Research Article

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Numerical and experimental research on solidification of T2 copper alloy during the twin-roll casting

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Abstract: Based on CAFE theory and KGT model, the twinroll strip casting mathematical model was established to solve the dendrite growth and solidification of T2 copper alloy in the molten pool. The influence mechanism of casting temperature, heat transfer, and other technological conditions on the microstructure of strip was analyzed. The results showed that the liquid metal formed 35 µm chilling layer after touching the rollers, and the layer was consisted of a high number of small and equiaxed crystals. Then some grains would appear close to the newly chilling layer, and grow toward the core of molten pool competitively. The dominant grains mainly grew along the (001) orientation into columnar crystals, and the rest grains that grew out of alignment were eliminated gradually. The number of grains declined, and the radius of columnar grains became coarsening. The Kiss point is a key factor for solidification structure, and the lower location of the Kiss point could limit the growth spaces of columnar crystals, which refined the grains.

Keywords: T2 copper, twin-roll strip casting, dendritic growth, Kiss point

1 Introduction

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Twin-roll strip casting copper alloy process is one of near-net-shape continuous casting technologies. In this

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Xi-Liang Zhang: School of Materials Science and Engineering, Hebei University of Engineering, Handan 056038, China process, liquid metal is injected into the space between two casting rolls, which are rotating oppositely (Figure 1), and the metal copper strip is formed by subrapid cooling, solidification, and rolling. Compared with the traditional process, this process has a lot of advantages such as short production cycle, high efficiency, low energy consumption, what's more, the strips also have the characteristics of fine grains, low segregation, and uniform microstructure [1,2].

However, the processing technology is not mature because of the complex thermophysical field. Cao et al. [3], Han et al. [4], and Nishida et al. [5] had prepared copper alloy strips in laboratory, but the mechanical properties of their strips were very different. Sobrero et al. [6] found that the copper alloy could evolve two kinds of martensitic under quenching, which could greatly improve the tensile strength of the metal (>90 MPa); Ji et al. [7] also pointed out that there was a strong connection between the mechanical behavior and microstructure of copper alloy. Tang et al. [8] found that the macrostructure and microstructure of the strips were directly affected by the casting process, so they believed that the casting process determined the mechanical properties of the strip, such as strength, elongation, and hardness [9], but the influencing mechanism needs to be studied further. Based on the CAFE model, Bo et al. [10] and Yurko et al. [11] considered the competitive growth mechanism of the dendrite tips and grain nucleation, explored the competitive growth and dendrite evolution of aluminum alloy crystals and stainless steel, and analyzed the influence of nucleation on the finally formed structure. However, the rules of copper alloy dendrite evolution by casting process are not clear.

This article obtained 2 mm thick T2 copper strip by φ 265 twin-roll casting mill. The solidification structure of molten pool was obtained by emergency stop (E-stop) process, and its forming rule and evolution mechanism were analyzed. Then, this study established a mathematical model by coupling temperature-flow-macrostructure based on CAFE theory, and the main process parameters of continuous

2 — Zheng Lv et al. DE GRUYTER

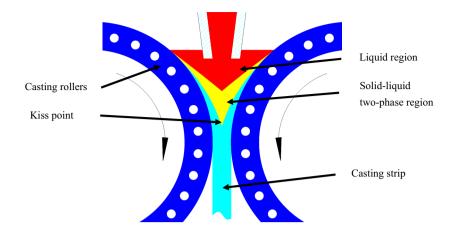


Figure 1: The twin-roll strip casting process.

casting, dendrite growth, and strip microstructure were explored.

2 CAFE mathematical model

The CAFE method is established by the coupling of cellular automata (CA) method and finite element (FE) method. The CA method explains the dendrite growth dynamics and grains crystallization, and it is mainly used to calculate nucleation and dendrite growth, by considering the competitive growth mechanism of dendrite tips. The FE method introduces the differential factors during nucleation and dendrite growth to make the latent heat released effect on the nodes, and the temperature of each node is updated in real time [12].

2.1 Heat transfer model

In the twin-roll strip casting process, the heat transfer between the molten pool and the casting roll is relatively complex. In this calculation, it was assumed that the side seal plate was completely adiabatic during the process, and the flow behavior of liquid metal was described by energy equations, momentum equations, and mass conservation equations [13]. The calculation of the temperature field in the molten pool is mainly based on the heat diffusion equation:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) + Q, \quad (1)$$

where ρ is the metal density (kg·m⁻³), c is the constant pressure specific heat (kJ·kg⁻¹·K⁻¹), t is the time (s), T is the temperature (K), λ is the thermal conductivity (K·m⁻¹), Q is the latent heat of solidification, and x, y, and z are the coordinate of the three directions.

