**Effect of casting speed on solidification structure and central macrosegregation during continuous casting of high-carbon rectangular billet**

J. Zeng, W. Chen

Production of continuously cast high carbon steel that very low center macrosegregation is an important objective in meeting high quality requirements. Product quality and production efficiency depend essentially on the appropriate casting speed. In the present research, the solidification structures and macrosegregation of high carbon rectangular billet with a section size of 180 mm × 240 mm in different casting speeds were simulated using ProCAST. The adequacy of the model was compared with the simulated and actual surface temperature and macrostructures of 82B steel. The effects of different casting speeds on solidification structures including the total number of whole cross section of the rectangular billet and carbon macrosegregation were calculated. Besides, an industrial test was conducted to investigate the effects of different casting speeds on dendrite morphology and center carbon macrosegregation of 82B steel. A similarity between the calculated and industrial result is achieved. Decreasing the casting speed from 1.35 or 1.30 to 1.25 m/min could increases the cooling intensity and decreases the centreline carbon macrosegregation.

**KEYWORDS:** RECTANGULAR BILLET CONTINUOUS CASTING - CASTING SPEED 
PROCAST SIMULATION - TOTAL GRAIN NUMBER - CARBON MACROSEgregation

**INTRODUCTION**

Solidification structure and macrosegregation have great influence on the quality of high carbon steels. Center segregation in high carbon steel results in a high concentrations of chemical components especially carbon element and has a great influence on the quality of wire rod [1-3]. Wire rod with center cementite network resulting from severe segregation not only shows low ductility in the center portion, but also exhibits cup fracture during drawing [4]. A fundamental task of high carbon steel continuous casting is to optimize the processing parameters to minimize the formation of carbon macrosegregation. The optimization of the process variables may provide a simple low cost solution to controlling macrosegregation [5].

Product quality and production efficiency depend essentially on the appropriate casting speed. The effect of casting speed on the middle size of 180 mm × 240 mm rectangular billets in continuous casting has not been researched before. As is known, different billet sizes require different casting speeds in order to reduce the center macrosegregation and increase the production efficiency. Generally, the billet size less than 160 mm × 160 mm needs high casting speeds to increase the production efficiency by using intensive cooling intensity in secondary cooling zone. Intensive cooling intensity can achieve a rapid temperature drop at the surface corresponding to the temperature drop at the center when the latter solidifies and, consequently decreases the grain size and prevents V-segregation formation [6]. The blooms generally need small casting speeds in continuous casting by using softer cooling intensity. It is known that “soft” cooling intensity can minimizes alloy components segregation intensity and increases equiaxed grain ratio [4]. So, to the middle size rectangular billet, it is of great importance to study the casting speed on macrostructure and center segregation.

The solidification structures including the total grain number and the dendrite morphology can affect the center macrosegregation. The grain number can be used to evaluate the mean grain size in the whole cross section and large grain number in the cross section means that the mean grain size is small. The liquid flow comes from interdendritic areas and therefore, is highly enriched, which causes the central macrosegregation. This liquid flow from the interdendritic region can be effectively influenced by the grain size [7]. Besides, center macrosegregation is closely related
to dendrite morphology of the cast structure. Any parameters that influence the dendrite morphology will also affect the macrosegregation.

In the present research, the FE-CA coupling model [3, 8] was used to simulate the solidification structures of high carbon 82B steel, in which different casting speeds were taken into consideration. The effect of casting speeds on the solidification structure including the total grain number of whole cross section of billet was calculated. Besides, the centreline macrosegregation was simulated by combining the solute field, temperature field and flow field during solidification. The industrial tests were conducted to investigate different casting speeds on dendrite morphology and center carbon macrosegregation of 82B steel. The specimens from the rectangular billet were collected to analysis the secondary dendrite arm spacing (SDAS) in different casting speeds. Based on the simulation and industrial test, the effects of different casting speeds on center carbon segregation were discussed during continuous casting.

