Influence of casting parameters on shrinkage porosity of a 19 ton steel ingot

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In order to improve metal yield during manufacture of steel ingots, influences of casting parameters on the shrinkage porosity of a 19 ton steel ingot were investigated by numerical simulation. A three-dimensional numerical model of filling and solidification of a 19 ton steel ingot was developed. The model was validated by method of infrared temperature surveying. Based on this model, a series of numerical experiments was carried out and the influences of casting parameters such as height-to-diameter ratio (H/D), taper, height of insulation, pouring temperature and pouring rate on the depth of shrinkage cavity and the tightness in structure were investigated. Two dimensionless factors were proposed to help to evaluate the effect of these casting parameters on the shrinkage porosity. In which, the absolute difference of the maximum and minimum values of each parameter allowed in industrial process, the difference of the two values used in the simulation of each parameter and the difference of the depth of shrinkage cavities calculated under the smaller and larger values of each parameter were all taken into consideration. Results show that decreasing taper, pouring rate and H/D ratio, or increasing height of insulation can all reduce the depth of shrinkage cavity in the ingot effectively so as to improve the metal yield. While, pouring temperature almost has no influence on the depth of shrinkage cavity. H/D ratio and pouring rate have significant negative correlations with density ratio of the ingot. On the contrary, taper has a positive correlation with density ratio of the ingot. Pouring temperature and height of insulation have few influences on the density ratio of the ingot. Decreasing H/D ratio and pouring rate within acceptable limits can reduce the depth of shrinkage cavity and increase the density ratio significantly.

KEYWORDS: STEEL INGOT - SOLIDIFICATION - SHRINKAGE POROSITY - NUMERICAL SIMULATION

INTRODUCTION

Iron and steel industry is a big consumer of energy, especially the foundry practice. The high efficiency utilization of resources depends on the metal yield to a great extent in the foundries. As for manufacture of steel ingots, the metal yield has a great deal to with the shrinkage porosity in ingot. While, there're many casting parameters that have influences on shrinkage porosity such the height-to-diameter ratio (H/D ratio), taper, height of insulation, pouring temperature, pouring rate, etc. Therefore, in order to improve metal yield in manufacture of steel ingots, influence of casting parameters on shrinkage porosity should be made clear first.

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With development in computer technology, numerical simulation is being increasingly applied to manufacture of steel ingot[1-6]. Compared with the experimental investigation, numerical simulation can help researchers gain more information of the ingot solidification process with less expenditure. Z. Radovic and M. Lalovic [7] developed a two-dimensional numerical model of ingot solidification based on the Fourier's differential equation. Temperature distribution, temperature gradient, distribution solid and liquid phase and increment of solid fraction were calculated. Tashiro, Watanabe et al. [8] analyzed the influence of hot top and mould design on the formation of central porosities and loose structure in heavy forging ingots by using finite element method. They found that the geometry of hot top and mould design play the most important role in the manufacture of sound heavy ingots. A. Kermanpur et al. [9] investigated the effects of casting parameters on solidification behavior and crack susceptibility during subsequent hot forging of a ingot of 6 ton low alloy steel by finite element method in three dimensions. M. Heidarzadeh and H. Keshmiri [10] investigated the solidification of 4.4 t cold work tool steel ingot type X210Cr12 by finite difference method using Magma software. They designed a new 2.8 t ingot mould which includes some parametric changes to produce sound ingots.

Jiaqi Wang et al. [11] proposed a criterion which can be used to reproduce precisely the experimental size and distribution of the shrinkage porosity in heavy steel ingots through FEM simulation in combination with the experimental sectioning investigation of a 100 ton ingot.
However, there are few reports about the influences of casting parameters on shrinkage porosity in steel ingot. In the current study, a three-dimensional numerical model of the filling and solidification of 19 ton steel ingots was developed. Two new dimensionless factors were proposed to help evaluate the effect of these casting parameters on the depth of shrinkage cavity and the tightness in structure. Results indicate decreasing H/D ratios and pouring rate within acceptable limits can reduce the depth of shrinkage cavity and increase the density ratio significantly so as to improve the metal yield.

