Numerical simulation on the solidification structure of Ø600mm continuous casting round bloom

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Abstract. A FE (Finite Element)—CA (Cellular Automation) coupling model was developed for the simulation of solidification structure formation during the Ø600mm round bloom continuous casting process of Q345E steel. The simulation result of the temperature field was consistent with the nail-shooting experimental result, and the simulated solidification structure of the bloom was in great agreement with corrosion testing under the same casting condition. The simulation results showed that the centre equiaxed crystal ratio increased slightly with the increase of secondary cooling water rate and decreased with the increase of casting temperature and casting speed. When the secondary cooling water rate was over 0.08L/kg, it had less effect on the solidification structure. As the casting temperature increased by 1°C or the casting speed increased by 0.01m/min, the centre equiaxed crystal ratio would decrease by 0.4%~1.2% and 0.3%~0.8% respectively. According to the simulation results, the optimized continuous casting process of Ø600mm round bloom should be the secondary cooling water rate of 0.08L/kg, the casting temperature of 1532°C~1539°C and the casting speed of 0.20m/min~0.22m/min. It was found that the solidification structure of Ø600mm Q345E steel round bloom was much improved after the optimized continuous casting process was adopted in practical production.

1. Introduction
The solidification structure of continuous casting bloom has an important effect on the quality of final steel products. A columnar structure will lead to the deterioration of mechanical properties and the centre equiaxed grains are helpful for improving the mechanical properties of the bloom. So it is of great significance to study the proper continuous casting technology to enhance the centre equiaxed grains in the bloom. In recent years, there is an increasing demand for large section continuous casting blooms. However, it is difficult to get the optimum process with the help of practical industrial trials, particularly for large section continuous casting. A dozen years ago, Rappaz and Gandin [1-3] and Zhu et al [4, 5] successfully predicted the transition from columnar to equiaxed zone by coupling the CA method with the finite element method (FEM). Then, the CAFÉ model was widely cited by the world’s metallurgists [6-9] to improve the solidification structure of their research objects. But the method is rarely used on the continuous casting process and research on blooms with a diameter over 500mm is rarely reported. This makes the present study valuable to the continuous casting process of large-size blooms.

In this paper, the CAFÉ method was developed to simulate the solidification structure of Ø600mm
continuous casting round bloom of Q345E steel. The simulated results of the temperature field and solidification structure were verified by a nail shooting experiment and corrosion testing respectively. The effects of casting parameters on the solidification structure were discussed based on production. Then the proper casting condition to enhance the internal quality of the bloom could be found to guide the production of the specific steel.

2. Model description

2.1. Heat transfer model of FE

2.1.1. Solidification model of heat transfer. The heat transfer characteristics and industrial conditions of continuous casting round bloom are taken into consideration to simplify the calculation process of numerical simulation. Based on the assumptions in Ref. [10, 11], the heat transfer during the continuous casting process of Ø600mm round bloom can be simplified to a two-dimensional unsteady heat transfer model, thus a sheet shifting method can be developed to build a geometric model for the round bloom during continuous casting which is subsequently calculated by ProCAST. Suppose that a circular slice is formed at the meniscus, and the heat of the slice passes from the centre to the surface during the solidification process. Then a solidified shell gradually grows from the surface to the centre until the bloom is completely solidified.

2.1.2. Initial and boundary conditions. The temperature of liquid steel in the slice is supposed to be equally distributed and equal to the temperature of liquid steel in the tundish. A continuous caster’s cooling area consists of the mould, secondary cooling zone and air cooling zone, which have different heat transfer conditions. The detailed boundary conditions of heat transfer in each part can be handled as follows:

In the mould, the boundary condition of heat transfer is described by average heat flux, which is calculated by the following equation [12]:

\[ q = \frac{\rho_w \times c_w \times W \times \Delta T}{S_{eff}} \]  

(1)

where \( q \) is the average heat flux of the slice in the mould, \( W/m^2 \); \( \rho_w \) is the density of cooling water, \( kg/m^3 \); \( c_w \) is specific heat, \( J/(kg\times K) \); \( W \) is the flow rate of cooling water, \( m^3/s \); \( \Delta T \) is the temperature difference between the water at inlet and outlet, \( K \); \( S_{eff} \) is the active area of mould, \( m^2 \).