**NUMERICAL MODEL**

In the present model, the cellular automaton method (CA) was combined with the heat transfer calculation during the continuous casting process. The CAFE model simulating the solidification structure mainly includes heat transfer model, nucleation model and dendrite tip growth kinetics.

**HEAT TRANSFER MODEL**

A two-dimensional unsteady state heat transfer equation is available as follows:

\[\rho C \frac{dT}{dt} = \frac{\partial}{\partial x}\left(k \frac{dT}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{dT}{\partial y}\right)\]

where \(\rho\) is density, \(C\) is specific heat capacity and \(k\) is thermal conductivity. The evolution of latent heat during solidification is incorporated to the calculation by using the effective specific heat method, as shown in the following equation.

\[C'_e = C_e - L \left(\frac{df_s}{dT}\right)\]

where \(C'_e\) is the effective specific heat, \(L\) is the latent heat and \(f_s\) is the solid fraction.

The heat transfer model based on the moving slice method is established to simulate the solidifications of 82B steel. Figure 1 shows the boundary conditions of the heat transfer model during the continuous casting process. The section size of slice is the same as the rectangular billet, 180 mm x 240 mm and the thickness is 25 mm.

![Fig. 1 - Schematic illustration of boundary conditions and the moving slice method](image)

**Tab. 1 - The boundary conditions and the calculated formula of 82B steel**

<table>
<thead>
<tr>
<th>Section</th>
<th>Length/m</th>
<th>Boundary Condition</th>
<th>Calculated Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mould</td>
<td>0.8</td>
<td>(q_m)</td>
<td>(q_m = (2.04 - 0.535) \times 10^4) [g]</td>
</tr>
<tr>
<td>Secondary cooling zone</td>
<td>7.9</td>
<td>(q_s = a(T - T_e))</td>
<td>(a = 200 + 10.4W^{0.8}) [W/m²·K]</td>
</tr>
<tr>
<td>Air cooling zone</td>
<td>10.0</td>
<td>(q_a = e[(T+273)^0.5 - (T_e +273)^0.5])</td>
<td>(e = 5.67 \times 10^{-8}) [W/(m²·K)] (\varepsilon = 0.8) [g]</td>
</tr>
</tbody>
</table>
NUCLEATION MODEL

Nucleation can be divided into homogeneous nucleation and heterogeneous nucleation during solidification process. In the present study, the continuous heterogeneous model [11] is applied. A continuous nucleation distribution function, dn/d(ΔT), is used to describe the grain density change, dn is induced by increase of the undercooling, d(ΔT). The distribution function is expressed by Eq. (3):

\[
\frac{dn}{d(\Delta T)} = \frac{n_{\text{max}}}{\sqrt{2\pi} \Delta T_{\text{m}}} \exp \left[ -\frac{1}{2} \left( \frac{\Delta T - \Delta T_{\text{m}}}{\Delta T_{\text{m}}} \right)^2 \right]
\]

where \(T\) is the calculated temperature, \(K\); \(T_{l}\) is the liquidus temperature, \(K\); \(\Delta T\) is the calculated heat undercooling (\(\Delta T = T - T_{l}\)), \(K\); \(\Delta T_{\text{m}}\) is the mean undercooling, \(K\); \(\sigma\) is the standard deviation, \(K\); \(n_{\text{max}}\) is the maximum nucleation density, \(m^{-3}\).

DENDRITE TIP GROWTH KINETICS

The growth kinetics of both columnar and equiaxed morphologies can be calculated. The KGT (Kurz, Givoanola, Trivedi) model [12, 13] is used as the model of growth kinetics of a dendrite tip in the 82B steel. Based on the marginal stability criterion, Eq. (4) is obtained.

\[
V^2 A + VB + C = 0
\]

where 

\[
A = \frac{\pi^3 \Gamma}{p^3 D^2}, \quad B = \frac{mC_o(1-k_o)\xi_c}{D[1-(1-k_o)\nu(P)]}, \quad C = G \Gamma
\]

