

# SIMULATION STUDY ON THE INFLUENCE OF BOTTOM SUB-REGIONAL COOLING ON 45 TONS UNIDIRECTIONAL SOLIDIFICATION OF STEEL INGOT

Received – Priljeno: 2020-05-25

Accepted – Prihvaćeno: 2020-07-20

Original Scientific Paper – Izvorni znanstveni rad

In this paper, the temperature field and heat transfer stress mathematical model of the unidirectional solidification ingot of the traditional water-cooled chasis and the improved water-cooled chasis are established, and the numerical simulation calculation of 45 tons unidirectional solidification ingot is carried out by using the finite element simulation analysis method. The results show that adding proper forced cooling conditions to the bottom of ingot is beneficial to the balanced advance of the solidification front of molten steel. The improvement of the bottom forced cooling scheme obviously shortens the solidification time of the ingot. The water cooling at the bottom of the ingot is adapted to the air gap distribution to achieve uniform air gap distribution. The ingot solidifies evenly in the longitudinal direction to avoid bottom warpage.

*Key words:* steel ingot; bottom; sub-regional cooling; unidirectional solidification; numerical simulation

## INTRODUCTION

As another key technology in directional solidification ingot process, chasis cooling scheme has significant influence on strengthening bottom cooling and realizing directional solidification process of ingot[1]. In the production process, the unreasonable bottom cooling and the formation of uneven air gap will lead to uneven solidification, so cracks are easy to form at the weak points[2]. According to the air gap distribution between ingot and chasis, the optimization of chasis cooling is carried out. The water-cooled chasis adopts multiple sets of cooling systems. Through the cooling control of different strength in different regions, the water cooling at the bottom of the ingot can adapt to the air gap distribution and solidify evenly in the longitudinal direction[3]. The temperature field and heat transfer stress mathematical model of directional solidification ingot of traditional and improved water-cooled chasis were established. The numerical calculation of 45 ton ingot is carried out by using the finite element method and mathematical model. In order to optimize the technological parameters of directional solidification of 45 ton ingot, the temperature field of traditional and optimized water-cooled chasis was simulated and calculated.

## CALCULATION MODEL ESTABLISHMENT

### Geometric model and grid partition

In order to study the effect of chasis cooling scheme on unidirectional solidification, a ingot cooling model

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is established in this paper. The chasis modeling and grid division diagram is shown in Figure 1.

## The heat transfer and stress model

The heat transfer stress model of ingot is established, and the temperature distribution and solidification state of ingot bottom surface with traditional chasis heat transfer and chasis sub-regional cooling which using different cooling strength are analyzed. Area division is shown in Figure 2, The whole bottom surface is composed of three cooling zones, which are zone 1, zone 2 and zone 3 from the outside to the inside.

The boundary conditions are as follows:

In each scheme, the side of the ingot mould is air-cooled. The bottom surface cooling schemes are[4]:

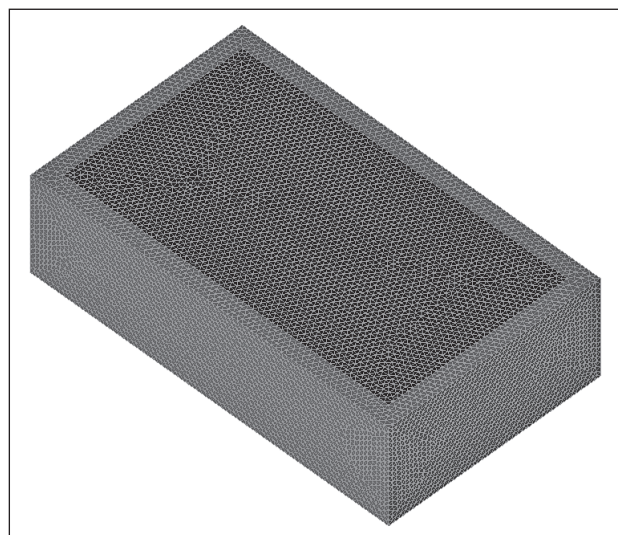
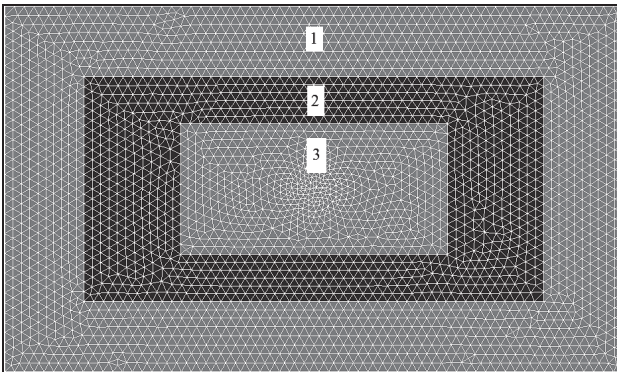


