Uneven Solidification during Wide-thick Slab Continuous Casting Process and its Influence on Soft Reduction Zone

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A two-dimensional heat transfer model was developed to analyze the uneven solidification, particularly the shape of solidification end in wide-thick slab continuous casting process. In order to ensure the accuracy of simulation, material properties of peritectic steel were calculated by weighted averaging of phase fractions, and the boundary conditions were obtained by realistic water flux distribution on the slab transverse surface. The model was verified by nail shooting results at different locations of strand, and the absolute value of relative error was found to be no more than 2.12%. According to the simulation results, the liquid core around 1/8 location of slab width increased after the water flux was decreased around the slab corner to reduce transverse corner cracks. The soft reduction (SR) zone was optimized to reduce macro-segregation both at the slab center and 1/8th location. The plant results showed that the inner quality of wide-thick slab was significantly improved in the whole transverse section with the optimized SR zone parameters.

KEY WORDS: wide-thick slab; continuous casting; nozzle arrangement; soft reduction zone; solidification end; peritectic steel; nail shooting.

1. Introduction

The basic principle of soft reduction (SR) is to apply a certain amount of reduction at the solidification end of the strand for compensating liquid core shrinkage and preventing the flow of residual molten steel toward the center of the strand. As a result, the central segregation and porosity of strand would be reduced.1,2) SR zone is one of the most important SR parameters, which decides where the SR should be implemented, and it is usually determined and presented by solid fraction of the strand centerline.3) However, in some cases, this determination method would limit the implementation effects of SR because the uneven solidification end of slab could not be predicted accurately only by the solid fraction of strand centerline, and the center macro-segregation would not be reduced effectively except around the slab center as shown in Fig. 1.

The uneven shell thickness at the slab solidification end is usually caused by the non-uniform distribution of secondary cooling water flux along the slab transverse surface. Due to the larger width, the non-uniformity of shell thickness is more serious concern in wide-thick slab continuous casting process. Shen et al.4,5) built a 3-D heat transfer model which considered the position and distribution of spray nozzles, and the predicted results were in better agreement with the measured results than those by using average boundary conditions. F. Ramstorfer et al.6) carried out a series of testing experiments of water flux and its correlation with heat transfer coefficients at different air/water pressures and different distances from the nozzle tip to the surface, and the correlations between water flux and heat transfer coefficient were presented. Q. Wang et al.7) presented their experience on slab corner temperature control and reduction in transverse cracks by use of asymmetric nozzles. M. J. Long et al.8) studied the non-uniform behavior of shell growth by nail shooting method, and optimized the nozzle arrangement in order to obtain uniform shell thickness at the solidification end and good soft reduction effect.9) However, in order to avoid the slab corner falling into the brittle temperature range during the straightening process, especially for some micro-alloyed steel and peritectic steels, the water flux has to be decreased around the slab corner,10) which resulted in the reduced growth of slab shell. In this case, the soft reduction (SR) zone has to be adjusted to fit the irregular morphology of slab solidification end.

In the present work, with the practical parameters of wide-thick continuous casting machine, a two-dimensional...
heat transfer model was developed to predict the morphologies of slab solidification end. In this model, the material properties of peritectic steel between solidus and liquidus temperature were calculated from the relationship of phase fractions and temperature, which in turn were derived by micro-segregation model. In order to describe the uneven solidification shell accurately, the boundary conditions of secondary cooling zones were derived by real water flux distribution of secondary cooling nozzles, and finally, the shell thickness was verified by means of the nail shooting method. The non-uniformity of solidification end under different casting conditions for different casting speeds and nozzles arrangement, were simulated and analyzed. Thus the position and length of SR zone were optimized. Finally, the plant results before and after the application of optimized SR zone configuration were compared.