EXPERIMENTAL

Solidification characteristic of 19 ton steel ingot

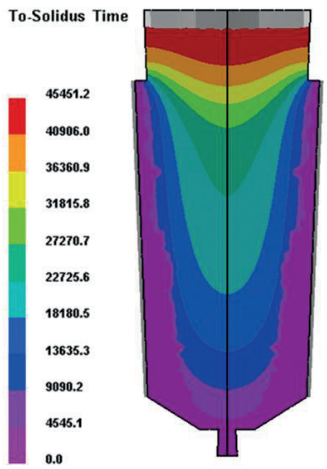

Fig. 1 - Contour line of solidification time in 19 ton ingot

During solidification of steel ingots, when there's insufficient molten steel compensating the contraction of solidification, shrinkage porosity forms. Therefore, shrinkage porosity defects occur easily in the part which solidifies latest. From the contour line of solidification time in a 19 ton ingot as shown in Fig. 1, it can be seen that solidification sequence is upward and inward. Consequently the center of upper part of the ingot solidifies latest and shrinkage porosities are likely to form there.
Latent heat and sensible heat of steel are extracted outside through different heat transfer sections during solidification of steel ingots. Heat transfer downward is mainly based on the ability of heat conductivity and absorption of heat of the stool. In transverse direction, heat is extracted outside through several sections such as solidified shell, ingot/mould interface and mould. Solidification sequence of ingots depends on heat transfer rates of different parts in the ingot. There're many factors that have influences on heat transfer rates of different parts of the steel ingot, such as taper, H/D ratio, cooling conditions on outer wall of the mould, heat insulation on hot top, pouring temperature and pouring rate.
In general, ingots with a large taper have a large specific surface area, which can lead to weak cooling intensity at lower part and strong cooling intensity at upper part. Ingot with a large H/D ratio looks slim and has a large lateral area for heat transfer, which can lead to a large transverse solidification rate and shrinkage porosities in steel ingot. Casting parameters such as pouring temperature and pouring rate also have influences on solidification sequence so as to affect shrinkage porosity in the steel ingot. In order to make clear the degree of impacts of these casting parameters on shrinkage porosity in steel ingot, in this paper, influences of casting parameters on solidification and shrinkage porosity in steel ingot were investigated by method of numerical simulation.

Numerical simulation of mould filling and solidification of a 19 ton steel ingot

Assumptions are made that the temperature and velocity of the molten steel poured into the mould from the bottom has an even distribution. A three dimensional model was developed based on governing equations such as the continuity equation, the Navier-Stokes equation, the transport equations for the standard k-ε model, and Fourier's equation. In addition, the Volume Fraction Equation as shown in equation was used during the mould filling process.

$$\partial F/\partial t + u\,\partial F/\partial x + v\,\partial F/\partial y + w\,\partial F/\partial z = 0 \qquad 1)$$

Where x, y, z are the components in the Cartesian coordinates, u, v, w are velocity components of molten steel in x, y, z direction, respectively, t is the time. The molten steel's volume fraction in a cell is denoted as F. F=0: the cell is empty; F=1, the cell is full; 0<F<1, the cell contains the interface between the molten steel and air.
During the solidification the shrinkage porosity forms and the POROS model was used in order to predict the shrinkage porosity in the ingot.
The metal-mould interface heat transfer coefficient varies with time[12-14]. Li Wensheng et al.[15] found that 2800s could be regarded as formation time of metal-mould gap during solidification of a 53 ton steel ingot which was as high as 4.5 meters. In this paper, a lot of numerical simulations with different metal-mould interface heat transfer coefficients were conducted. And the results were compared with temperature measurement on mould wall during solidification of the 19 ton steel ingot. By trial and error, finally it was assumed that the gap between the metal and the mould was not formed until the 38th minute and the metal-mould interface heat transfer coefficient was 2000 W/(m^{2}K). And then, it was reduced to 400W/(m^{2}K) linearly from the 38th minute to the 73th minute. Finally, it was reduced very slowly to 100 W/(m^{2}K) until the end of solidification.
The heat transfer coefficients of both of the metal-hot top interface and the mould-insulation brick interface were 30 W/(m^{2}K)[3, 10]. Heat transfer from surface of hot top to surroundings is mainly by methods of radiation and convection. So, the heat transfer coefficient of hot top was calculated according to temperature measurement on surface of the hot top. The heat transfer coefficient of the air around mould wall was assigned according to the following formula in which both of radiation and convection heat transfer were taken into consideration [16].

$$h_{eff} = \varepsilon_{sm} \times \sigma\left(T_{sm}^2 + T_e^2\right) \times \left(T_{sm} + T_e\right) + 1.24 \times \left(T_{sm} - T_e\right)^{0.33} \quad 2)$$

Where T_{sm} is the temperature around mould wall, T_e is the equivalent temperature of surroundings, ε_{sm} is the heat emissivity coefficient which was assigned as 0.85, σ is the Stefan-Boltzmann constant.