Figure 1 Chassis modeling and grid division diagram



**Figure 2** Schematic diagram of the subregional chassis cooling system

**Scheme 1:** the chassis is not cooled in different areas, and the bottom boundary condition is  $h = 300 / W/^{\circ}C$ ,  $t = 25 / ^{\circ}C$ .

**Scheme 2:** the boundary of zone 1 is  $h = 300 / W/^{\circ}C$ ,  $t = 25 / ^{\circ}C$ ; zone 2 is  $1\ 000 / W/^{\circ}C$ ,  $t = 25 / ^{\circ}C$ ; zone 3 is  $2\ 000 / W/^{\circ}C$ ,  $t = 25 / ^{\circ}C$ .

**Scheme 3:** the boundary of zone 1 is  $h = 300 / W/^{\circ}C$ ,  $t = 25 / ^{\circ}C$ ; zone 2 is  $1000 / W/^{\circ}C$ ,  $t = 25 / ^{\circ}C$ ; zone 3 is  $4000 / W/^{\circ}C$ ,  $t = 25 / ^{\circ}C$ .

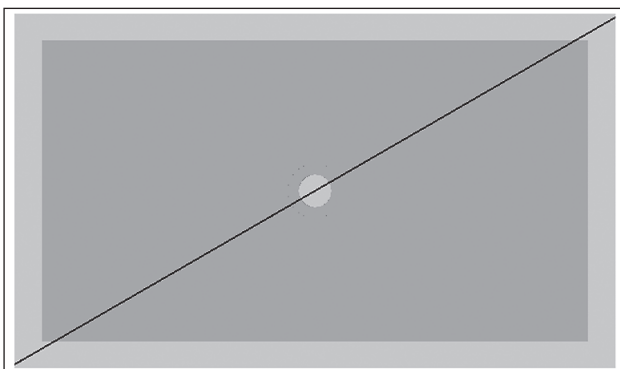
**Scheme 4:** the boundary of zone 1 is  $h = 300 / W/^{\circ}C$ ,  $t = 25 / ^{\circ}C$ ; zone 2 is  $3\ 000 / W/^{\circ}C$ ,  $t = 25 / ^{\circ}C$ ; zone 3 is  $4000 / W/^{\circ}C$ ,  $t = 25 / ^{\circ}C$ .

## Simulation results and analysis

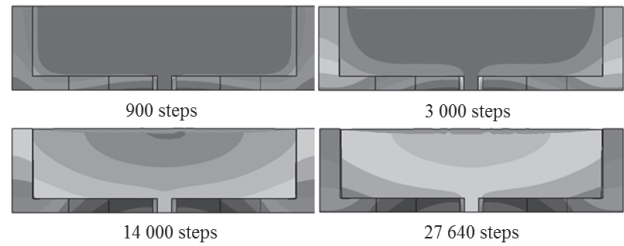
According to the simulation results, a corner at the bottom of the ingot is set as the origin, and each point on the line from this point to the center of the slab is taken as the target to study the temperature and heat flow distribution (as shown in Figure 3).

## ANALYSIS OF TEMPERATURE DISTRIBUTION IN INGOT

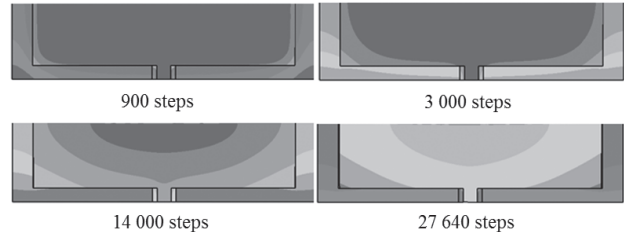
It can be seen from Figure 4 that the inclination of the isotherm inside the ingot is further improved due to the further strengthening of the cooling of the inner ring relative to scheme 2. However, due to the large gap between the cooling strength of the inner ring and the ad-