2. Heat Transfer Model

As shown in Fig. 2, the wide-thick slab continuous casting machine is composed of 1 bender, 6 bow segments, 2 straightener segments, and 6 horizontal segments from mold end to caster end, and it is divided into 10 cooling zones. All segments are composed of 7 roller pairs and could execute soft reduction function by adjusting the taper of segment inner and outer frames. 7 to 10 nozzles are arranged between every two neighboring rollers in the 1st to 4th secondary cooling zones, while there are only 3 110 flat air-mist cooling nozzles in one row from the 5th to 8th cooling zones.

Based on some simplified assumptions,

1) the mathematical heat transfer model of quarter slab transverse section was developed to predict the temperature field of wide-thick slab. A two-dimensional transient heat conduction equation was employed to describe the heat transfer behavior as follows:

\[
\rho(T)c(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T}{\partial y}\right) \ldots (1)
\]

Where, \(T\) and \(t\) are temperature, °C and calculation time, s, respectively. \(\rho(T), c(T)\) and \(\lambda(T)\) are the density, kg/m³, specific heat, J/(kg·°C), and heat conductivity, W/(m·°C), respectively.

The explicit finite difference method was adopted to calculate Eq. (1) with non-uniform grid method. In the present work, peritectic steel with casting temperature 1545°C was chosen as specific research steel grade, and its main compositions was 0.17 Wt Pct C, 0.15 Wt Pct Si, 0.60 Wt Pct Mn, 0.015 Wt Pct P, and 0.010 Wt Pct S.

2.1. Material Properties

In order to obtain more accurate material properties of peritectic steel between the solidus and liquidus temperatures range, a one-dimensional direct finite-difference model was developed to track the \(\delta/\gamma\) transformation and to predict the solute redistribution. Based on the assumption of Ueshima et al.,

2) the transverse section of the growing dendrite was a regular hexagon as shown in Fig. 3(a), and one sixth of a dendrite was taken as the modeling domain with a length of \(\lambda/2\), which was divided into 100 nodes as shown in Figs. 3(b) and 3(c). According to the Fick’s second law, the solute diffusion control equation was expressed as follows

\[
\frac{\partial C_i'}{\partial t} = \frac{\partial}{\partial x}\left( D_i'(T) \frac{\partial C_i'}{\partial x}\right) \ldots (2)
\]

Where \(D_i'(T)\) is the diffusion coefficient of solute element \(i\) in solid phase, m²/s, \(C_i'\) is the solute concentration of element \(i\) in the solid phase.

The liquid motion of inter-dendrite was neglected, and the total mass of solute element \(i\) was assumed to be constant during the dendrite growth process. The primary dendrite arming layer, \(\lambda\), was calculated by:

\[
\lambda = 278.748 \cdot C_R^{-0.206278} \cdot w_C^n \ldots (3)
\]

Where, \(C_R\) is the effective cooling rate, and it is set as 1.78°C/s according to the previous research of present authors; \(w_C\) is nominal steel carbon content; \(n\) is index obtained from the following equation:

\[
n = \begin{cases} 
0.316225 + 2.0325 C_R & 0 \leq C_R \leq 0.15 \\
0.0819 - 0.491666 C_R & 0.15 < C_R \leq 1.0 
\end{cases} \ldots (4)
\]

The liquidus temperature, \(T_l\) and the \(\delta/\gamma\) phase transformation temperature, \(T_{Ar4}\) were determined by the solute concentrations in the interface nodes as given below:

\[
T_l = 1536 - \sum_i m_i \left(\text{wt}\% C_i\right) \ldots (5)
\]

\[
T_{Ar4} = 1392 - \sum_i n_i \left(\text{wt}\% C_i\right)
\]

Fig. 2. The division of cooling zones for the continuous caster.

Fig. 3. Schematic diagram of the dendrites morphology and calculation domain: (a) an overview of the dendrites array, (b) transverse sections of dendrites, and (c) the structure of the modeling domain.
Where \( m_i \) and \( n_i \) are the slope of the liquidus and the interface between \( \delta \) and \( \gamma \) phase in the Fe-\( i \) binary phase diagram; \( N \) is the number of solute elements considered in the model.