The initial temperature of the mould and insulation brick was 40°C. The composition of the ingot and the mould is shown in Table 1. Some properties of the molten steel were calculated with Scheil model using ProCAST 2013.0 software. The thermal conductivity of the insulation brick was measured by experiment[17].

Tab. 1 - Composition of the ingot and the mould

material	code	Composition (Wt, %)							
		C	Mn	Si	P	S	Cr	Ni	Mo
melt	1.2738	0.35~0.4	1.3~1.6	0.2~0.4	≤0.02	≤0.02	1.8~2.1	0.9~1.2	0.15~0.25
mould	Ductile iron	3.2~3.8	0.8~1.2	-	≤0.05	≤0.05	-	-	-

Fig. 2 shows the geometry of the 19 ton steel ingot and the mould. In consideration of the axial symmetry, a quarter was modeled. The finite element mesh of the mould and the ingot consisted of 22968 nodes and 104838 tetrahedral elements which were selected based on several mesh refinements. The mould filling and solidification processes were performed using finite element method in ProCAST package. Ten different simulation runs were conducted as listed in Table 2 to investigate the influences of casting parameters on the shrinkage porosity of the 19 ton steel ingot.

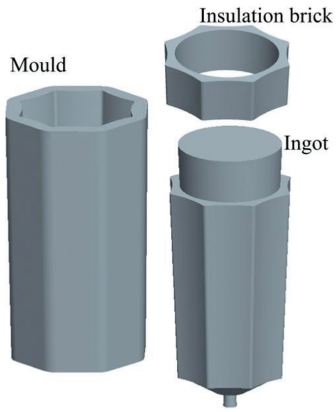

Fig. 2 - The geometry of the 19 ton steel ingot and the mould

Tab. 2 - Experimental conditions for simulations and simulation results

r#	start&boundary conditions						simulation results	
	H/D ratio	Taper	The height of insulation (mm)	Pouring temperature (°C)	Pouring rate (kg/s)		Depth of shrinkage cavity (mm)	Density ratio [a]
					Mould	Hot top		
1#	2.00	7.95%	430	1540	14.58	5.02	188.9	62.12%
2#	2.45	7.95%	485	1540	14.58	5.02	291.1	36.77%
3#	2.23	6.76%	470	1540	14.58	5.02	178.2	52.50%
4#	2.23	9.15%	450	1540	14.58	5.02	337.3	58.46%
5#	2.23	7.95%	410	1540	14.58	5.02	290.3	72.05%
6#	2.23	7.95%	510	1540	14.58	5.02	224.6	70.47%
7#	2.23	7.95%	460	1530	14.58	5.02	164.1	70.41%
8#	2.23	7.95%	460	1550	14.58	5.02	148.4	67.52%
9#	2.23	7.95%	460	1540	13.25	4.56	266.5	53.23%
10#	2.23	7.95%	460	1540	16.20	5.58	427.8	41.22%

[a] Density ratio: percentage of the area where the shrinkage porosity is lower than 0.03.

Temperature surveying experiment

The melting and casting process of 19 ton 1.2738 steel ingots was conducted in company ANSTEEL. Temperature evolution on the mould wall during the filling and solidification of the ingot was measured in order to check the accuracy of the results calculated. Temperature measurement was carried out on the mid-point of the mould wall with an infrared radiation thermometer. Comparison of the calculated temperature with the measured one is shown in Fig. 3. It can be seen that the calculated values agree well with the measured ones.