2.2 Nucleation model

It was used to describe the grain density that the continuous and discrete Gaussian distribution function proposed by Rappaz. The grain nucleation density was obtained from the function of nucleation distribution from 0 to ΔT interval (ΔT is the undercooling degree), and the Gaussian distribution $dn/d(\Delta T)$ is given by the following equation:

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

where $d(\Delta T)$ is the unit undercooling, $\Delta T_{\rm max}$ is the mean undercooling, ΔT_{σ} is the standard deviation of undercooling, and $n_{\rm max}$ is the maximum nucleation density.

2.3 Dynamic model of dendritic growth

The KGT model was used to describe the growth of dendrite tip. In the solidification process, thermal undercooling $\Delta T_{\rm c}$, solute undercooling $\Delta T_{\rm c}$, curvature undercooling $\Delta T_{\rm r}$, and kinetic undercooling $\Delta T_{\rm k}$ were contributing factors. Total undercooling $\Delta T = \Delta T_{\rm c} + \Delta T_{\rm k} + \Delta T_{\rm r} + \Delta T_{\rm t}$. Generally, the value of $\Delta T_{\rm k}$, $\Delta T_{\rm t}$, and $\Delta T_{\rm r}$ are negligible for alloys. In this study, the KGT model had to be modified and overfit to obtain the dendrite tip growth rate ν polynomial:

Table 1: Chemical composition of T2 copper

Element	Fe	Pb	S	Bi	Sb	Ni	Cu + Ag
Mass fraction (%)	0.0041	0.0015	0.005	0.001	0.002	0.005	≥99.90

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

where a_2 and a_3 are the grain growth coefficient of the alloy, and ΔT is the undercooling at the dendrite tip.

2.4 Parameters of CAFE model

T2 copper alloy was used in this model (the compositions are shown in Table 1). The casting process parameters are listed in Table 2, where $T_{\rm in}$ is metal casting temperature, $h_{\rm b}$ is strip thickness, v is rolling speed, $h_{\rm t}$ is equivalent heat transfer coefficient between copper roll and molten pool, and L is the molten pool height. Moreover, CAFE model parameters are shown in Table 3, where a_2 and a_3 are polynomial coefficients, $N_{\rm Max}$ is volume nucleation rate, G_{Max} is surface nucleation rate, DT_{m} is volume nucleation average undercooling, $dT_{\rm m}$ is surface nucleation undercooling, DT_s is volume nucleation undercooling variance, and dT_s is surface nucleation undercooling variance.

3 Analysis of experimental and simulation results

This study used the φ 265 × 160 twin-roll casting mill to prepare copper strip. The T2 copper alloy was heated to 1,130°C in the heating furnace and kept warm for 20 min. The casting rolling speed was 12 m⋅min⁻¹. The 2 mm thick copper alloy strip was prepared successfully, and the solidification structure of T2 copper alloy molten pool area was obtained by E-stop process; the solidified structure was eroded with an aggressive agent (20% HCl, 10% FeCl₃, and 70% H₂O), and the macrostructure of T2 molten pool is shown in the Figure 2a.

By the effects of casting rollers, the fine equiaxed crystals thin layers (about 35 µm) are formed on the surface of the casting rollers. Some crystals grow to the core of the molten pool; dendrites have formed λ -fibrous branching $\{\langle 001 \rangle //ND\}$ without bending; then the volume of grains increases and the number of grains declines; and the radius of columnar crystal is about 0.38 mm in the end. The thickness of columnar crystal layer is about 1.5-5 mm, and the dendrites orientation tends to be consistent. After the columnar crystals grow to the core of molten pool, the dendrites evolve into equiaxed crystal.

Figure 2b shows the solidification structure of T2 copper alloy calculated by CAFE mathematical model. According to the results, the metal material is flow state at start time. When the liquid T2 copper contact the roller surfaces, a quenching layer would be formed immediately. Because of the large temperature difference between the casting roller surfaces and the liquid metal, the quenching layer would form many high-density crystal nucleus. However, these crystal nuclei cannot grow fully due to the small space of the quenching layer and then form equiaxed crystal finally.