The rates of diffusion into solid and liquid phases were determined by diffusion coefficients and equilibrium distribution coefficients of the elements.\(^{1,2,15}\) The fundamental equations were described in detail by Ueshima et al.\(^{12}\)

Figure 4(a) shows the phase fraction evolution of peritectic steel during its solidification, and (b), (c), and (d) show its conductivity, density and enthalpy, respectively, which were calculated by weighted phase fraction equations that were described in detail by Li and Thomas.\(^{16}\)

It should be noted that the thermal conductivity of liquid steel is usually increased compared to its solid state conductivity due to its flow and convection\(^{11,17}\) in the calculations.

2.2. Boundary Conditions

The boundary conditions for heat transfer are divided as mold, secondary cooling, and air cooling from mold level to the end of strand.

(1) Mold cooling

The heat extraction in mold was calculated as follows:

\[
-\lambda(T) \frac{\partial T}{\partial n} = q_{\text{mold}} \]

(6)

Where, \( \partial n \) represents length dimensions (\( \partial x \) for the slab narrow face and \( \partial y \) for the slab wide face); \( q_{\text{mold}} \) is mold heat flux, Mw/m².

The heat flux was decreased from slab surface center to the corner because the shrinkage of slab corner would increase heat resistance between the slab and the mold. Therefore, \( q_{\text{mold}} \) was calculated as follows:

\[
q_{\text{mold}} = q_{\text{center}} \cdot (1 - \exp(a_1 x - a_2)) \]

(7)

Where, \( a_1 \) and \( a_2 \) are parameters according to different height in mold; \( x \) is position from surface center to corner, \( m \); the \( q_{\text{center}} \) is the heat flux of the surface center along the casting direction, Mw/m². It was calculated from the Eq. (8) proposed by Savage and Pritchard\(^{18}\)

\[
q_{\text{center}} = A - B \sqrt{t} \]

(8)

Where, \( q_{\text{center}} \) is the heat flux on the broad face center, Mw/m²; \( A \) and \( B \) are coefficients depending on the mold cooling conditions; \( t \) is time on the mold, s.

The final calculation results were calibrated and verified by the authors’ previous work, which gave the heat flux distribution between the mold and slab surface and slab temperature distribution based on the distribution of mold flux, the air gap distribution and slab solidification shrinkage.\(^{19}\)

(2) Secondary cooling

In the 1st to 8th cooling zone, the water was sprayed directly towards the slab. In this area, the heat of the strand is mainly taken away by the cooling water in the form of convection, and an equivalent convection coefficient, \( q_{\text{sec}} \), was taken to calculate heat extraction.

\[
-\lambda(T) \frac{\partial T}{\partial n} = q_{\text{sec}} = h_{\text{sec}} \cdot (T_{\text{surf}} - T_{\text{amb}}) \]

(9)

Where, \( T_{\text{surf}} \) and \( T_{\text{amb}} \) are the surface temperature of the strand and the ambient temperature, respectively, in °C in \( h_{\text{sec}}, h_{\text{rad}}, h_{\text{iec}} \) calculations, and the unit is K in \( h_{\text{rad}} \) calculations; \( h_{\text{sec}} \) is the effective heat transfer coefficient, w/(m²·°C), and it could be expressed by:

\[
h_{\text{sec}} = h_{\text{rad}} + h_{\text{iec}} + h_{\text{w}} \]

(10)

Where, \( h_{\text{rad}}, h_{\text{iec}}, h_{\text{w}} \) is the heat transfer coefficient of radiation, roller contact and water spary in \( i \)th cooling zone, w/(m²·°C). The \( h_{\text{rad}} \) is calculated as follows:

\[
h_{\text{rad}} = \sigma \cdot \varepsilon \cdot ((T_{\text{surf}} + 273) + (T_{\text{amb}} + 273)) \cdot \\
\quad ((T_{\text{surf}} + 273)^2 + (T_{\text{amb}} + 273)^2) \]

(11)

Fig. 4. Phase fraction and material properties of peritectic steel: (a) phase fraction, (b) conductivity, (c) density, and (d) enthalpy.
Where, \( \sigma \) is Stefan-Boltzmann constant, \( 5.67 \times 10^{-8} \) w/(m\(^2\)·K\(^4\)); \( \varepsilon \) is steel emissivity.