In the secondary cooling zone, the heat transfer coefficient in the water spray region is calculated by equation (2); in the air-mist spray region, the heat transfer coefficients are calculated by equation (3).

\[ h = 581w^{0.541}(1 - 0.0075t_w) \]  

(2)

\[ h = 350w + 130 \]  

(3)

where \( h \) is the heat transfer coefficient at the bloom surface, \( W/(m^2\times °C) \); \( w \) is the spraying water density, \( L/(m^2\times s) \).

In the air cooling zone, the heat flux density can be calculated by the following equation:

\[ q = \varepsilon\sigma(T^4-T_w^4) \]  

(4)

where \( \sigma \) is the Steven—Boltzmann constant, \( 5.67\times10^{-8} W\times m^2\times K^{-4} \); \( \varepsilon \) is blackness; \( T \) and \( T_w \) are the surface temperature of the bloom and the ambient temperature respectively, \( K \).
2.2. CA model

2.2.1. Heterogeneous nucleation. A continuous nucleation distribution function \( dn/d(\Delta T) \) is used to describe the grain density change which is induced by an increase in the under-cooling. The function is described by following equation [2].

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

(5)

where \( n_{\text{max}} \) is the maximum nucleation density, which integrates from 0 to \( \infty \) according to a normal distribution when all the nucleation sites are activated; \( \Delta T \) is the mean nucleation undercooling temperature (°C ); \( \Delta T_{\text{s}} \) is the nucleation undercooling temperature for the standard deviation (°C ). In this case, \( \Delta T_{s,\text{max}} = 2°C \), \( \Delta T_{s,\sigma} = 1°C \), \( n_{\text{max}} = 10^8 \text{ m}^{-2} \), \( \Delta T_{v,\text{max}} = 5°C \), \( \Delta T_{v,\sigma} = 2°C \), \( n_{v,\text{max}} = 10^9 \text{ m}^{-3} \) (“s” is the index of surface nucleation, “v” is the index of volume nucleation).

2.2.2. Kinetics of dendritic tip growth. In the calculation of the solidification process, the growth kinetics of both columnar and equiaxed morphologies can be calculated with the aid of the KGT model [13]. In the actual simulation process, in order to accelerate the computation, the KGT model is fitted and the following equation is gained.

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

(6)

where \( \Delta T \) is the total undercooling of dendrite tip (°C ); \( a2 \) and \( a3 \) are the coefficients of the multinomial of dendrite tip growth velocity, which are calculated to be \( a_2 = 0 \) and \( a_3 = 8.712 \times 10^{-6} \text{ m} \times \text{s}^{-1} \times \text{K}^{-3} \) based on the data of partition coefficient, liquidus slope, diffusivity in liquid and Gibbs-Thomson coefficient of Fe-X (X = C, Si, Mn, P, S) alloys.

2.3. Casting parameters

The main chemical composition of Q345E steel is showed in table 1, and most of the thermo-physical parameters of the steel can be calculated by inputting the chemical composition into ProCast. There, the liquidus and solidus temperature of Q345E steel is 1517°C and 1472°C respectively.

| Main Elements | C | Si | Mn | P | S | Al | V | Nb | Ti |
|---------------|---|----|----|---|---|----|---|----|----|
| Mass%         | 0.15 | 0.25 | 1.34 | 0.007 | 0.003 | 0.025 | 0.035 | 0.032 | 0.006 |

3. Results and discussions

3.1. Examination of model

The nail-shooting experiment is an effective and widely used method to measure the solidified shell thickness of continuous casting billets in many steelmaking plants. In this paper, the nail-shooting experiment was used to examine the simulation result of temperature field, the results are shown in figure 1 and table 2; the simulated solidification structure was compared with a corrosion test, which can be seen in figure 2 (owing to the centre symmetry and area of the bloom on the same cross-sectional, a one-fourth cross-sectional was taken to simulate the solidification structure).