\(\Gamma\) is the Gibbs-Thomson coefficient (\(\Gamma = 1.9 \times 10^{-7}\)), \(V\) is the growth velocity of a dendrite tip, \(P\) is the Peclet number for solute diffusion, \(D\) is the diffusion coefficient in the liquid, \(m\) is the liquidus slope, \(C_o\) is the initial concentration, \(k_o\) is the partition coefficient, \(\nu(P)\) is the Ivantsov function, \(\xi_c = \pi / (k_o p)\) and it closes to unity at low temperature gradient, \(G\) is the temperature gradient. For the dendrite growth regime, \(G\) has little effect on the growth velocity \(V\) and can be regarded as zero.

\[
\Delta T = mC_o \left[ 1 - \frac{1}{1-(1-k_o)\nu(P)} \right] + \frac{2T_{\text{g}}}{r}
\]

where \(r\) is the dendrite tip radius. The relationship between the undercooling \(\Delta T\) and \(V\) can be calculated by substituting an arbitral value of the Peclet number into Eqs. (4) and (5). The chemical compositions of high carbon 82B steel and materials properties used in the simulation are given in Table 2.

| Tab. 2 - The chemical composition of 82B steel and materials properties used in the simulation |
|-----------------------------------------------|--------|--------|--------|--------|--------|--------|
| Composition | C | Si | Mn | P | S |
| Mass fraction, % | 0.82 | 0.20 | 0.70 | 0.014 | 0.008 |
| Partition coefficient, \(k_o\) [14] | 0.35 | 0.52 | 0.75 | 0.06 | 0.025 |
| Liquidus slope, \(m\) | -60 | -8 | -5 | -34 | -40 |
| Diffusivity in liquid, \(D\), m²/s [15] | 2.0×10⁻⁸ | 2.4×10⁻⁸ | 2.0×10⁻⁸ | 4.7×10⁻⁹ | 4.5×10⁻⁹ |

To accelerate the computation speed, set of values for the undercooling and growth velocity of the dendrite tip are calculated in Eqs. (4) and (5). At last, the following Eq. (6) is obtained.

\[
V(\Delta T) = a_2 \Delta T^2 + a_3 \Delta T^3
\]

where \(V(\Delta T)\) is the growth velocity of the dendrite tip; \(a_2\) and \(a_3\) are the fitting coefficients. Using the simulation and based on the Table 2, the calculated values of \(a_2\) and \(a_3\) are 0 and 1.257×10⁻⁵ m/(s·K³).

MODEL VALIDATION

Heat Transfer Model Validation

The validation of the heat transfer model was performed by a comparison of the calculated surface temperatures and the measured temperatures at the following continuous casting conditions: the casting speed was 0.9 m/min, the secondary cooling water intensity was 0.9 L/kg and the superheat was 23°C. The surface temperatures were measured using infrared pyrometer. A comparison between the simulation and measured temperatures is shown in Fig. 2. This result show fairly good agreement between the temperature results of simulations and experiments. It is indicated that the present model can be used to calculate the temperature during continuous casting of steel.
CAFE Model Validation

The validation of the CAFE model was performed by a comparison of the simulated solidification structures and the actual solidification structures under the same continuous casting conditions. The casting conditions were as follows: the casting speed was 1.30 m/min, the secondary cooling water intensity was 0.9 L/kg and the superheat was 25°C. A comparison between experimental results and simulated results in the same conditions is shown in Fig. 3. The typical solidification macrostructures include three parts: outer chill zone, intermediate columnar zone and central equiaxed zone. It can be seen from Fig. 3 that the simulated solidification macrostructures by CAFE were compatible with the actual results and the ratio of equiaxed grain zone in experimentally observed and simulated were about 58%. This result indicates that the selected nucleation parameters are reasonable and the present model can be used to simulate the solidification structure during continuous casting of 82B steel.

