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SIMULATION ANALYSIS ON THE ROUND BILLET MACROSTRUCTURE OF SPECIAL STEEL VERTICAL CASTER

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Original scientific paper
This paper provides an analysis of the 42CrMo round billet by the vertical caster. Based on ZhongYuan Special Steel continuous casting process parameters and CAFE nucleation parameters, the ProCAST chip-moving boundary method is adopted to conduct the numerical simulation of round billet. Simulation and practical cases both have the same macrostructure morphology, the round billet has the center equiaxial crystal of 41,2 %. As the superheat of liquid steel and cooling intensity is reduced, the average radius of crystal decreased, the number of crystal increased, and the macrostructure showed a trend of progressive elaboration.

Keywords: *big round billet; 42CrMo; macrostructure; vertical caster*

Simulacijska analiza na makrostrukturi okruglog trupca od posebnog vertikalno ljevanog čelika

Izvorni znanstveni članak
Ovaj rad daje analizu okruglog trupca 42CrMo vertikalno ljevanog. Temelji se na parametrima procesa kontinuiranog lijevanja ZhongYuan specijalnog čelika i parametrima CAFE nukleacije, usvojenom metodom "ProCAST chip-moving boundary" za provođenje numeričke simulacije okruglog trupca. Simulacijski i praktični slučajevi imaju istu makrostrukturnu morfologiju, okrugla kladica ima središnji istoosni kristal od 41,2 %. Kako je smanjeno pregrijavanje tekućeg čelika i intenziteta hlađenja, prosječni radijus kristala se smanjio, broj kristala se povećao, a makrostruktura je pokazala trend progresivnog razrađivanja.

Ključne riječi: *42CrMo; makrosturktura; veliki okrugli trupac; vertikalno ljevanje*

1 Introduction

During the solidification of molten steel, the nucleation and growth of crystal affect the macrostructure of round billet. While the macrostructure is the basis of the internal quality of round billet, it may affect the composition uniformity and hardenability. The form of continuous casting machine influences the solidification process and the macrostructure of round billet. Compared with the traditional vertically-curved caster, there is no bending and straightening process of the vertical caster, so there are no crack defects on the surfaces of round billet. There is no internal and external arc difference in the vertical caster, the inner arc does not gather inclusions [1], and the temperature field and stress field are uniform. The 420 × 530 mm slab vertical caster of POSCO was put into production in 2012 [2]. The 480 × 610 mm slab vertical caster of Timken Steel Corporation was put into production in 2014 [3]. The continuous caster of ZhongYuan Special Steel is the world's first vertical round billet caster, it can produce the round billet of maximum 800 mm diameter.

Table 1 Main composition of 42CrMo (wt%)

El.	C	Si	Mn	Cr	Mo	P	S	Ni	Cu
Co.	0,41	0,25	0,65	1,05	0,2	0,015	0,01	0,02	0,02

2 Heat transfer and solidification model

The billet of ∅600 × 20 mm is used as the computing model, the tetrahedral mesh has been adopted, and the two dimensional non steady state models are established [4]. Using the chip-moving boundary method to create a numerical simulation of temperature field, and then select a ∅600 × 2 mm slice on the model and use CAFE module to the numerical simulation of macrostructure. The main composition of 42CrMo is shown in Tab. 1, and the ProCAST database is calculated to thermophysical parameters.

2.1 Heat transfer model

According to the characteristics of heat transfer in the vertical round billet caster, and for convenience in calculation, the following assumptions are adopted regarding the temperature field: 1) the influence of molten steel flow on heat transfer is ignored; 2) the axial heat transfer is ignored; 3) the influence of mould vibration on heat transfer is ignored; 4) mould heat transfer is assumed using the average heat flux; 5) secondary cooling water is assumed evenly sprayed.

Table 2 The computational formula of heat transfer model

Stage	Computational formula
Mould	$Q = Q_W C_W \Delta T_W / F$
Secondary cooling system	$h = 350 \times W^{0,351}$
Air cooling system	$q_r = k\sigma[(T_b+273)^4-(T_a+273)^4]$

Table 3 The working condition of mould

Project	Numeric
Casting Temperature /°C	1523
superheat /°C	30
Water temperature difference /°C	5
Cooling water /L·min^{-1}	2650
Length /m	0,7
casting speed /m·min^{-1}	0,18

From the beginning of the mould meniscus, the slice continuously passes through the mould, secondary cooling system and air cooling system. The computational formula of heat transfer model is shown in Tab. 2. Among them, the boundary condition of secondary cooling system is treated by the MCA method [5], to obtain the comprehensive heat transfer coefficient h [6]. The working condition of mould is shown in Tab. 3.

In Tab. 2, Q is the average heat flux density of the mould, in W/m^2; Q_W is the cooling water consumption of the mould, in kg/s; ΔT_W is the water temperature difference between inlet and outlet of the mould, in K; F is the effective cooling area of the mould and round billet, in m^2; h is the surface heat transfer coefficient of round billet, in W/(m^2·K); W is water flow density, in L/(m^2·s); q_r is the radiant heat flux, in W/m^2; σ is the Boltzmann constant; k is the surface emissivity; T_b is the surface temperature of round billet, in °C; T_a is the environment temperature, in °C.