As shown in figure 1 and table 2, the error of simulation results for solidified shell thickness was under 4% compared with the results of the nail-shooting experiment. Figure 2 shows the comparison between the corrosion test and the simulated solidification structure, in which about 22.5% center equiaxed grain ratio could be observed in the simulation result and about 23.2% centre equiaxed grain ratio could be counted in the corrosion test. The simulation results for error of solidification structure was about 3% compared with the corrosion test.
Table 2. Simulation and measured results of solidified shell thickness of the bloom.

| Cross section | Distance from mould (m) | Experimental results (mm) | Simulation results (mm) | Relative error (%) |
|---------------|-------------------------|---------------------------|-------------------------|--------------------|
| 600mm         | 12.1                    | 185                       | 178                     | 3.78               |
|               | 14.9                    | 215                       | 213                     | 0.93               |

Figure 3. The simulated solidification structure under different water rates.

(a) R=0.07L/kg  (b) R=0.08L/kg  (c) R=0.09L/kg  (d) R=0.10L/kg

Figure 4. The proportion of equiaxed grain at different water rates.

3.2. Secondary cooling water rate
The solidification structures under different water rate (0.07L/kg ~ 0.10L/kg) were investigated to find a proper value of water rate for the secondary cooling zone. The simulation results are shown in figure 3, and the centre equiaxed grain variation is presented in figure 4.
As can be seen in figure 3 and figure 4: (1) with the increase of secondary cooling water rate, the proportion of centre equiaxed grains increased slowly; (2) as water rate increases by 0.01L/kg, the proportion of equiaxed grains increased by about 0.5%, and when the secondary cooling water rate was over 0.08L/kg, it had less effect on the solidification structure; (3) by comprehensive consideration of the impact of water rate on the solidification structure and production costs, the water rate should be settled at a specific value of 0.08L/kg.

3.3. Casting temperature and casting speed
The influences of casting temperature and casting speed on the solidification structure of the bloom were discussed to determine a group of reasonable casting parameters for the continuous casting bloom. In this research, four different casting speeds and six groups of casting temperature were discussed to find the specific effects of casting speed and casting temperature on the solidification structure of Ø600mm round bloom. The variables of casting speed and temperature are shown in table 3.

| Casting temperature (℃) | 1527 | 1532 | 1539 | 1547 | 1552 | 1557 |
|-------------------------|------|------|------|------|------|------|
| Casting speed (m/min)   | 0.20 | 0.22 | 0.24 | 0.25 |

Figure 5. The influence of casting speed and casting temperature on the solidification structure

The simulation results of centre equiaxed grain variation under different casting speeds and casting temperatures are presented in figure 5. With the increase of casting speed and casting temperature, the proportion of centre equiaxed grains apparently decreased. As the casting temperature increased by 1℃ or the casting speed increased by 0.01m/min, the centre equiaxed grain ratio in the bloom decreased by about 0.4%~1.2% and 0.3%~0.8% respectively.

The casting temperature should be controlled within a certain range to ensure stable direct motion and the internal quality of the bloom, and the casting speed is also one of the key parameters that affect the surface quality of the bloom and the whole efficiency of the casting process; the casting temperature of Ø600mm round bloom Q345E steel should be properly controlled within 1532℃~1539℃, and the casting speed should be set within the range of 0.20m/min~0.22m/min. The casting parameters mentioned above met the plant conditions and the centre equiaxed grain ratio was enhanced to a higher degree.
5. Conclusions
1. The simulation results of Ø600mm Q345E steel during the continuous casting process was consistent with the experimental results, as the relative error of temperature field was under 4% compared with the nail-shooting experiment, and the simulated solidification structure of the bloom was in great agreement with the corrosion test.
2. The proper continuous casting process of Ø600mm Q345E steel should be water flow rate at 0.08L/kg, casting temperature within 1532°C~1539°C and casting speed in the range of 0.20m/min~0.22m/min.
3. After the optimized continuous casting process was put into practice, it was found that the proportion of centre equiaxed grains of Ø600mm round bloom Q345E steel apparently increased and the quality of the practical product improved greatly.

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