RESULTS AND DISCUSSION

Modeling results

Effect of Casting Speed on the Number of Grains

In this research, the effect of casting speed on the number of grains was calculated while other casting conditions remain unchanged. At first, the simulated results of different casting speeds on solidification structures are given in Fig. 4. It can be seen from the figure that the solidification structures mainly include the columnar grain zone and equiaxed grain zone. The total number of grains is listed in Fig. 5. The Fig. 5 shows that the number of grains increases by about 204 as the casting speed decreases by 0.05 m/min.

Figure 6 shows the comparison of the final solidification time under different casting speeds. It demonstrates that the final solidification time is decreased with the casting speed reduces from 1.35 to 1.25 m/min. This is probably because that the cooling intensity increases with the decrease of casting speed and that lead to the solidification time reduced and the grains have less time to grow up. What’s more, the decreasing of casting speed leads to the cooling intensity increases and results in a large temperature gradient at liquid-solid interface during solidification process. The large temperature gradient is beneficial to crystal nucleation and thus increases the grain density.

Fig. 3 - Comparison of actual (left) and simulated (right) solidification macrostructures

Fig. 4 - The simulated solidification structures of 82B steel under different casting speeds:
(a) 1.25 m/min, (b) 1.30 m/min, (c) 1.35 m/min
EFFECT OF CASTING SPEED ON THE SIMULATED MACROSEGREGATION

The effects of different casting speeds on the carbon macrosegregation is calculated by ProCAST. In the model, the solute field, temperature field and flow field are calculated together and the molten steel in rectangular billet is free convection. At first, simulated macrosegregation of 82B steel in the longitudinal section with casting speeds of 1.35 m/min and 1.30 m/min is shown in Fig. 7. It can be seen from the figure that the macrosegregation is formation in the center of rectangular billet and the centerline macrosegregation is incontinuous distribution. The simulated results of different casting speeds on the centerline macrosegregation are given in Fig. 8. It can be seen from the figure that the maximum carbon macrosegregation is about 1.24 and the macrosegregation is trend to decreases with the casting speeding decreasing from 1.35 m/min to 1.25 m/min. The Fig. 9 shows the simulated distribution of carbon segregation in the width direction of rectangular billet at a casting speed of 1.30 m/min. It can be seen that the center macrosegregation is formed in a range of about 50 mm.
INDUSTRIAL RESULTS

Effect of Casting Speed on the Dendrite Morphology

Dendrite morphology has a significant impact on the internal quality of rectangular billet such as center macrosegregation, central porosity, and central shrinkage cavity. SDAS (secondary dendrite arm spacing) is a very important parameter during the molten steel solidification. The size of the SDAS is closely related to the cooling system of continuous casting process and the size variation has an obvious significant on the internal quality of the billet such as macrosegregation [16]. In order to reveal the dendrite structure, samples were etched with the following solution: Picric acid (60 g) + CuCl₂ (15 g) + liquid soap (60 cm³) + water (3000 cm³) [17].

Figure 10 shows the influence of casting speed on dendrite morphology of continuously cast rectangular billet and the surface of the billet is on the left of the macrograph. It can be seen from the figure, the casting speed has a great effect on the dendrite morphology and a compactly and uniform dendrite is obtained as the casting speed decreases from 1.35 or 1.30 to 1.25 m/min. A comparative assessment of the influence of casting speed on SDAS is given in Fig. 11. As shown in Fig. 11, the SDAS in different casting speeds is measured by measuring the average value of 50 secondary dendrite arm spacing and the corresponding cooling rate was calculated according to the following formula. Based on the measured data of SDAS (λ) under different casting speeds, an empirical relationship between the SDAS (λ) and cooling rates (C_r) was obtained by a best fit as follows [18]:

\[ \lambda = \begin{cases} 
169.1 - 720.9w_{[C]} & , 0 < w_{[C]} \leq 0.15 \\
143.9 - 0.166w_{[C]} & , 0.5501 - 1.996w_{[C]} \leq w_{[C]} \\
143.9 - 0.3616w_{[C]} & , w_{[C]} > 0.15 
\end{cases} \]  