**Figure 3** Section division of studying on ingot temperature field



**Figure 4** The temperature distribution of steel ingot during solidification process in solution 3



**Figure 5** The temperature distribution of steel ingot during solidification process in solution 4

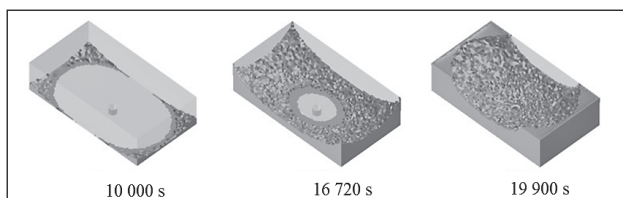
acent cooling area, there is no transition, resulting in that the cooling of the molten steel in the inner ring area is faster than that in the adjacent cooling area in a period of time, resulting in uneven advance of the solidification front result.

It can be seen from Figure 5 that due to the improvement of the smooth transition of the cooling strength of the zone from inside to outside, the inclination of the isotherm inside the ingot is better improved, and the uneven solidification caused by the strong cooling of the inner ring is eliminated.

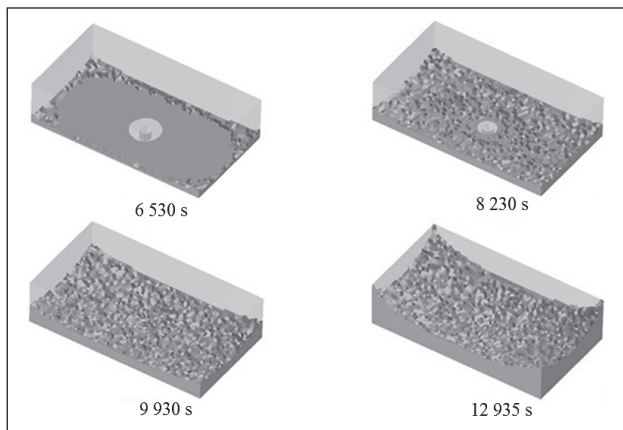
In addition, the forced cooling of the bottom part, especially the central strengthening cooling, began to play an obvious role in the uniform bottom cooling at 900 steps (about 620 seconds); the effect gradually weakened at 3 000 steps (about 2 720 seconds), and the inclined state of the section isotherm at 14 000 steps (about 13 730 seconds) was basically fixed, and then almost no change was found until the end of solidification. The main reason is that when a thick solidification layer is formed at the bottom, the effect of strong cooling at the bottom on the solidification front will be correspondingly weakened, while the two-dimensional cooling effect of the corner will play a strong role in the later longer time, and with the solidification of the side molten steel, the temperature gradient will be reduced, and the corner cooling will also be limited to a certain level, thus forming the effect from 13 730 seconds to the end of solidification. Relatively stable temperature distribution.

## RESULTS AND ANALYSIS OF THE SHAPE OF INGOT SOLIDIFICATION FRONT

Figure 6 shows the solidification front state of each time point in scheme I. It can be seen from the Figure



**Figure 6** The solidification front state in solution 1



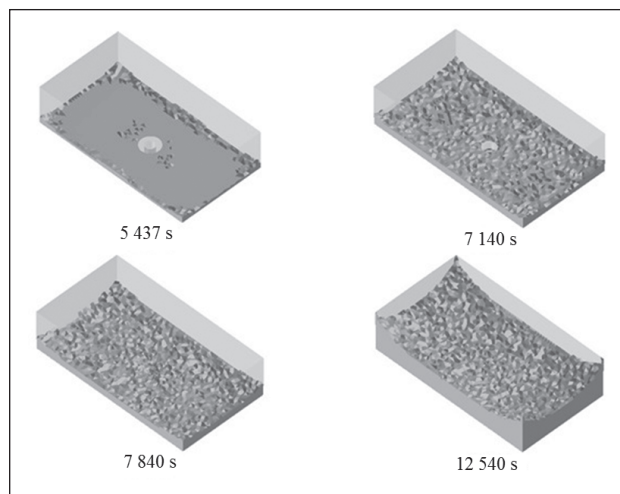
**Figure 7** The solidification front state in solution 2

that the molten steel at this position solidifies first due to the simultaneous heat transfer in two sides and three directions at the bottom of the corner. At 16 720 / s, the bottom of the ingot is not fully solidified until 19 900 / s. At this time, the corner area has solidified to the top of the ingot. At the same time, the solidification front of the wide and narrow areas near the periphery has advanced to a higher level, the height of the whole solidification front forms an obvious "concave" shape.

