$  criterion: (a) the preliminary design, (b) good insulating hot top material, (c) preheating the hot top mold, (d) the optimized mold, (e) the optimized mold + good insulating hot top, (f) the optimized mold + preheating the hot top mold, (g) the optimized mold + hollow insulation bricks in the hot top mold and (h) a whole of optimized condition by combining all these terms (including good insulating hot top, preheating the hot top mold, the optimized mold and hollow insulation bricks).

# 3. Design 2: An optimized design

# 3.1. The proposal of a package of optimized techniques

In order to eliminate the centerline shrinkage porosity, it is important to apply an optimized design during the process. Koichi Flemings has stressed that to design any hot top the ideal way is not to put heat into it, but rather to prevent heat from leaving and the efficiency of the exothermic material can be greatly improved by surrounding it with insulating material [16]. TASHIRO has represented that the geometry of hot top and the mold design play the most important role in the formation of central porosities and loose structure in heavy forging ingot [15]. Scepi has put forward some options to improve the quality of heavy forging ingots. For instance, (1) H/D should be never more than 1.3, (2) the mass ratio of the hot top of the ingot should be no less than 23%, and (3) the pouring time should be decreased whereas the pouring temperature should be increased, and so on [17]. Kermanpur suggested that the inner defects and the riser efficiency can be greatly improved by pouring the melt under a constant rate, reducing the mold slenderness ratio, and using a proper design for the hot top isolate [18].

In our 100-ton ingot, the H/D and the taper of the preliminary ingot are 1.04 and 8.5%, respectively, which are proper according to the widely-accepted censuses. As a result, the middle mold design with the same H/D and taper can be adopted (as shown in the preliminary design). The optimized design mainly focuses on the hot top and the tail cone of the ingot. Here, it is proposed that, in

order to reduce the inner defects of the ingot, a series of techniques should be adopted through (1) utilizing better thermal insulation material, (2) adding a circle of hollow insulation bricks in the hot top mold, (3) preheating the hot top mold, (4) decreasing the taper

![](_page_6_Figure_7.jpeg)

**Fig. 9.** Influence of the tapper of the hot top on the shrinkage porosity of the ingot (the optimized design): (a) 15.8% and (b) 28%.

![](_page_6_Figure_9.jpeg)

Fig. 8. Influence of the preheat temperature of the hot top mold on the shrinkage porosity of the ingot (the preliminary design): (a) 80 °C (b) 200 °C (c) 350 °C (d) 500 °C (e) 650 °C (f) 800 °C (g) 950 °C and (h) 1150 °C.

of the hot top, (5) increasing the mass ratio of the hot top, and (6) finally optimizing the tail cone design.

The differences for the design between the preliminary and optimized processes for the 100-ton ingot were further compared in Fig. 6. The details on the design were listed in Table 3. Furthermore, the influence of each term of the optimized design was also investigated as to how it affects the centerline shrinkage porosity of the ingot under the same condition of  $G/R_s^{0.5} < 2.5 \,^{\circ}\text{C s}^{0.5} \,\text{mm}^{-1.5}$  criterion. It has been found that each term exhibits a good effect to significantly reduce the shrinkage porosity in the ingot, as illustrated in Fig. 7a–g. In particular, through combining all these optimized techniques as one whole of design, the simulated results

exhibit that the shrinkage porosity could be nearly eliminated as evidenced in Fig. 7h.

# 3.2. Results and discussion

This part describes how each of the proposed techniques affects the centerline shrinkage porosity of the ingot.

# 3.2.1. Influence of the insulation material and the hollow insulation bricks in the hot top mold

As shown in Fig. 7a, b, d and e, the influence of the insulation material demonstrates that the better insulation material is the

![](_page_7_Figure_8.jpeg)

Fig. 10. Influence of the height of the hot top on the shrinkage porosity of the ingot (optimized design): (a) 600 mm (b) 800 mm and (c) 1000 mm.

