Solidification Structure and Compactness Degree of Central Equiaxed Grain Zone in Continuous Casting Billet Using Cellular Automaton-Finite Element Method

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A Cellular Automaton-Finite Element (CAFE) coupling model was developed to analyze the evolution of solidification structure of high-carbon steel continuous casting billet and the compactness degree of central equiaxed grain zone. Comparison between the simulated and actual solidification structure was first made under three different conditions, *i.e.*, without MEMS (mould electromagnetic stirring), with MEMS and with MEMS plus intensive cooling. It is indicated that the model can provide a good simulation of the actual solidification structure. Thereafter, the model was used to simulate the solidification structure under different superheats and casting speeds. It is shown that the width of equiaxed grain zone increases with the decrease of the superheat, and decreases with the decrease of the casting speed. The compactness degree of central equiaxed grain zone is also evaluated by the grain number in the same area under different conditions in this study. It is demonstrated that the compactness degree of central equiaxed grain zone in the billet is increased obviously when the MEMS is applied, and is further increased with MEMS plus intensive cooling. In addition, it is also increased when decreasing the casting speed. However, the compactness degree of central equiaxed grain zone is decreased when decreasing the superheat. Moreover, it is found that the compactness degree of central equiaxed grain zone in the billet is closely related to the centre solidification time, *i.e.*, it decreases with the increase of the centre solidification time.

KEY WORDS: continuous casting billet; solidification structure; cellular automaton-finite element method; compactness degree; central equiaxed grain zone; centre solidification time.

1. Introduction

Solidification structure and macrosegregation of continuous casting billet of steel have a significant effect on the quality of the final steel products. Therefore, both of them should be controlled properly during continuous casting process.¹⁻⁴⁾ Although many experimental works have been carried out in order to obtain the optimum condition for solidification process of continuous casting, it is also very desirable to establish mathematical models to simulate the evolution of solidification structure. The simulation methods can be divided into deterministic models and stochastic models, which have been developed rapidly over the last couple of decades.⁵⁾ Cellular automaton method is one of the stochastic models. Rappaz and Gandin,^{6,7)} Nasatac and Stefanescu^{8,9)} are the earliest researchers engaged in this field.⁵⁾ Moreover, Rappaz and Gandin simulated the solidification structure and CET (columnar grain to equiaxed grain transition) of metals using the CAFE method (cellular automaton-finite element method) for the first time.^{6,7)} Recently, the CA (cellular automaton) model also considered the effects of fluid flow on the solidification process.⁵⁾ However, there are only a few models for the solidification structure of continuous casting steel billet due to the com-

plexity of the continuous casting process up to now.^{1,4)}

The macrosegregation of the billet is closely related to the ratio of equiaxed grain zone in the billet, and the ways to increase the area ratio of the equiaxed grain zone has been proposed by many researchers.^{1-4,10,11)} However, the compactness degree of equiaxed grain zone has not yet been specially investigated. The compactness degree of equiaxed grain zone can be evaluated by the grain number or the grain size. That is to say, for the same area of equiaxed grain zone, high compactness degree means that the grain number is large or the grain size is small. The formation of macrosegregation has a close relationship with the liquid flow between the dendrites,¹²⁻¹⁴⁾ and the liquid flow between the dendrites can be influenced by the grain size, *etc.*¹⁵⁻¹⁷⁾ Then, macrosegregation formation is greatly influenced by the compactness degree of the grains. Therefore, it is very valuable to investigate the compactness degree of equiaxed grain zone in continuous casting billet.

In the present work, using the CAFE method, the solidification structure of high-carbon steel continuous casting billet was simulated considering the phase transformation and the effect of mould electromagnetic stirring (MEMS). Firstly, comparison between the simulated and actual solidification structure was made to verify the model. Based on the result, the simu-

lated solidification structures of continuous casting billets under different superheats and casting speeds were compared. Moreover, the compactness degree of central equiaxed grain zones under different conditions was specially discussed.