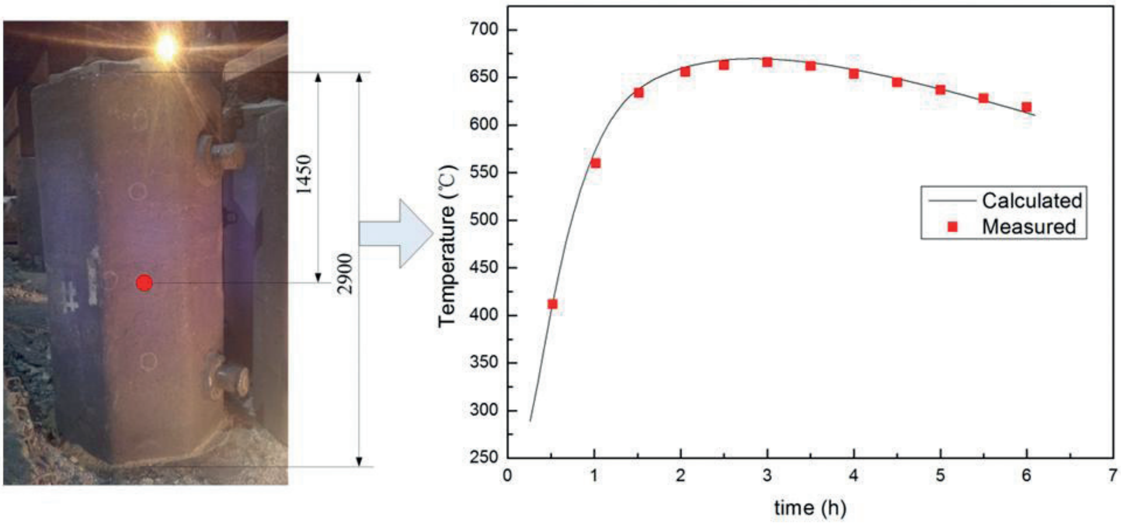

Fig. 3 - Comparison of the calculated temperature with the measured one on the mid-point of the mould wall of the 19t 1.2738 ingot

As for verification of simulation results of ingot solidification, methods of temperature measurement and anatomical experiment are used mostly. Temperature measurement can check the calculated results of temperature evolution during solidification of steel ingot, and then indirectly verify the simulated distribution of shrinkage porosity which is calculated based on temperature evolution.

Method of anatomical experiment can directly evaluate the distribution of shrinkage porosity in steel ingot and verify the simulated results. Martin Balcar et al.[18] examined distribution of shrinkage porosity of about 8 ton steel ingot by cross sectioning and longitudinal sectioning. Tashiro, K et al. [8] conducted simulations of porosity and loose structure in 110 and 135 ton steel ingots. They compared their calculated results with sectioning investigation of the 110 and 135 ton ingots to verify their simulations.

However, anatomical experiment on steel ingot is expensive and time consuming, especially on large steel ingot. In this paper, the depth of shrinkage cavity in hot top of the 19 ton ingot was measured without destruction of the ingot. The measured value was 420 mm, which is 1.8% smaller than the calculated result.

RESULTS

Effect of H/D ratios

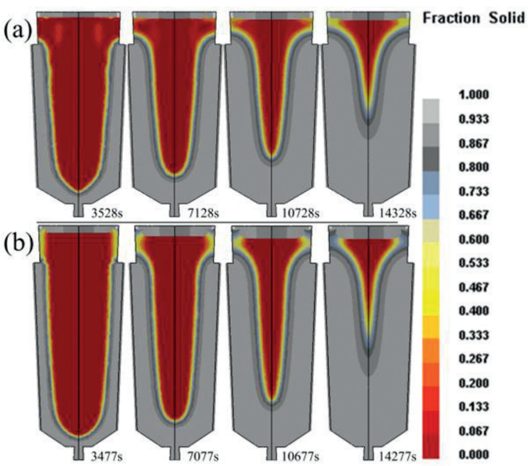

Fig. 4 - Distribution of solid fraction during the solidification of the ingot with different H/D ratios: (a) 1#, 2.00, (b) 2#, 2.45

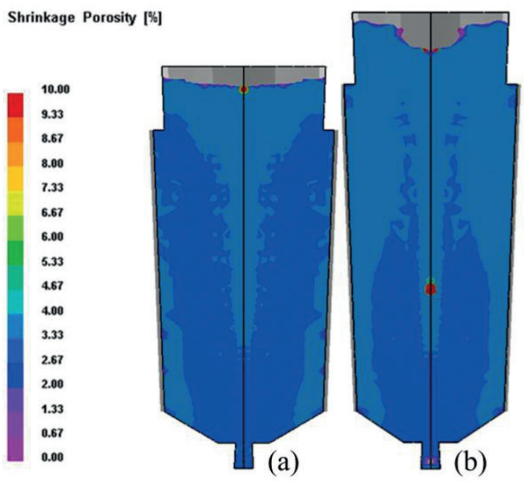

Fig. 5 - Effect of the H/D ratios on the shrinkage porosity of the ingot: (a) 1#, (b) 2#