![](_page_7_Figure_10.jpeg)

Fig. 11. The flow vector of the half-filling ingot: (a) the preliminary tail cone and (b) the optimized tail cone.

less likelihood of the centerline shrinkage porosity is, however, the effect of insulation material on reducing the centerline shrinkage porosity is not very significant. It is easy to image that better insulation material can bring better insulation effect in the hot top. Therefore, the solidification in the hot top will be delayed and the liquid metal in the hot top will have more chances to feeding the inner ingot. However, the insulation material of the preliminary design is good ( $\lambda_{insulation brick} \approx 0.9 \text{ W/m/K}$ ,  $\lambda_{insulation board} \approx$ 0.4 W/m/K, where  $\lambda$  is the coefficient of thermal conductivity), and just using the better insulation material ( $\lambda_{\text{better insulation brick}}$  $\approx 0.6$  W/m/K,  $\lambda_{better\ insulation\ board} \approx 0.3$  W/m/K) has no appreciable influence on the solidification pattern of the inner ingot body. The reason is that rather than by emission from the outer surface of the hot top, the heat in the hot top is absorbed by the cast iron and the insulation material of the hot top because of their large heat capacity. In the same way, adding hollow insulation bricks  $(\lambda_{\text{hollow insulation brick}} \approx 0.5 \text{ W/m/K})$  in the hot top can reduce the centerline shrinkage porosity of the ingot to some extent(as illustrated by Fig. 7d and g), but it would not have significant effect.

As discussed above, it can be demonstrated that just using better insulation material or adding a layer of hollow insulation bricks in the hot top mold cannot obtain significant effect to reduce the centerline shrinkage porosity of the heavy ingot. The shape of the ingot and the hot top is more important. However, the factory can still adopt the two economical ways to improve the insulation effect of the hot top and to obtain better quality ingots.

# 3.2.2. Influence of the preheat temperature of the hot top mold

Fig. 8 shows the influence of the preheat temperature of the hot top mold on the centerline shrinkage porosity of the ingot. It can be demonstrated that the higher preheat temperature of the hot top mold is, the less centerline shrinkage porosity is. As discussed above, the most heat in the hot top is absorbed by the cast iron and the insulation material of the hot top due to their large heat capacity, so it is significant to decrease the whole heat capacity of the hot top mold by preheating it. If the preheating temperature of the hot top mold is low (namely, 80-350 °C, as shown in Fig. 8ac), the effect of decreasing the centerline shrinkage porosity is not significant. The reason is that the low preheating temperature cannot compensate the large heat capacity of the hot top mold. However, if preheating the hot top mold at a much higher temperature (namely, 500-1150 °C, as shown in Fig. 8d-g), the effect of decreasing the centerline shrinkage porosity is much stronger. At this time, the heat capacity of the hot top mold is decreased significantly; meanwhile the insulation effect of the hot top mold is also strengthened signally. Therefore, it is more beneficial to the ingot's sequential solidification and there will be much more chances for

![](_page_8_Figure_6.jpeg)

Fig. 12. Distribution of simulated solid fraction during filling and solidification of the optimized design of the 100-ton ingot at: (a) 139 s, (b) 1154 s, (c) 1819 s, (d) 7405 s, (e) 32,605 s, (f) 57,805 s, (g) 80,205 s, and (h) 158,605 s.

the melt of the hot top to feeding the lower part of the dendritic structure of the inner ingot.

# 3.2.3. Influence of the tapper of the hot top

As shown in Fig. 9, the influence of the tapper of the hot top demonstrates that, the larger the tapper is, the more likelihood of the centerline shrinkage porosity is. The reason is that the larger trapper will cause narrower and deeper unsolidified molten pool during the middle of the solidification period (about 16–18 h after pouring). Consequently, the formed dendrite will cause bridging and then the feeding channels of the liquid metal into the inner ingot must be blocked significantly. However, smaller tapper of the hot top can provide wider unsolidified molten pool than that of the larger tapper one. Therefore, the feeding channels into the lower part of the dendritic structure should be much wider, and it will have the effect of less likelihood of the formation of the centerline shrinkage porosity.