2. Model Descriptions

In the present work, the model simulating the solidification structure mainly includes nucleation model, dendrite tip growth kinetics and heat transfer calculation. **Table 1** presents the composition of the high-carbon steel, which was produced by a curved caster (the radius is 9 m) with a billet size of 170 mm × 170 mm.

2.1. Nucleation Model

Nucleation in the solidification process is generally divided into homogeneous nucleation and heterogeneous nucleation. In Ref. [18], the nucleation can be described by instantaneous model and continuous model. In the present work, continuous heterogeneous model was adopted.^{6,19)} The continuous nucleation distribution function, $dn/d(\Delta T)$, is used to describe the change of nucleation density, dn , which is caused by the increase of the undercooling, $d(\Delta T)$. And this distribution function is expressed by Eq. (1).

$$\frac{dn}{d(\Delta T)} = \frac{n_{\max}}{\sqrt{2\pi} \cdot \Delta T_{\sigma}} \exp \left[-\frac{1}{2} \left(\frac{\Delta T - \overline{\Delta T}}{\Delta T_{\sigma}} \right)^2 \right] \quad \text{..... (1)}$$

where $n_{\max}$ is the maximum nucleation density which integrates from 0 to ∞ according to normal distribution when all the nucleation sites are activated; $\overline{\Delta T}$ is the mean undercooling, K; ΔT_{σ} is the standard deviation, K. When $n_{\max}$, $\overline{\Delta T}$, ΔT_{σ} are given, the relationship between the nucleation density and undercooling can be determined.

2.2. Dendrite Tip Growth Kinetics

In casting, the growth kinetics of both columnar and equiaxed morphologies can be calculated by the dendrite tip growth kinetics, *i.e.*, the KGT model.^{20,21)} Based on the marginal stability criterion, Eq. (2) is obtained.

$$V^2 A + V B + C = 0 \quad \text{..... (2)}$$

where $A = \frac{\pi^2 \Gamma}{P^2 D^2}$, $B = \frac{m C_0 (1 - k_0) \xi_c}{D [1 - (1 - k_0) Iv(P)]}$, $C = G$, V is the growth velocity of a dendrite tip. Γ is the Gibbs-Thomson coefficient, P is the Peclet number for solute diffusion, D is the diffusion coefficient in the liquid. m is the liquidus slope, C_0 is the initial concentration, k_0 is the partition coefficient,

$Iv(P)$ is the Ivantsov function, $\xi_c = \frac{\pi^2}{k_0 P}$ and it close to unity at low growth velocity. G is the temperature gradient. For the dendrite growth regime, the imposed temperature gradient, G , has little effect on the growth velocity of a dendrite tip, V , and can be regarded as zero.

Moreover, the undercooling at a dendrite tip, ΔT , is expressed by Eq. (3). The relationship between the undercooling, ΔT , and the growth velocity, V , can be calculated by substituting an arbitral value of the Peclet number into Eqs. (2) and (3).

$$\Delta T = m C_0 \left[1 - \frac{1}{1 - (1 - k_0) Iv(P)} \right] + \frac{2\Gamma}{r} \quad \text{..... (3)}$$

where r is the dendrite tip radius, $r = (2D \cdot P)/V$.

To accelerate the computation speed, the set of values for the undercooling and the growth velocity of the dendrite tip were calculated first by Eqs.(2) and (3), and then presented as the form of Eq. (4) using the least-square method.

$$V = a_2 \Delta T^2 + a_3 \Delta T^3 \quad \text{..... (4)}$$

where V is the growth velocity of the dendrite tip, m/s. a_2 and a_3 are the fitting coefficients.

In order to calculate the coefficients for the investigated steel which is composed of various different elements (as shown in Table 1), the Bobadilla, Lacaze and Lesoult approach²²⁾ was adopted. Therefore, a_2 and a_3 were determined as 0 and $1.356 \times 10^{-5} \text{ m/(s} \cdot \text{K}^3)$ using the ProCAST software, respectively, and the relevant parameters are listed in Table 1.