Some nuclei near the layer are free from the influence of the quenching and grow along the orientation, which is the opposite of heat flow. What's more, the grains that grow out of the orientation are eliminated gradually because of competitive growth, so the number of grains decline, and the radius of columnar grains would be

Table 2: Process parameters of casting strip

	T _{in} (°C)	$h_{\rm t}~(\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{^oC}^{-1})$	v (m·min ⁻¹)	L (mm)	h _b (mm)
Value	1,130-1,170	4,000-7,000	12	50	2

Table 3: Parameters of mathematical model

Parameter	$N_{\rm max}/(1\cdot {\rm m}^{-3})$	DT _m /K	DT _s /K	$G_{\rm max}/(1\cdot {\rm m}^{-3})$	d <i>T</i> _m /K	d <i>T</i> ₅/K
Value	2×10^{12}	1.5 × 10 ¹	1×10^{1}	1×10^{12}	1.5 × 10	1 × 10 ¹

coarsening. The dendrites continue to grow until to the area near the Kiss point, the growth of columnar crystals is inhibited by the influence of flow field, element distribution, and unstable supercooling degree [14]. Most nuclei grow isotropically at the liquid-solid phrase area near the Kiss point. Therefore, some equiaxed grains appear at the core of the molten pool and form the central equiaxial layer of the copper strips. What's more, when the metal near the gap is at the temperature of recrystallization, the rolling effect may result in dynamic recrystallization, which could refine the strip structure further [15,16].

The dendrite growth trend, grain appearance, and texture distribution of the mathematical model are basically consistent with the experimental results, which also verify the CAFE model in this study.

4 Effect of casting process parameters on microstructure

4.1 Effect of casting temperature

This study also explores the influence mechanism of casting temperature on the solidification structure. The casting temperatures are 1,130, 1,150, and 1,180°C. The simulation results of solidification structure are shown in Figure 3.

With the increasing of casting temperature, the chilling layer supercooling degree is reducing, and the nucleation rate in the metal melt is decreasing, which

results in a slight increase in the equiaxed crystal size of the chilling layer. The temperature gradient in the molten pool is rising with the increasing of casting temperature, which promotes the tip growth rate of columnar crystals. However, due to the reduction of the Kiss point, the distance between the roller surfaces and the Kiss point is reduced, which limits the growth spaces of columnar crystals. The columnar crystals have reached the Kiss point area before fully growing. The proportion of columnar crystals in strip increases, and the grains are also more finer. In addition, because the solidification rate is slowed down with the increase of casting temperature, the flow field has a stronger influence on the dendrite growth, and the dendrite deflection angle also increases accordingly (as shown in Figure 4).

4.2 Effect of interfacial heat transfer

The material and roughness of the casting roller and other factors could affect its heat transfer rules. This study explores the influence of the interface heat transfer coefficient on the solidification structure based on the CAFE model, and the dendrite results are shown in Figure 5, when the interface heat transfer coefficients are 4,000, 5,500, and 7,000 W·m⁻²·k⁻¹.

With the enhancement of the interface heat transfer, the Kiss point position moves up, the proportion of the solidification area increases significantly. The columnar crystals growth spaces greaten, which is not conducive to



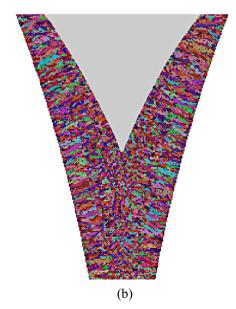


Figure 2: Solidification structure and simulation results of T2 copper molten pool area. (a) T2 copper solidification structure and (b) simulation results of T2 copper.

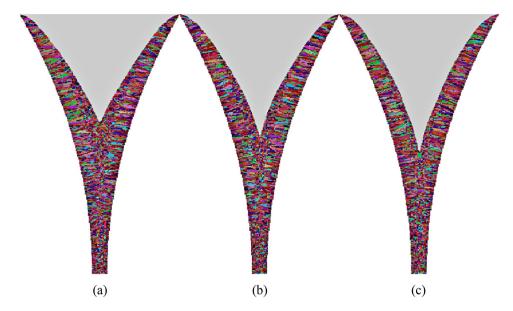


Figure 3: Solidification microstructure of molten pool at different casting temperatures. (a) 1,130°C, (b) 1,150°C, and (c) 1,180°C.