The \( h_{ic} \) is calculated as follows:

\[
h_{ic} = \frac{h_i \cdot N_R \cdot R_i \cdot L_i}{Z_i} \quad \text{(12)}
\]

Where, \( N_R \) is the roller number of \( i \)th cooling zone; \( R_i \) is the contact length between roller and slab in \( i \)th cooling zone, m; \( Z_i \) is the length of the \( i \)th cooling zone, m. According to the previous research,\(^{17,20,21}\) \( h_i \) is set as 0.4–1.4 Kw/(m\(^2\)·°C), and \( R_i \) is equal to 0.02 m.

According to the experimental results of F. Ramstorfer \textit{et al.} \(^6\) and Nozaki \textit{et al.} \(^{11}\), \( h_{iw} \) is the function of the water flux distribution, and it could be expressed as:

\[
h_{iw} = \alpha_i \cdot W_i(x) \cdot 5.55 \cdot (1 - 0.0075T_w) \quad \text{(13)}
\]

Where, \( \alpha_i \) is a modified parameter of \( i \)th cooling zone, which depends on the caster parameters; \( T_w \) is the cooling water temperature, °C; \( W_i(x) \) is the water distribution flux in \( i \)th cooling zone (l/(m\(^2\)·min)), where \( x \) is the distance from the slab surface center to corner.

In order to improve the accuracy of boundary conditions in the secondary cooling zones, the water-air flow rate and water flux distribution of all nozzles were measured, and the Fig. 5 gives the water flux distribution of two typical nozzles. The 110° nozzle was originally used in the 7th and 8th cooling zones, and the 90° nozzle was used to compare its cooling effects with that of originally nozzle. The measured results show that the water flow distribution of nozzles are both subject to the Gaussian distribution, and the highest point of water flow is in or around the nozzle centerline position.

Based on the smooth Gaussian fitting data and the nozzle arrangement, \( W_i(x) \) was derived. Figure 6 gives the nozzles arrangements of 5th to 8th cooling zones, and Fig. 7 presents the example of water flux distribution of different nozzle arrangements in 8th cooling zone while the air and water pressure are both equal to 0.1 MPa.

(3) Air cooling

In 9th and 10th cooling zones, the water spray was towards the rollers instead of the slab, so only radiation and roller contact were considered. The heat extraction \( q_{air} \) is calculated as follows:

\[
-\lambda(T) \frac{\partial T}{\partial n} = q_{air} = (h_{rad} + h_{ic}) \cdot (T_{surf} - T_{amb}) \quad \text{(14)}
\]

2.3. Model Validation

A typical example of the steady-state casting process is presented to verify the model. The peritectic steel was cast at 0.9 m/min, while the casting temperature was 1545°C and the slab section was 2100 mm × 250 mm at the room temperature. Figure 8 shows the profile of the mushy zone in the cross section of the middle of strand. In the casting direction, the isoline of \( f_s=0 \) is almost uniform from the slab center to about \( x=0.85 \) m, but the isolines of \( f_s \) around 1/8 slab width location are prolonged with increase of \( f_s \). In the transverse direction, the shell \( (f_s=0) \) develops almost equally from the slab center to \( x=0.55 \) m due to the stable cooling intensity as shown in Fig. 7, but the liquid core is prolonged gradually from location \( x=0.55 \) to 0.82 m due to the continuous decrease of cooling intensity.

Figure 9 shows the temperature profile of the slab transverse section at the end of 8th and 9th segments, which are located at 20.57 m and 22.95 m from the meniscus, respec-
tively, and it clearly indicates the dumbbell-shaped solidification end.