# 3.2.4. Influence of the height of the hot top

Fig. 10 shows the influence of the height of the hot top on the centerline shrinkage porosity of the ingot. It demonstrates that the higher the hot top is, the less likelihood of the centerline shrinkage porosity is. The reason is that the higher hot top means the larger heat capacity; meanwhile, the feeding pressure of the liquid metal to the center part of the ingot is also increased. Then it is more beneficial to the ingot's sequential solidification and the feeding channels to the center ingot are smoother. However, it is not necessary to increase the height of the hot top infinitely, as it decreases the yield of the large ingot and it costs a lot.

# 3.2.5. Influence of the tail cone design

The simulation reveals that the optimized tail cone as shown in Fig. 6b can make the liquid melt run along the edge of the cone, effectively eliminating the turbulence and eddy from the bottom of the ingot. However, if using the preliminary design as illustrated in Fig. 6a the liquid melt runs unsmoothly, away from the edge of the cone due to the obvious occurrences of the turbulence and eddy from the bottom of the ingot induced by the improper design of the tail cone. Their behaviors related to two designs of the tail cone are further evidenced by the flow vector with the half filling ingot in Fig. 11, from which it can be seen that the optimized tail cone make the flow vector much more stable than that in the preliminary design. Consequently, it is more beneficial to enhance the inclusion's floating and reduce its aggregation in the bottom of the ingot.

Finally, using the best combined conditions (as shown in Fig. 7h), the distribution of simulated solid fraction during filling and solidification of the optimized design ingot is shown in Fig. 12. It has been found that the solidification process of the optimized ingot is much better in comparison with those in the preliminary design (as shown in Fig. 12d-h and Fig. 4d-h). Figs. 12f and 4f show the middle-term solidification period (namely, 16-18 h after pouring) of the preliminary and optimized design of the ingot. It can be seen from the figures that the "V-shaped" contour of the solidification front of the optimized design is much wider than that of the preliminary one. As discussed above, the "sharp V-shaped" framework causes bridging, and then the feeding channels are blocked by the intersection of the dendritic crystals. This is the main cause of the centerline shrinkage porosity. However, with the combined techniques, the "V-shape" is much wider (as shown in Fig. 12f); the formation of the dendritic crystal and bridging is harder; and the feeding melt from the hot top is much easier. Therefore, the formation of the shrinkage porosity is much more difficult. It is believed that the techniques that have been proposed will be useful not only for this 100-ton ingot, but also for the larger ingots (such as the 100–600 ton ingot) to produce high-quality heavy castings and forgings.

# 4. Conclusions

In order to effectively control the shrinkage porosity of the heavy forging ingots, through the three-dimensional finite element method the flow and solidification characteristics of a 100-ton ingot were simulated. The simulated results have been confirmed by our sectioning experimental results. The combined theoretical and experimental efforts further result in the proposal of the best criterion to predict the shrinkage porosity for heavy forging ingots. In addition, the optimized design to eventually eliminate the shrinkage porosity has been proposed to improve the quality of the ingot. The obtained results are summarized as follows:

- (1) The criterion of  $G/R_s^{0.5}$  <2.5 °C s<sup>0.5</sup> mm<sup>-1.5</sup>, where *G* and *R<sub>s</sub>* are the temperature gradient and solidification rate, respectively, can serve as the best criterion to predict the centerline shrinkage porosity of the heavy steel ingots. The theoretically simulated distribution and size of the shrinkage porosity agree well with the experimental results of the sectioning investigation.
- (2) In order to obtain high quality heavy ingots, the geometric design of the mold and hot top is fairly significant. Based on the proper H/D and taper of the ingot, it is proposed to increase the mass ratio of the hot top, to decrease the taper of the hot top, to use better thermal insulation material, to preheat the hot top mold, to add a circle of hollow insulation bricks in the hot top mold, and to optimize the tail cone design of the ingot. With the optimized design, the simulated results revealed that the shrinkage porosity could be nearly eliminated.

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