2.3. Heat Transfer Calculation during Continuous Casting

2.3.1. Governing Equations

Heat transfer calculation is based on the finite element method. Equation (5) shows the governing equation for two-dimensional heat transfer calculation. Axial heat conduction in the casting direction was ignored.

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho C_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad \text{..... (5)}$$

where λ is the thermal conductivity, ρ is the density, C_p is the specific heat. The evolution of the latent heat during the solidification was incorporated into the calculation by using the effective specific heat method, as shown in Eq. (6).

$$C_p' = C_p - L \left(\frac{df_s}{dT} \right) \quad \text{..... (6)}$$

where C_p' is the effective specific heat, L is the latent heat and f_s is the solid fraction.

2.3.2. Boundary Conditions

An unsteady heat transfer model based on the “slice moving method” was established to simulate the solidification of the billet, in which it was assumed that the slice moved down from the mould to the foot roller section, to the secondary cooling zone and finally to the air cooling zone. The section size of the slice was set as the same as the billet, *i.e.*, 170 mm × 170 mm and the thickness is 30 mm. By comprehensive consideration of calculation precision and calculation time, the computation domain was divided into 83 819

Table 1. Chemical composition of high-carbon steel and relevant parameters.

Composition	C	Si	Mn	P	S
Mass fraction, %	0.7	0.2	0.65	0.011	0.0023
Partition coefficient, k_0 ⁴⁾	0.35	0.52	0.75	0.06	0.025
Liquidus slope, m ⁴⁾	-60	-8	-5	-34	-40
Diffusivity in liquid, D ⁴⁾ , m ² /s	2.0×10^{-8}	2.4×10^{-9}	2.0×10^{-8}	4.7×10^{-9}	4.5×10^{-9}
Gibbs-Thomson, Γ ⁴⁾ , m·K	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}

nodes and 464 338 elements, as shown in **Fig. 1**. The two surfaces perpendicular to the casting direction, *i.e.*, Y direction (as shown in Fig. 1), were assumed to be adiabatic, and the solidification process of the continuous casting billet was simulated by changing the heat transfer conditions of other four surfaces of the slice with lapse of the time.

The lengths, the boundary conditions and the relevant formulas of mould, foot roller section, secondary cooling zone and air cooling zone are shown in **Table 2**. And when the superheat is 25°C, the casting speed is 1.8 m/min and the specific water ratio is 0.63 L/kg, the water amounts at different sections are shown in Table 2. However, the water amount will change in the case of changing the casting speed or intensive cooling. q_m , q_f , q_k and q_a are the heat flux of mould, foot roller section, secondary cooling zone and air cooling zone, respectively, kW/m²; t is the holding time in the mould, s; β is a coefficient about the shape of the mould and the parameter of casting, kW/(m²·s^{1/2}); h_f and h_k are the heat transfer coefficient of foot roller section and secondary cooling zone, W/(m²·K); w is the water flow rate, L/(m²·min); ε is the radiation coefficient; σ is Stefan-Boltzmann constant, 5.67×10^{-8} W/(m²·K⁴); T , T_f , T_w , T_a are the temperature of the billet surface, the water of foot roller section, the water of secondary cooling zone, the environment of air cooling zone, respectively, K.

2.3.3. Initial Condition

The initial condition is given by Eq. (7):

Fig. 1. Slice of heat transfer model of the continuous casting billet.

$$T(x, y, z)|_{t=0} = T_{cast} \dots \dots \dots (7)$$

where T_{cast} is the casting temperature in the tundish, K.

2.4. Calculation Procedure

The flowchart of the simulation process is shown in **Fig. 2**. The three-dimensional grid model was first established by using PRO/E software, then the thermal field was calculated by ProCAST, and finally the solidification structure was simulated by the CAFE calculation. The CAFE model is one module of the ProCAST software. The FE mesh was used to calculate the heat transfer process and the CA cell (much smaller grid) was used to calculate the grain growth process. To predict simultaneously the microstructure development as a function of the thermal field and the influence of the latent heat release of the grains on the calculated thermal his-

Fig. 2. Flowchart of the simulation model.