Distribution of solid fraction during solidification of the ingots with H/D ratios of 2.00 and 2.45 respectively are shown in Fig. 4. Shrinkage porosity here is defined as porosity formed due to volume shrinkage during solidification. It can be seen that the liquid region in the hot top of the ingot with smaller H/D ratio is larger than that of the ingot with larger H/D ratio. This proves that ingot with low H/D ratio has a good thermal insulation effect in the hot top. Effect of the H/D ratios on the shrinkage porosity of the ingot is shown in Fig. 5 and Table 2. It can be seen that the ingot with a smaller H/D ratio has a smaller depth of shrinkage cavity and a larger density ratio. Ingot with a large H/D ratio has a large lateral area for heat transfer, and this leads to an intensive transverse cooling and less intensive longitudinal cooling. Therefore, ingot with large H/D ratio has a large transverse solidification rate, which will result in shrinkage porosities in steel ingot center and deep shrinkage cavity in hot top.

As a consequence, we can draw the conclusion that decreasing H/D ratio of an ingot can decrease the depth of shrinkage cavity.

Effect of taper

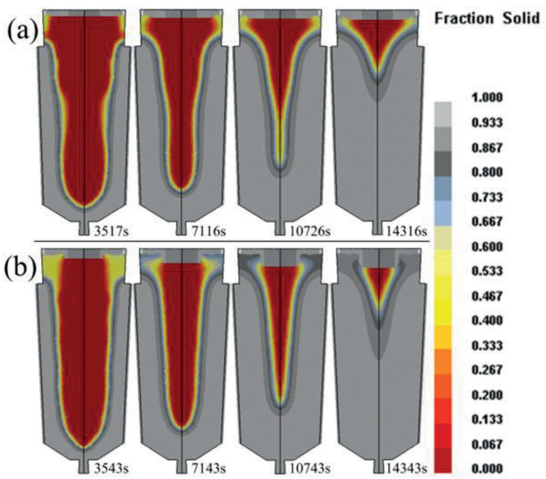

Fig. 6 - Distribution of solid fraction during solidification of the ingot with different tapers: (a) 3#, 6.76%, (b) 4#, 9.15%

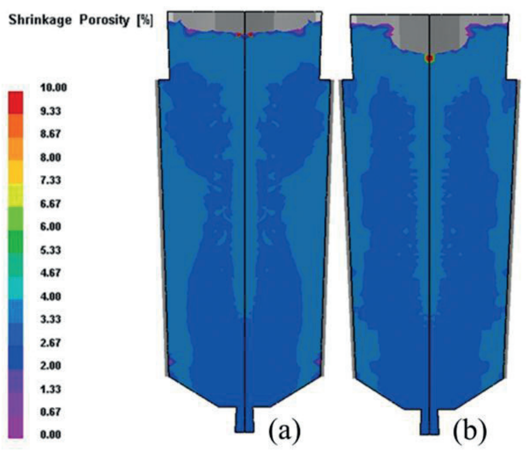

Fig. 7 - Effect of taper on the shrinkage porosity of the ingot: (a) 3#, (b) 4#

Distributions of solid fraction during solidification of the ingot with different tapers of 6.76% and 9.15% are shown in Fig. 6. Taper here is defined as the value calculated from the difference of diameters of top and bottom of ingot divided by height of the ingot.

It can be found that there is a camber outward in the middle of the U-shape solidification front of the ingot with smaller taper compared with the ingot with larger taper. It's known that a solidification front with a V-shape which has a broad apex and a narrow base has an almost unidirectional solidification and leads to a compact structure of an ingot. Therefore, an ingot with a large taper is favorable toward tightness in structure. As for an ingot with a large taper, specific surface area of the lower part is larger than that of the upper part. As a result, cooling intensity in the lower part is larger than the upper part. Therefore, the solidification sequence of ingot from bottom to top is strong, which is beneficial to the denseness in structure. Effect of the taper on the shrinkage porosity of the ingot is shown in Fig. 7 and Table 2. It can be seen that the density ratio of the ingot with taper of 9.15% is larger than that of the ingot with taper of 6.76%. However, the depth of shrinkage cavity of the former one is much larger than the latter one.