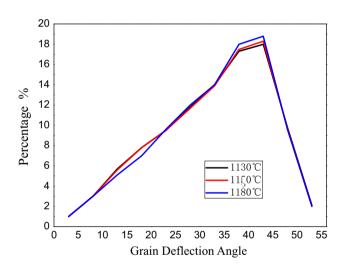


Figure 4: Distribution of grain deflection angle at different casting temperatures.

refine grains, and might result in coarse columnar crystals. CAFE results show that the columnar crystals dominate the solid phase area in the melt pool when the heat transfer is increased. The low heat transfer coefficient makes the Kiss point close to the roll gap. As the solid phase area move down, columnar crystals growth spaces reduce, which results in grains stop growing before coarsening, and it is helpeful to refine grains effectively. In addition, the low heat conductivity could keep the melt near the outlet on high temperature relatively, which is conducive to the dynamic recrystallization at the deformation area. Copper alloy has the properties of low

lamellar fault energy and high dislocation density of substructure. Gleeble results [17] also showed that new grain cores are easily formed at the grain boundary of the parent crystal to stimulate dynamic recrystallization at the temperature of 800–980°C, and the grains increase in amount and form equiaxed structure, which further refines the solidified macrostructure and microstructure. Dynamic recrystallization could be stimulated by increasing the deformation temperature and reducing the strain rate [18]. However, low heat transfer would reduce the production efficiency. Therefore, reasonable interfacial heat transfer of the casting roller could refine the microstructure and improve the mechanical properties of the strips.

4.3 Effect of molten pool height

Based on the CAFE model, this article also studies the height effect of molten pool on microstructure, and set height of the molten pool are 45, 50, and 55 mm, by keeping other conditions unchanged, and the results are shown in the Figure 6.

With the increase of molten pool height, the proportion of solid phase area is increasing gradually. Due to the increase of Kiss point, the columnar crystal become coarsening when it grows to the core of the melt pool, and the coarsening phenomenon is very obvious with the Kiss point moving up.

According to the results, columnar crystals dominate in the solid phase area when the liquid level height 6 — Zheng Lv et al. DE GRUYTER

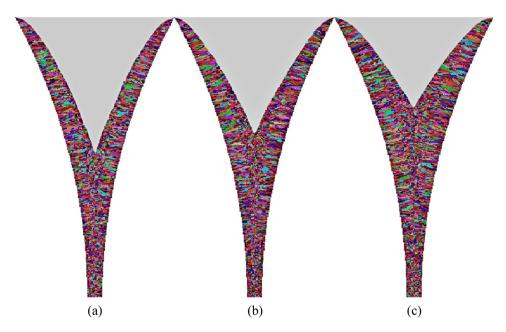


Figure 5: Solidification structure at different interfacial heat transfer coefficients. (a) $4,000 \text{ W} \cdot \text{m}^{-2} \cdot \text{k}^{-1}$, (b) $5,500 \text{ W} \cdot \text{m}^{-2} \cdot \text{k}^{-1}$, and (c) $7,000 \text{ W} \cdot \text{m}^{-2} \cdot \text{k}^{-1}$.

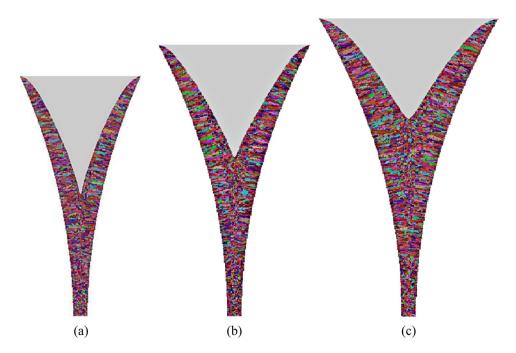


Figure 6: Solidification microstructure at different molten pool heights. (a) 45 mm, (b) 50 mm, and (c) 55 mm.

reduces, and only a small amount of equiaxed crystals appear in the area near the Kiss point. As the molten pool height increases, and the flow area enlarges [19], the proportion of equiaxed crystals in the strip would increase accordingly. Therefore, the height of liquid level and Kiss point could change the proportions of columnar crystals and equiaxed crystals.

5 Conclusion

The strip of T2 copper alloy was successfully obtained by the φ 265 × 160 twin-roll casting mill. A mathematical model of casting molten pool was established based on CAFE theory and KGT theory, which agreed with the experimental results well. Moreover, the microstructure

distribution, grains, and dendrite evolution mechanism were analyzed.

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Based on the mathematical model and experiment results, the solid phase area in the melt pool is dominated by columnar crystals, and the columnar crystals will be coarsening gradually during its growth process. Kiss point is a key factor of the solidification structure, and the methods of moving Kiss point down could limit the growth spaces of columnar crystal and refine the grains of strip, such as improving casting temperature, reducing the heat transfer and melt pool height. When the liquid level and Kiss point moves up, the equiaxed grains at the core of strip will increase.

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