In order to verify the uneven shape of solidified shell, the nail shooting was carried out at different locations in the transverse and casting directions. The measured results are shown in Fig. 10. Nail shooting is a kind of simple and effective method to measure shell thickness, and it had been successfully used by many researchers.8,22–24) The principle of the nail shooting method is that sulphur was embedded in the slot of the nail surface, and after the nail was shot into the slab, the nail could not melt in the solidified shell while sulphur hardly redistributed. However, the nail would gradually melt from solidus to the liquid core, and the diffusion of sulphur would be increased correspondingly. Therefore, the shell thickness is the length with the clear mark of nail boundary, and the reference lines, which are perpendicular to the slab thickness direction, as shown in Fig. 10 to indicate shell thickness.

The shooting locations, predicted results, measurements, and the errors are listed in Table 1 and are compared in Fig. 11.

The predicted results of the shell thickness agreed well with the nail shooting measurement results, and the absolute value of relative errors were found to be less than 2.12%

![Fig. 8. The isolines under different $f_s$ on the middle section of the strand.](image)

![Fig. 9. The temperature profile of transverse section at 20.57 m and 22.95 m from the meniscus.](image)

![Fig. 10. Nail shooting results of different location: (a) 1/2 wide of slab (slab center) at the 7th segment end; (b), (c), and (d) were 1/2, 1/4 and 1/8 width of slab at the 8th segment end respectively.](image)

![Fig. 11. Comparison between predicted results and measurements of shell thickness.](image)

<table>
<thead>
<tr>
<th>Strand position</th>
<th>Predicted results (mm)</th>
<th>Measured</th>
<th>Calibrated</th>
<th>Absolute (mm)</th>
<th>Relative (%)</th>
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<tr>
<td></td>
<td>From meniscus (m)</td>
<td>Of slab width</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.34</td>
<td>1/2</td>
<td>102.88</td>
<td>97</td>
<td>101.18</td>
<td>1.70</td>
</tr>
<tr>
<td>20.57</td>
<td>1/2</td>
<td>112.94</td>
<td>108</td>
<td>112.32</td>
<td>0.62</td>
</tr>
<tr>
<td>20.57</td>
<td>1/4</td>
<td>110.74</td>
<td>106</td>
<td>110.24</td>
<td>0.50</td>
</tr>
<tr>
<td>20.57</td>
<td>1/8</td>
<td>101.59</td>
<td>101</td>
<td>103.80</td>
<td>2.21</td>
</tr>
</tbody>
</table>
which may be caused by the delay of nail melting and measurement errors.8)

3. Optimizing the Soft Reduction Zone

According to the research by Takahashi,25) the flow ability of metal would decrease with the increase of the solid fraction, but liquid steel could flow freely in the low solid fraction regions, while in the high solid fraction the solute segregation would increase due to no supply of the liquid steel. Therefore the soft reduction should be applied to high solid fraction region, so the solute-enriched liquid could be squeezed out of the slab center. Based on the previous research by the present authors,2,3) the soft reduction parameters of peritectic steel were chosen from \( f_s = 0.6 \) to 0.9 in slab continuous casting process in present work. Furthermore, the location of 1/8 slab width, where its length of liquid core was almost equal to the max length on the whole slab width as shown in Fig. 8, was chosen to present the maximum length of uneven solidification end compared to the other locations.

3.1. Effect of Different Casting Speeds

The peritectic steel slab of 2100 mm×250 mm section was simulated with different casting speed, while the casting temperature was 1545°C.

Figure 12(a) presents the isolines of SR zone in the middle of the thickness cross section of the strand. With the increase of the casting speed, the secondary cooling intensity enhances, however the time for heat release decreases, and therefore the strand position of the SR zone moves towards cast end either on the 1/2 or 1/8 location of slab width. For instance, when the casting speed increases from 0.9 to 1.0 m/min, the SR start and end point of 1/2 location (slab center) move towards cast end with 2.08 and 2.28 m, respectively.