Effect of height of insulation

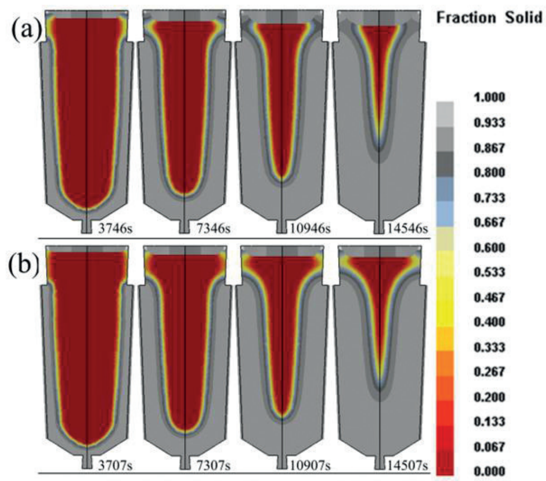

Fig. 8 - Distribution of solid fraction during solidification of the ingot with different height of insulations: (a) 5#, 410 mm, (b) 6#, 510 mm

The filling and solidification of the ingots with different height of insulations of 410 mm and 510 mm (5# and 6#) were investigated.

Distributions of solid fraction during solidification of the ingots with different height of the insulations are shown in Fig. 8. It can be seen that ingot with higher insulation brick has more molten steel in the hot top than ingot with lower insulation brick at middle and late stages of solidification. This proves that ingots with high insulation bricks have a good insulation effect in the hot top and is beneficial to feeding during late stage of solidification, which can decrease the depth of shrinkage cavity and eliminate secondary piping.

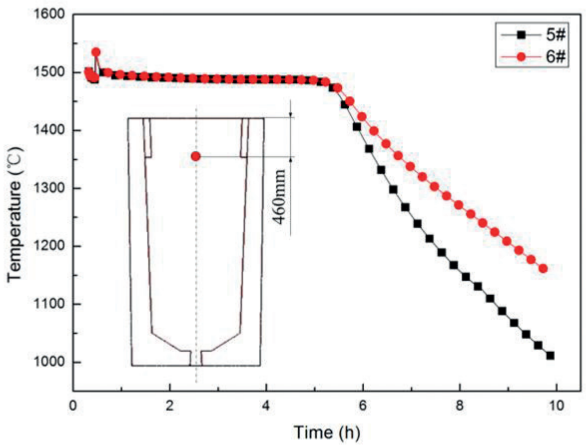

Fig. 9 - Simulated cooling curves of the position in the bottom of the hot top of two ingots with insulation height of 410mm and 510mm respectively (5# and 6#)

Cooling curves of the feature point of the two ingots are shown in Fig. 9. It can be seen that the hot top of an ingot with a large height of insulation cools slowly. This also proves that ingot with higher insulation brick has a better insulation effect than ingot with lower insulation brick. From Table 2 it can be seen that increasing height of insulation will reduce the depth of shrinkage cavity significantly. In addition, there is little influence of height of insulation brick on density ratio of ingot.

Effect of pouring temperature and pouring rate

From Table 2 it can be seen that an increasing pouring temperature can decrease the depth of shrinkage cavity and density ratio to a small extent. While increasing the pouring rate can increase the depth of shrinkage cavity to a great extent and decrease the density ratio.

DISCUSSIONS

During the solidification of steel ingots, shrinkage is inevitable and can lead to shrinkage cavities in the hot top which will be cut off in the following process. It's obvious that a small depth of shrinkage cavity results in a high metal yield.

However, there are many casting parameters which have influences on the depth of shrinkage cavity, such as H/D ratio, taper, height of insulation, pouring temperature, pouring rate. In order to evaluate the effect of these casting parameters on the depth of shrinkage cavity so as to provide guidelines to production practice, a new dimensionless factor ε was defined in the following formula:

$$\varepsilon_i = \frac{R_i \cdot \Delta d_i}{\Delta x_i \cdot H} \qquad 3)$$

Where ε_i is the shrinkage cavity factor of casting parameter i, and number H/D ratio as parameter 1, taper as parameter 2, height of insulation as parameter 3, pouring temperature as parameter 4, pouring rate as parameter 5. Δx_i is the difference of the two values used in the simulation of parameter i. R_i is the absolute difference of the maximum and minimum values of parameter i allowed in industrial process according to the experience in the ingot production. Δd_i is the difference of the depth of shrinkage cavities calculated under the smaller and larger values of parameter i, respectively. H is the average height of the insulation, 500mm.