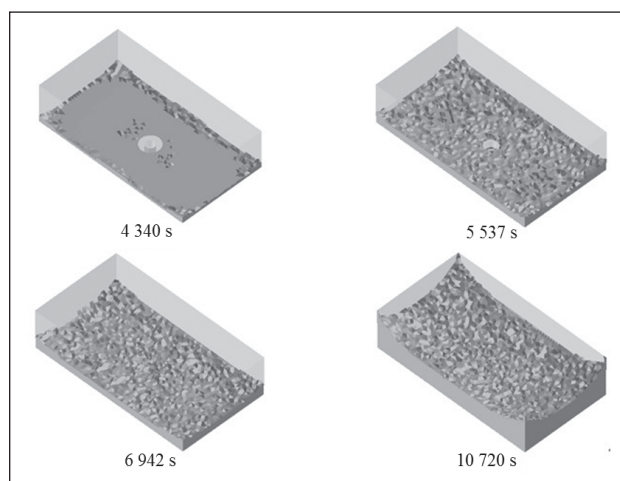
Figure 7 shows the state of solidification front in scheme II. As the forced cooling boundary conditions (1 000 / W/°C in zone 2 and 2 000 / W/°C in zone 3) are added in the central area, the bottom of ingot starts to cover the solidified phase at 6 530 / s except the central point, and the bottom completely covers the solidified phase at 9 930 / s. At this time, the height of solidification phase advance in corner and side area is significantly lower than that in scheme 1.

Figure 8 shows the solidification phase of scheme 3. In scheme 3, compared with scheme 2, the cooling strength of zone 3 is further improved ( $H = 4\,000 / \text{W}/^\circ\text{C}$ ). At 5 437 / s, the solidified phase began to cover the bottom, and a certain thickness of solidified phase began to appear in the central region. When the time goes to 7 840 / s, the bottom surface is completely covered by solidified phase, and the height of solidification front in corner and side area is lower than that in scheme II. However, the difference between the cooling strength of zone 3 (i.e. central region) and that of zone 2 is too large, which leads to the uneven solidification front at this time, i.e. the solidification front of central region and corner region is higher.

Figure 9 shows the solidification front of scheme 4. Compared with scheme 3, the scheme further improves



**Figure 8** The solidification front state in solution 3



**Figure 9** The solidification front state in solution 4

the cooling strength of zone 2, which makes the distribution of solidification front more uniform. At 6 942 / s, the solidified phase completely covers the bottom and the front of solidification is relatively flat.

To sum up, adding proper forced cooling conditions to the bottom of ingot is conducive to the balanced advance of the solidification front of molten steel. Under this simulation condition, scheme 4 has the best effect. In addition, due to the addition of bottom forced cooling, the solidification time of ingot is significantly shorter than that without bottom forced cooling. The time to reach the calculation end point is 2 7 324 / s in scheme 1, 20 935 / s in scheme 2, 19 938 / s in scheme 3 and 18 638 / s in scheme 4, respectively.

## CONCLUSIONS

In the early stage of solidification, when there is no bottom area for forced cooling, the temperature in the middle of ingot mold can not be synchronized with the corner temperature due to the rapid cooling of two-dimensional cooling due to the thermal restriction, thus forming the isotherm with obvious inclination relative to the horizontal plane.

Adding proper forced cooling conditions to the bottom of ingot is beneficial to the balanced advance of molten steel solidification front.

The improvement of the bottom forced cooling scheme obviously shortens the solidification time of the ingot. The water cooling at the bottom of the ingot is adapted to the air gap distribution to achieve uniform air gap distribution. The ingot solidifies evenly in the longitudinal direction to avoid bottom warpage.

### Acknowledgements

This work has been supported by The Liaoning provincial science and Technology Department Project under No.201602386 and the Metallurgical Engineering Laboratory.

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**Note:** The responsible translator for English is Yan Wu, University of Science and Technology Liaoning, Anshan, China