Figure 12(b) indicates that the isolines of SR zone are more and more non-uniform in the transverse direction with increase of the casting speed owing to the hysteresis of heat transfer. The strand position of SR start point of 1/8 location are prolonged to that of 1/2 location (slab center) with 1.57, 1.81 and 2.09 m, and extended to the SR end point at 2.00, 2.28 and 2.52 m, when the casting speed is 0.9, 1.0 and 1.1 m/min, respectively.

The length of SR zone of 1/8 location is longer than that of 1/2 location due to the prolonged liquid core as shown in Fig. 12(b). It is obvious that the original SR zone, which was designed based on the solid fraction at the slab centerline, could not reduce the segregation around 1/8 location of slab width. In the present work, original SR start position is considered as that of whole slab width, but the SR end point of whole slab width was improved according to that of 1/8 location. As shown in Fig. 13 the length of SR zone increased almost linearly about 0.24 m, 0.23 m, and 0.51 m for 1/2 location, 1/8 location, and for whole slab width, respectively, when the casting speed increases by 0.1 m/min.

3.2. Effect of Different Nozzle Arrangements

The overcooling on slab corners reduces the ductility of the slab, which would cause the corner transverse cracks during the straightening stage. The nozzles arrangement could effect the water flux distribution significantly, and in order to reduce the transverse corner cracks of 2100 mm width slab, 90° air-mist nozzles were chosen instead of the original 110° one in the 7th and 8th cooling zones.26) The water flux distribution characteristics for these nozzles are shown in Fig. 5(b).

Figures 14(a) and 14(b) compare the isolines of SR zone of 2100 mm×250 mm slab before and after changing the nozzle arrangement in the middle of width and thickness.
cross section of strand, when the casting speed is 0.9 m/min.

Figure 14(a) indicates the position of SR zone of 1/2 location is not quite different under two kinds of nozzles arrangements. At the slab center, the water flux under 90° nozzles arrangement is lower than that of 110° ones as shown in Fig. 7, which caused the SR start and end points move towards cast end with 0.067 m and 0.048 m after the 90° nozzles used. Because the water flux of 90° nozzles is higher than that of 110° ones at the location of 1/8 shown in Fig. 7, the SR start and end points under 90° nozzles move forward to meniscus by 0.22 m and 0.12 m than that of 110° nozzles, respectively.

As shown in Fig. 14(b) the isolines of SR zone from x=0 (slab center) to x=600 mm are almost same under two different nozzles arrangements, because the water flux with the two nozzle arrangements is nearly same as shown in Fig. 7. From x=600 mm to x=850 mm, the water flux of 90° nozzles is higher than that of 110° ones, which reduced the length of liquid core. In the last 200 mm near the slab corner, the isolines of SR zone are almost unchanged before and after the 90° nozzles were applied. This is because the cooling effect of the narrow surface is more significant than that of the wide surface and the water flux does not change much after nozzle arrangement was adjusted. Therefore, the SR zone is almost invariable after the 90° nozzles were replaced with the 110° ones in 2100 mm width slab continuous casting process.

In order to meet different customer’s demands, the wide-thick slab continuous casting machine was also used to produce narrower section slabs, such as 1600 mm width, and the overcooling of slab corner is more serious as shown in Fig. 7. Therefore, the nozzles arrangement of the 7th and 8th cooling zones was modified in the 1600 mm width slab casting process in that only the center nozzle was left with reduced water flow rate.\textsuperscript{26}

**Figure 15** compares the isolines of SR zone of 1600 mm×250 mm slab before and after adjustment of nozzles arrangement, while the casting speed was 1.0 m/min. Figure 15(a) indicates that the SR zone of 1/2 and 1/8 locations are almost same under three 110° nozzle arrangements due to the nearly same cooling intensity at these two locations as shown in Fig. 7. After the side nozzles were removed in 7th and 8th cooling zones, the cooling intensity of 1/8 location was reduced, which prolonged the SR start and end position with 1.8 m and 2.2 m towards the cast end, respectively. It can be seen from Fig. 15(b) clearly that the SR zone is almost constant from x=0 (slab center) to x=0.55 m under three nozzle arrangements. But when the side nozzles were removed, the SR prolonged gradually from the slab center to x=0.55 m due to the continuously decrease of water flux. Therefore, after the side nozzles were removed in the 7th and 8th cooling zone, the length of SR zone gradually prolonged from the slab center to around location of 1/8 width, and SR should be finished by 9th and 10th segments together instead of only the 9th segment.