Tab. 3 - Shrinkage cavity factors of different casting parameters

number	casting parameter	Δx_i	R_i	Δd_i	ε_i
1	H/D ratio	0.45	0.60	102.2 mm	0.273
2	taper	2.4%	4.0%	159.1 mm	0.533
3	height of insulation	100 /mm	160 /mm	-65.7 mm	-0.210 [a]
4	pouring temperature	20 /°C	30 /°C	-15.7 mm	-0.047
5	pouring rate	2.95 /kg·s^{-1}	5.00 /kg·s^{-1}	161.3 mm	0.547

[a] If ε_i is negative, it means there is a negative correlation between parameter i and the depth of shrinkage cavity.

The shrinkage cavity factors of different casting parameters calculated according to the simulation results are shown in Table 3. It can be seen that both taper and pouring rate have the most significant influences on the depth of shrinkage cavity, followed by H/D ratio and height of insulation. While, pouring temperature almost has no influence on the depth of shrinkage cavity. Among these parameters, height of insulation has a negative correlation with the depth of shrinkage cavity. Therefore, it can be concluded that decreasing taper, pouring rate and H/D ratio, or increasing height of insulation can all reduce the depth of shrinkage cavity in the ingot effectively so as to improve the metal yield. Among which, decreasing taper and pouring rate are the most effective measures.

Similarly, a new dimensionless factor η was defined as the following formula in order to evaluate the effect of these casting parameters on the denseness in structure.

$$\eta_i = \frac{R_i \cdot \Delta p_i}{\Delta x_i} \qquad 4)$$

Where η_i is the density ratio factor of casting parameter i, Δp_i is the difference of the density ratio calculated under the smaller and larger values of parameter i respectively.

Tab. 4 - Density ratio factors of different casting parameters

number	casting parameter	Δp_i	η_i
1	H/D ratio	-25.35%	-0.338
2	taper	5.96%	0.100
3	height of insulation	-1.58%	-0.025
4	pouring temperature	-2.89%	-0.043
5	pouring rate	-12.01%	-0.204

The density ratio factors of different casting parameters are shown in Table 4. It can be seen H/D ratio has the most significant influence on the density ratio of the ingot, followed by pouring rate and taper. Among which, H/D ratio and pouring rate have negative correlations with density ratio of the ingot. On the contrary, taper has a positive correlation with density ratio of the ingot. And this is in agreement with what is shown in Fig. 6 that the ingot with a larger taper has a stronger vertical solidification which increases the density ratio. In addition, pouring temperature and height of insulation have few influences on the density ratio of the ingot. When both of the shrinkage cavity factors and density ratio factors are taken into consideration, we can draw the conclusions that decreasing H/D ratio and pouring rate within acceptable limits can reduce the depth of shrinkage cavity and increase the density ratio significantly at the same time. Increasing height of insulation can reduce the depth of shrinkage cavity to a certain extent with little decreasing of density ratio of ingot. It should be noted that we concentrated only on the shrinkage porosities of the ingot, and the macro-segregation and grain structure were not taken into consideration. Notwithstanding its limitation, this study does provide the influences of casting parameters on the shrinkage porosities, and this is significant for the improvement of the metal yield.

CONCLUSIONS

The filling and solidification process of a 19 t ingot was simulated by three-dimensional finite element method. In consideration of axial symmetry of the ingot, simulation was conducted on a quarter of it. And the simulated results were confirmed by method of infrared temperature surveying. Based on this, a series of numerical experiments were carried out in order to investigate the effects of casting parameters on shrinkage porosity of the ingot. The obtained results are summarized as follows.

1) Decreasing taper, pouring rate and H/D ratio, or increasing height of insulation can all reduce the depth of shrinkage cavity in the ingot effectively so as to improve the metal yield. While, pouring temperature almost has no influence on the depth of shrinkage cavity.
2) H/D ratio and pouring rate have significant negative correlations with density ratio of the ingot. On the contrary, taper has a positive correlation with density ratio of the ingot. Pouring temperature and height of insulation have few influences on the density ratio of the ingot.
3) Decreasing H/D ratio and pouring rate within acceptable limits can reduce the depth of shrinkage cavity and increase the density ratio significantly.

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