Fig. 3. Relations between the FE mesh and the CA cells.

Table 2. Parameters and relevant computational formulas at different sections.

Section	Length, m	Water Amount, m ³ /h	Boundary Condition	Computational Formula
Mould	0.9	135.00	q_m	$q_m = (2.68 - \beta \sqrt{t}) \times 10^3 \quad ^{23)}$
Foot roller section	0.37	5.65	$q_f = h_f (T - T_f)$	$h_f = 480 \cdot \left(\frac{w}{60} \right)^{0.351 \quad 24)}$
First section of secondary cooling zone	2.6	4.20	$q_k = h_k (T - T_w)$	$h_k = 200 + 10.44 \cdot w^{0.851 \quad 25)}$
Second section of secondary cooling zone	4.2	3.70	$q_k = h_k (T - T_w)$	$h_k = 200 + 10.44 \cdot w^{0.851 \quad 25)}$
Third section of secondary cooling zone	2.2	1.15	$q_k = h_k (T - T_w)$	$h_k = 200 + 10.44 \cdot w^{0.851 \quad 25)}$
Air cooling zone	10	—	$q_a = \varepsilon \sigma (T^4 - T_a^4)$	$\varepsilon = 0.8^{23)}$

tory, interpolation coefficients were defined between nodal points of FE mesh and CA cells in order to combine the FE and CA calculation in a single model, as shown in Fig. 3.⁷⁾

In Fig. 3, the CA cell, V , with its centre in finite element I , has non-zero interpolation coefficients $\Phi_{V,i}$, $\Phi_{V,j}$ and $\Phi_{V,k}$ with FE nodes i , j and k , respectively. New nucleation is formed in the bulk volume when the local temperature of nucleating cell is below the critical temperature in the given time step. Crystallographic orientation of crystal growth is randomly chosen from predefined orientation classes, and the crystallographic orientation $\langle 100 \rangle$ is selected preferentially.

3. Model Validation

In this part, the composition of the steel is the same as that in Table 1. Firstly, the validation of the finite element model about thermal field was performed by a comparison of the calculated surface temperature and that measured by infrared radiation thermometer at five different locations, as shown in Fig. 4. The results indicate the measured temperature can be well predicted by this model.

Secondly, the validation of the CAFE model was performed by a comparison of the simulated solidification structures and the actual solidification structures under three different conditions, *i.e.*, without MEMS, with MEMS and with MEMS plus intensive cooling. Because the solidification structure in the inner curve side is always different from that in the outer curve side of the continuous casting billet, the sampling position in this study is perpendicular to the left side and the right side, which is also at the longitudinal section, as shown in Fig. 5.

Comparison of the actual solidification structure without MEMS and with MEMS is shown as Fig. 6. When without MEMS, the superheat was 25°C, the casting speed was 1.8 m/min, the specific water ratio was 0.63 L/kg, and the width of equiaxed grain zone was 80 mm (*i.e.*, the distance of its boundary to the centerline was 40 mm). In order to avoid the white band, weak stirring was used (the current is 350 A, the frequency is 2 Hz in the MEMS system). After with stirring, the width of central equiaxed grain zone increased from 80 mm to 90 mm, and the characteristics of centerline segregation also varied.

Comparison of the actual solidification structure with MEMS and with MEMS plus intensive cooling is shown in

Fig. 4. Surface temperature profiles with measured data points.

Fig. 7. Intensive cooling in this study means that the water amounts of foot roller section, the first section and the second section of secondary cooling zone was 1.5 times as normal cooling. After adding intensive cooling, the width of the equiaxed grain zone decreased from 90 mm to 85 mm, and the characteristics of centerline segregation also varied.