(7)

where \( C_r \) is the cooling rate (°C/s) and \( w_{[C]} \) is the carbon content (wt.%). Due to the intensive cooling intensity at lower casting speed, a small SDAS is obtained and the cooling rate is increased. Besides, the SDAS is increased and the cooling rate is decreased as the increasing of distance from surface.
EFFECT OF CASTING SPEED ON THE CENTER CARBON SEGREATION

In the continuous casting of high carbon 82B steel, center carbon segregation is the most severe problems encountered in 180 mm×240 mm rectangular billets. Production of continuously cast high carbon steel that very low center macrosegregation is an important objective in meeting high quality requirements. The industrial tests were conducted to investigate the effect of different casting speeds on the macrosegregation of high carbon 82B steel and the validity of the simulation macrosegregation is verified by using the experimental data. The 82B steel was produced by a straight curved caster with a billet size of 180 mm×240 mm. In order to find out an appropriate process variables of low carbon segregation index, the industrial test was carried out by varying the casting speeds from 1.35 or 1.30 to 1.25 m/min while the tundish superheat was limited at 25±3°C. Besides, the F-EMS was closed.

The segregation index was evaluated by longitudinal cross section of 180 mm×240 mm rectangular billet. The carbon segregation was determined by total eight drillings along the center line of the rectangular billet. Each sample was drilled out 4 mm depth with 5 mm diameter drill along the central longitudinal direction. The carbon segregation was defined as C/C₀, where C is center carbon content (drilling test) and C₀ is carbon content in liquid steel (tundish test).

A similarity between the calculated and industrial result is achieved. Figure 12 shows the variations of center carbon segregation degree with different casting speeds. The results are shown in Fig. 12 presenting that the carbon segregation degree reduces most effectively at the casting speed of 1.25 m/min. The center segregation degree of carbon is aggravated when casting speeds increase from 1.25 to 1.35 m/min. The mean center segregation degree of carbon decreases from 1.16 to 1.09 when the casting speed decreases from 1.35 to 1.25 m/min. The calculated center carbon macrosegregation is about 1.24 and the industrial macrosegregation is less than 1.25. The calculated macrosegregation data in Fig. 8 is consistent with the measured data in Fig. 12.

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**Fig. 11** - Measured values of SDAS (a) and corresponding cooling rates (b) under different casting speeds

**Fig. 12** - Effect of casting speed on the degree of center macrosegregation
Explanations are made to correlate the carbon macrosegregation data with the solidification structures and dendrite morphology. An important phenomenon could be discovered by combining Fig. 5, Fig. 8, Fig. 11 and Fig. 12. The total grain number is increased and the secondary dendrite arm spacing is decreased as the casting speed reduces from 1.35 to 1.25 m/min, correspondingly, the mean center segregation degree of carbon is decreased. The results of this exercise demonstrate that the center segregation has a very close relation with the solidification structure and increasing the grain number or decreasing the SDAS is conductive to improving the center segregation. It is important to adopt an appropriate casting speed in consideration of its effect on center carbon segregation. For the rectangular billet continuous casting, the casting speed of 1.25 m/min is determined as a result for providing a valuable production data for plant operation.

CONCLUSIONS
A coupled model has been used to simulate the solidification structures and macrosegregation during continuous casting of high carbon 82B rectangular billet. The present model was validated by experimental data. This study simulated the effects of different casting speeds on the solidification structure and macrosegregation of 82B steel. Besides, an industrial trial was carried out to assess the influence of casting speed on the SDAS and center macrosegregation of rectangular billet. The findings resulting from simulation and industrial test can be summarized as follows:
(1) It is found that the total grain number was increased and the secondary dendrite arm spacing was decreased with the decreasing of casting speed.
(2) Encouraging macrosegregation results were obtained by means of numerical calculation and industrial test with the casting speeds decreasing from 1.35 or 1.30 to 1.25 m/min.
(3) The center macrosegregation may be improved with a large number of grains and small SDAS during continuous casting process.

REFERENCES