Comparing Figs. 14(b) and 15(b), it can be seen that the
effect of nozzle arrangements on the SR zone of 1 600 mm width slab is more significant than that of 2 100 mm width slab. On one hand, the slab corner water flux before and after nozzle arrangement optimized for 1 600 mm width slab was changed more than that of 2 100 mm width slab, and therefore the effect of constant narrow side cooling plays a more significant role on the heat extraction around slab corner in casting of 2 100 mm wide slab. In fact, at the end of 8th cooling zone the slab corner temperature of the 1 600 mm width slab is improved more than 160°C, while that of the 2 100 mm width slab is only about 60°C.26) On the other hand, as shown in Fig. 7, the water flux changed on the whole transverse surface of 1 600 mm width slab after adjustment of the nozzles arrangement, but in 2 100 mm width it only changed around the slab corner. As a result, the wider range of uneven water flux caused more significant non-uniformity of the SR zone.

According to the simulation results, it can be concluded that the liquid core around 1/8 location of slab width is significantly longer than that of slab center both for 1 600 mm and 2 100 mm wide slabs due to the reduced water flux around slab corner.

4. Results in Plant Application

According to the simulation results, in 2 100 mm×250 mm section slab continuous casting process, the SR was usually executed by two segments, the first segment was used to eliminate the macro-segregation from 1/2 to 1/4 location of slab width, and the macro-segregation around 1/8 location was reduced by the next segment. To be specific, SR were executed by 8th and 9th segment for casting speed 0.9 m/min, 9th and 10th segment for casting speed 1.0 m/min, and 10th and 11th segment for casting speed 1.1 m/min. The originally designed SR rate was adopted for the first segment, and it was usually set as 0.8–2.2 mm/m according to the slab thickness and specific strand position. However, there is a brittle temperature range between the zero strength temperature (ZST) and zero ductility temperature (ZDT) at the solidification end due to the presence of interdendritic liquid films caused by the micro segregation of solute elements.31) If the SR is applied on this area with large SR rate, the center cracks would be induced. In order to solve this contradiction, the SR rate of the second segment was prolonged by change of nozzles arrangement, SR zone moved towards the cast end with increase of casting speed and length of the SR zone increased almost linearly about 0.24 m, 0.23 m, and 0.51 m for 1/2 location, 1/8 location and whole slab width, respectively when the casting speed was increased by 0.1 m/min. For 2 100 mm width slab, the SR zone gradually prolonged from the slab center to around 1/8 location of slab width because the water flux reduced after the side nozzles were removed in 7th and 8th cooling zones.

At last, the SR zone was optimized based on the predicted

<table>
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<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>total</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>total</th>
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<td>149</td>
<td>508</td>
<td>115</td>
<td>144</td>
<td>76</td>
<td>335</td>
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<tr>
<td>Central segregation ≤1.0</td>
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<td>56.35%</td>
<td>62.42%</td>
<td>62.00%</td>
<td>93.91%</td>
<td>93.75</td>
<td>90.79%</td>
<td>93.13%</td>
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<td>Central porosity ≤1.0</td>
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<td>100%</td>
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Table 2. The defect inspection statistical results of slabs before and after optimization.

![Fig. 16. The transverse macrographs of the 2 100 mm×250 mm slab before (a) and after (b) the optimization of SR zone.](image-url)
results, and the SR rate was adjusted accordingly. The plant results showed that the macro-segregation was significantly improved after optimization, and the proportions of central segregation and central porosity which the defects grade is not higher than 1.0 reach 93.13% and 100%, respectively.

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