Figure 8 shows the simulated solidification structure of billets under the above-mentioned three different conditions using the CAFE method. In this research, the way to determine the CET location was based on Ref. 26). Namely, the location was described as the CET location when the average ratio of the longest axis to the shortest axis in grains at this location was greater than 0.4.²⁶⁾ By using the image analysis software MiVnt, the CET location was determined, and the widths of the simulated equiaxed grains zone without MEMS, with MEMS and with MEMS plus intensive cooling in Fig. 8 were 80 mm, 90 mm and 85 mm, respectively.

When simulating the solidification structure without MEMS, the mean undercooling was determined as 2.5°C, the standard deviation ΔT_σ was determined as 1°C and the maximum nucleation density of volume was determined as $2 \times 10^9 \text{ m}^{-3}$. As for MEMS, two methods have been reported for incorporating its effect into the calculation: changing the thermal conductivity of liquid and changing the nucleation density of volume, and all of these two methods have been adopted in the model.^{1,27)} When with MEMS, the thermal conductivity of solid, *i.e.*, 29.7 W/(m·°C), was used in the zone of solid and the mushy zone with solid fraction (f_s) larger than 0.7, but a 3 times higher thermal conductivity was used in the liquid zone and mushy zone with $f_s < 0.3$, and in the mushy zone with $0.3 \leq f_s \leq 0.7$, thermal conductivity was assumed to change with f_s linearly. At the same time, the maximum nucleation density of volume was changed from $2 \times 10^9 \text{ m}^{-3}$ to $2.5 \times 10^9 \text{ m}^{-3}$. In this way, the solidification structures under the above-mentioned three different conditions were simulated, and the simulated results agreed well with the actual results, as shown in Figs. 6, 7 and 8. Consequently, the established model is effective for simulating the solidification process of the actual continuous casting billet.

Fig. 5. Sampling position of continuous cast billet.

Fig. 6. Comparison of actual solidification structure without MEMS and with MEMS.

Fig. 7. Comparison of actual solidification structure with MEMS and with MEMS plus intensive cooling.

4. Results and Discussion

Based on the validation, the model was used to investigate the influence of superheat and casting speed on the solidification structure and the compactness degree of central equiaxed grain zone in the billet.

4.1. Simulated Solidification Structure under Different Superheats

Figure 9 shows the simulated results for solidification structure under different superheats and casting speeds. Under different superheats, the casting speed and the specific water ratio were the same, *i.e.*, 1.8 m/min and 0.63 L/kg, respectively. Meanwhile, MEMS was used under different superheats. As seen from this figure, the width of the equiaxed grain zone increased with the decrease of the superheat. This is mainly because the number of nucleation cores increases and the temperature gradient at liquid-solid interface decreases. The similar phenomenon was also found in

Ref. 28). The total grain number of whole cross-section of the billet can be computed by the ProCAST software, as shown in Fig. 10. As seen from the figure, the total grain number of the whole cross-section increased with the decrease of the superheat, which can be attributed to the increase in the number of nucleation cores of the whole cross-section during the solidification.

4.2. Simulated Solidification Structure under Different Casting Speeds

In this study, the superheat (25°C), the specific water ratio (0.63 L/kg), the proportions of water amount at different sections in the secondary cooling zone and other parameters were the same, although the total water amount in the secondary cooling zone varied when changing the casting speed. Meanwhile, MEMS was used under different casting speeds. It is also indicated in Fig. 9 that the width of the equiaxed grain zone decreased with the decrease of the casting speed. The reason may be that the cooling intensity

Fig. 8. Simulated solidification structure without MEMS, with MEMS and with MEMS plus intensive cooling.

Fig. 9. Simulated solidification structure under different superheats and different casting speeds.

Fig. 10. Total grain number of whole cross-section of the billet under different superheats.