2.2 Solidification model

M. Rappaz [7] proposed a Gaussian distribution to describe the nucleation intensity d$n/\Delta T$, and to determine the local density of crystal in this way. The distribution d$n/\Delta T$ is described by this equation:

$$\frac{\mathrm{d}n}{\mathrm{d}(\Delta T)}=\frac{n_{\max}}{\sqrt{2\pi}\Delta T_\sigma}\exp\left[-\frac{1}{2}\left(\frac{\Delta T-\Delta T_{max}}{\Delta T_\sigma}\right)\right], \tag{1}$$

Among them, total supercooling degree of dendrite tip for ΔT, is given as follows:

$$\Delta T=\Delta T_{\mathrm{c}}+\Delta T_{\mathrm{t}}+\Delta T_{\mathrm{r}}+\Delta T_{\mathrm{k}}, \tag{2}$$

The crystal grain growth is calculated based on a simplified KGT model [8], and the growth speed of the dendrite tip can be calculated as follows:

$$v(\Delta T)=a_2\Delta T^2+a_3\Delta T^3. \tag{3}$$

Where: $\Delta T_{\max}$ is the average nucleation undercooling, in K; ΔT_σ is the standard deviation of the distribution, in K; $n_{\max}$ is the maximum nucleus density; ΔT_c, ΔT_t, ΔT_r and ΔT_k are the constitutional supercooling, thermodynamic undercooling, interface curvature undercooling and growth kinetics of supercooling; a_2 and a_3 are the coefficients.

Nucleation number of volume and area is as follows: $\Delta T_{v,\max}$=5,5 K, $\Delta T_{v,\sigma}$=1,5 K, $n_{v,\max}=1\times10^8$, $\Delta T_{s,\max}$=0,5 K, $\Delta T_{s,\sigma}$=0,1 K, $n_{s,\max}=1\times10^7$.

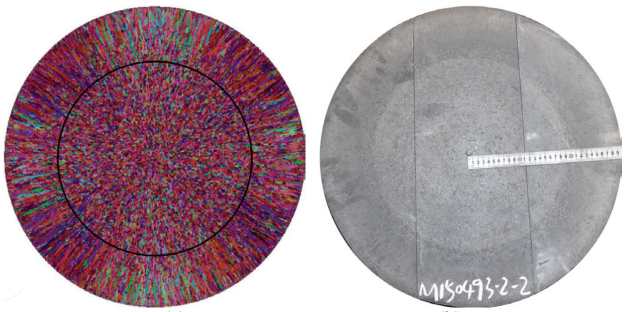
2.3 Model coupling

In order to create the heat transfer model and solidification model coupled together, and make sure that the macrostructure is a function of temperature field. Between the FE node and the CA cell, the interpolation factor is defined, the interpolation factor combined with nodes determines the cell temperature, updates the node temperature [9] in the process of crystal nucleation.

3 Model verification and simulated results
3.1 Model verification

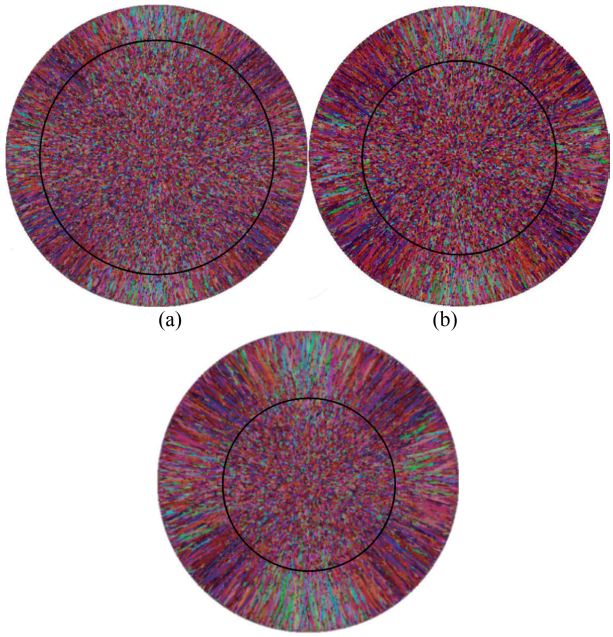
Based on the continuous casting process parameters and CAFE nucleation parameters, the simulation result of round billet is shown in Fig. 1a, the colour depth indicates the growth direction of crystal grain [10]. The macrostructure of round billet after pickling is shown in Fig. 1b. Simulation and experiment both have the same macrostructure morphology, the round billet has the centre equiaxial crystal of 41,2 %.

The chilling layer, the columnar zone, and the centre equiaxial zone can be clearly identified from Fig. 1b. Firstly, the high temperature molten steel is subjected to strong cooling in the mould, and the surfaces of round billet are formed with a thin layer of fine equiaxial crystal, the chilling layer. Secondly, the columnar zone is then formed by the directional growth of bulky columnar crystal. Finally, with the growth of columnar crystal, the temperature gradient of solid-liquid mixed areas gradually decreased, the columnar crystal growth getting slow and CET transformation occurs, forming the centre equiaxial crystal zone.



(a) (b)

Figure 1 Comparison between the simulation and experimental results (a) simulation result (b) experimental result



(a) (b) (c)

Figure 2 Macrostructure with different superheat (a) 20 °C (b) 30 °C (c) 40 °C

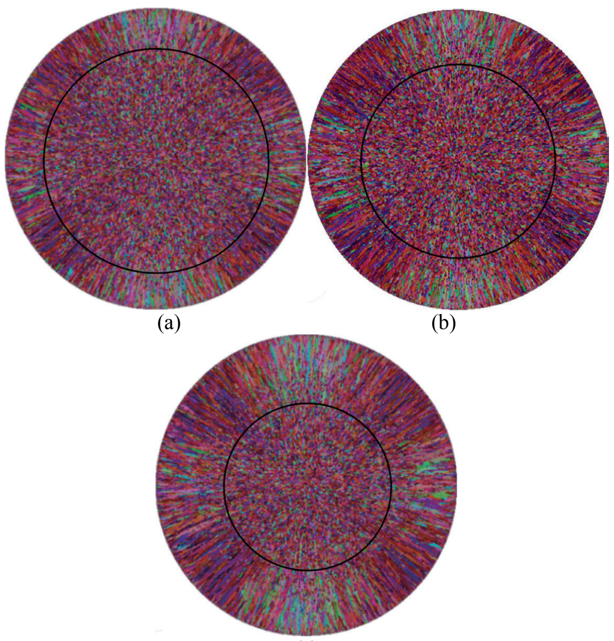
3.2 The effect of superheat

The superheat of liquid steel is one of the key process parameters to ensure the quality of round billet. Simulation results of 20 °C, 30 °C and 40 °C superheat are shown in Fig. 2, the other parameters remain the same. Gradual coarsening macrostructure can be seen with an increase in superheat of the liquid steel. Specifically, when the superheat increases from 20 °C to 40 °C, the number of crystal decreases from 10 619 to 8142, the average radius of crystal increases from 1125 μm to 1536 μm, and the centre equiaxial crystal decreases from 59,4 % to 32,3 %.

First, the decrease in the number of nuclei with the increase in superheat causes the reduction of the maximum density of crystal nucleus. Secondly, it is not easy to cool the cellular to form a crystalline nucleus with an increase in superheat, which is suitable for the growth of columnar crystals. On the contrary, the decreasing superheat is conducive to the formation of a large number of crystal grains. The crystal grains grow up and form the centre equiaxial crystal, which will prevent the growth of the columnar crystal. Therefore, in the round billet, the low superheat is helpful for the improvement of the equiaxial crystal.

3.3 The effect of cooling intensity

Tab. 4 provides data for three types of cooling system. The other parameters remain the same, the simulation results are shown in Fig. 3. Gradual coarsening macrostructure can be seen with an increase in cooling intensity of the liquid steel. Specifically, when the cooling intensity increases from 1 to 3 group, the number of crystal decreases from 9817 to 7532, the average radius of crystal increases from 1187 μm to 1675 μm, and the centre equiaxial crystal decreases from 54,7 % to 30,9 %.



(a) (b) (c)

Figure 3 Macrostructure with different cooling intensity
(a) 1 group (b) 2 group (c) 3 group

Firstly, considering the growth rate of dendritic crystal, high cooling intensity results in the decreasing surface temperature of round billet, and the increasing temperature gradient, which is conducive to the growth of the columnar crystal. Secondly, high cooling intensity easily reached the average nucleation under cooling. Therefore, it is gradually increasing the equiaxial crystal with a decrease in cooling intensity.

In the actual production process, the different casting speed matches with different cooling system. The effects of casting speed on macrostructure are similar to the cooling intensity, gradual increasing the equiaxial crystal with a decrease in the casting speed.

Table 4 Different cooling system

Group	Cooling water of secondary cooling system /L·min^{-1}		
	One area	Two area	Three area
1	11,3	18	10
2	17	27	15
3	22,6	36	20

4 Conclusion

Based on ZhongYuan Special Steel continuous casting process parameters and CAFE nucleation parameters, the ProCAST is adopted to conduct a numerical simulation of the round billet. The simulation and experiment both have the same macrostructure morphology, the round billet has the centre equiaxial crystal of 41,2 %.

Gradual coarsening macrostructure can be seen with an increase in superheat of the liquid steel. Specifically, when the superheat increases from 20 °C to 40 °C, the number of crystals decreases from 10 619 to 8142, the average radius of crystals increases from 1125 μm to 1536 μm, and the centre equiaxial crystal decreases from 59,4 % to 32,3 %. The low superheat is helpful for the improvement of the equiaxial crystal.

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