Fig. 11. Total grain number of whole cross-section of the billet under different casting speeds.

increases with the decrease of the casting speed, which leads to a larger temperature gradient at liquid-solid interface during the solidification. The similar phenomenon was also found in Ref. 29). **Figure 11** shows the comparison of the total grain number of the whole cross-section for different casting speeds. As seen from the figure, the grain number increased with the decrease of the casting speed. This is

Fig. 12. Chosen location of central equiaxed grain zone of the billet under different conditions.

Fig. 13. Simulated solidification structure of central equiaxed grain zone without MEMS, with MEMS and with MEMS plus intensive cooling.

Fig. 14. Simulated solidification structure of central equiaxed grain zone under different superheats and different casting speeds.

mainly because that the cooling intensity increases with the decrease of the casting speed.

4.3. Compactness Degree of Central Equiaxed Grain Zone

For comparison of equiaxed grain zones which have different widths under the above different conditions, the same area in the equiaxed grain zone of the continuous casting billet was chosen to evaluate the compactness degree of equiaxed grain zone. The grain number is indirectly indicative of the grain size or the compactness degree, because the area of studied equiaxed grain zone is the same under different conditions. That is to say, larger grain number means higher compactness degree under the same area. The studied equiaxed grain zones which have the same area under different conditions are defined as central equiaxed grain zone in this study. Because the smallest width of equiaxed grain zones under different conditions was 80 mm in the research, the area of central equiaxed grain zone was chosen as 80 mm × 80 mm, and the locations of the central equiaxed grain zone in the billet under different conditions were the same, as shown in Fig. 12. Meanwhile, the number of grains in central equiaxed grain zone of the billet which could be computed by the ProCAST software was selected as the criterion to measure the compactness degree.

4.3.1. Effect of MEMS and Intensive Cooling on Compactness Degree of Central Equiaxed Grain Zone

Figure 13 presents the comparison of the grain numbers of the central equiaxed grain zone under three conditions, *i.e.*, without MEMS, with MEMS and with MEMS plus Intensive Cooling.

When the MEMS was adopted, the grain number of the central equiaxed grain zone increased from 4976 to 5981, the relative gain for the grain number was about 20%, which means that the compactness degree of central equiaxed grain zone with MEMS was obviously higher than that without MEMS. This is probably because the number of nucleation cores and conduction coefficient in the liquid zone increase using the MEMS.

The intensive cooling here is the same as the above mentioned, which means that the water amounts of foot roller section, the first section and the second section of secondary

cooling zone was 1.5 times as normal cooling. When the MEMS plus intensive cooling was applied, the grain number increased from 5981 to 6242, the relative gain for the grain number was about 4.4%. This can be attributed to the increase of the cooling intensity after using the MEMS plus intensive cooling.

In summary, the compactness degree of the central equiaxed grain zone in the billet with MEMS plus intensive cooling is the greatest among the three different conditions.

4.3.2. Comparison of Compactness Degree of Central Equiaxed Grain Zone under Different Superheats

Figure 14 shows the simulation results of central equiaxed grain zone under different superheats and casting speeds. Figure 15 shows the grain numbers of central equiaxed grain zone under different superheats, which were computed by the ProCAST software based on the results of Fig. 14. As shown in Fig. 15, the grain number decreased with the decrease of the superheat, which means that the compactness degree of central equiaxed grain zone decreased with the decrease of the superheat.

Based on the calculated thermal field results from the previous model using the finite element method, eliminating superheat time, whole solidification time and centre solidification time for the continuous casting billet were obtained, as shown in Fig. 16. In this research, the eliminating superheat time is the time needed for the temperature reduction of molten steel from pouring temperature to liquidus temperature at billet centre (The billet centre is the centre point in the billet, as shown in Fig. 12), the whole solidification time is the time needed for the temperature reduction of molten steel from pouring temperature to solidus temperature at billet centre, and the centre solidification time is the difference between eliminating superheat time and whole solidification time (the time needed for the temperature reduction of molten steel from liquidus temperature to solidus temperature at billet centre). As seen from the Fig. 16, the eliminating superheat time decreased with the decrease of the superheat, the whole solidification time also decreased with the decrease of the superheat, but the centre solidification time increased with the decrease of the superheat. The same trend was also found in Ref. 28). It is noted that the decreasing magnitude of eliminating superheat time is larger than the decreasing magnitude of whole solidifica-

Fig. 15. Grain number of central equiaxed grain zone of the billet under different superheats.

Fig. 16. Eliminating superheat time, whole solidification time and centre solidification time under different superheats.

Fig. 17. Nucleation model of normal distribution.

tion time when decreasing the superheat. This is probably because that the main thermal resistance in the late stage of solidification of the continuous casting billet comes from the solidifying shell, which means that compared with the initial stage of the solidification of the billet, the heat transfer in the late stage of the solidification is not sensitive to the superheat changing.

As for the solidification of equiaxed grain zone, the temperature can be almost considered as the same at different locations during solidification in the model.^{6,19)} Moreover, the nucleation model of normal distribution was used in this simulation, then the nucleation density at different temperatures is determined by Eq. (8).^{6,7,19)} The value of $\frac{dn}{d(\Delta T)}$ is described in Eq. (1).

$$n = \int_0^{\Delta T} \frac{dn}{d(\Delta T)} d(\Delta T) \dots\dots\dots (8)$$

Therefore, the nucleation density n increases with the decrease of the temperature, as shown in Fig. 17.¹⁹⁾ According to the above analysis, for the central equiaxed grain zone of the billet, when increasing the centre solidification time during solidification, the nucleation cores formed in the relatively high temperature region will have longer time to grow, which may lead to smaller space for the formation of new cores in the relatively low temperature region. Consequently, the grain number of the central equiaxed grain zone will decrease with the increase of the centre solidification time. This may be the reason why the grain number of the central equiaxed grain zone will decrease when the superheat decreases, *i.e.*, the centre solidification time increases.

4.3.3. Comparison of Compactness Degree of Central Equiaxed Grain Zone under Different Casting Speeds

Figure 18 shows the comparison of the grain number in central equiaxed grain zone under different casting speeds. It can be seen from the figure that the grain number increases with decreasing the casting speeds, which means that the compactness degree of central equiaxed grain zone increased with decreasing the casting speeds. Figure 19 shows the comparison of eliminating superheat time, whole solidification time and centre solidification time under different casting speeds. The eliminating superheat time, the whole solidification time and the centre solidification time all increased with the increase of the casting speed, as shown in Fig. 19. The same trend was also found in Ref. 29). As shown in Figs. 18 and 19, when the centre solidification time increased with the increase of the casting speed, the grain number in the central equiaxed grain zone would decrease. This mechanism is the same as it obtained under

Fig. 18. Grain number of central equiaxed grain zone of the billet under different casting speeds.

Fig. 19. Eliminating superheat time, whole solidification time and centre solidification time under different casting speeds.

different superheats. So it further indicated that the compactness degree of the central equiaxed grain zone will decrease with the increase of the centre solidification time.

5. Conclusions

In the present work, the solidification structure of the continuous casting billet was simulated using CAFE method. The validation of the model was first achieved by the comparison of the simulated solidification structure and the actual solidification structure under three different conditions, *i.e.*, without MEMS, with MEMS and with MEMS plus intensive cooling. Thereafter, the solidification structure and the compactness degree of the central equiaxed grain zone in the billet under different conditions were studied and the following conclusions can be obtained:

(1) The width of equiaxed grain zone increases with the decrease of the superheat, and decreases with the decrease of the casting speed.

(2) The compactness degree of central equiaxed grain zone in the billet is increased obviously when the MEMS is applied, and is further increased with MEMS plus intensive cooling. In addition, it is also increased when decreasing the casting speed. However, the compactness degree of central equiaxed grain zone is decreased when decreasing the superheat.

(3) The compactness degree of central equiaxed grain zone in the billet is closely related to the center solidification time, *i.e.*, it decreases with the increase of the centre solidification time.

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