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Numerical simulation of the solidification process of Cu-0.45% Sn alloy in upward continuous casting

Siming Hua, Pingze Zhang, Zili Liu and Chao Lu
1 College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing, 210000, People’s Republic of China
2 China Railway Construction Electrification Bureau Group Kangyuan New Material Co., Ltd, Jinjiang, 214500, People’s Republic of China
E-mail: zhangpingze@nuaa.edu.cn

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Abstract

Upward continuous casting is the key process in the production of contact wire for electric railway. The stability of the process and the quality of the produced billet are directly related to the performance of the contact wire and ultimately the safety of the railway operation. To ensure the quality of continuous-casting billet, the optimal process conditions need to be experimentally determined, which is not only costly but also time-consuming. To facilitate this optimisation process, the simulation of the solidification process of Cu-0.45%Sn alloy in upward continuous casting is described in this paper to assess the influence of casting temperature, upward continuous casting speed, the time of stop-pull, and primary cooling water flow rate on the liquid core length. The results show that the speed of upward continuous casting exhibits a great influence on the liquid core length, while the casting temperature has only little influence. In a certain range of the ratio of stopping time to pulling time, the quality of updraft Cu-0.45%Sn alloy billet is improved; exceeding a certain ratio results in a decrease of the surface quality and an increase in internal and external defects. The liquid core length of the continuous casting rod decreases with the increase of the cold water flow rate, and properties are stable when the flow rate reaches 0.45 m³·h⁻¹. For a billet with a diameter of 20 mm, the appropriate upward continuous casting process parameters are determined as a casting temperature of 1175 °C, an upward continuous casting speed not exceeding 25 cm·min⁻¹, a ratio of stopping time to pulling time not exceeding 2.13, and a cooling water flow rate of 0.45 m³·h⁻¹.

1. Introduction

The upward continuous casting process was invented by the Finnish company Outokumpu in the late 1960s [1–3]. In the upward continuous casting system, solidification occurs inside a submerged die after which the solid rod is pulled vertically upward [4]. The main advantages of upward continuous casting are: (1) molten-metal feeding can be controlled easily and accurately; (2) the coolers, including the graphite die, can be replaced separately; and (3) different shapes and sizes of billets can be cast in the same furnace.

While a considerable amount of research has been conducted on continuous casting and its mathematical model [5–8], upward continuous casting has been investigated to a lesser extent. Yuan [9] and Xu [10] prepared high-strength and high-conductivity Cu–Cr–Ag alloy by upward continuous casting. Yuan found that the columnar grains produced by this method can maintain ductility and enhance the strength of the alloy during the ageing process. The macrostructure of the Cu–Ag–Cr alloy rod along the longitudinal section was composed of equiaxed grains and columnar grains. The columnar grains in the centre of the casting rod were parallel to the direction of the casting billet, and the remaining grains are oriented at an angle of 45° to the casting direction, which is different to the typical macrostructure observed in traditional casting technology. The grains of Cu–Cr–Zr–Ti alloy prepared by upward continuous casting were coarse and exhibited clear dendritic segregation, and the crystal orientation of the alloy proceeded in the direction of decreasing temperature [11].

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Sun [12, 13] calculated the cooling water flow under the condition of heat balance and analysed the as-cast microstructure of upward continuous-casting Cu–Mg alloy rod under different process parameters. The temperature of the top Cu–Mg alloy rod was identified as a useful indicator to assess the cooling effect of the mould, which was appropriate when this temperature was below 100 °C; the grain size decreased with increasing cooling intensity and decreasing sectional area of the Cu–Mg alloy rod, since decreasing area size improves the cooling effect. Furthermore, the grains of Cu–Mg alloy coarsened when the upward speed was too fast. The optimum process parameters of upward continuous casting of Cu–Mg alloy rods were an upward speed of 261 mm·min⁻¹ and a cooling water flow of 25–30 l·min⁻¹. In addition, a temperature field model of the Cu–Mg alloy rod during upward continuous casting was developed to simulate the temperature field and to investigate the effects of casting temperature, upward speed, and top temperature on the temperature field of the Cu–Mg alloy rod. As a result, the length of the liquid core increased with increasing casting temperature and increasing upward speed.

Upward continuous casting is the key process in the production of contact wire for electric railway [14–17], and the stability of the process to manufacture billets is directly related to the performance of the contact wire and ultimately to the safety of the railway operation. To ensure the quality of continuous-casting billets, the optimum process conditions are determined through experiments, which is both costly and time-consuming. As reported in this paper, to assist in the development of a more efficient optimisation process, the solidification process of Cu-0.45%Sn alloy in upward continuous casting is simulated using ProCAST software to determine the influence of casting temperature, upward continuous casting speed, the time of stop-pull, and primary cooling water flow rate on the liquid core length and solid fraction.

2. Model and boundary conditions

2.1. Hypothesis and heat transfer equation

Since many factors contribute to the solidification process of upward continuous casting, the physical model of the solidification process of this casting method was partially simplified, for the convenience of simulation calculations, as follows:

(1) Using steady-state simulation, the temperature field is only considered when it reached stability under the set boundary conditions.

(2) Forced convection movement of the liquid phase occurs when the copper liquid enters the graphite mould. Therefore, considering the convective heat transfer of the liquid phase in the mould, the liquid phase area is treated as a quasi-solid, and the effective thermal conductivity is set to a large value [18], using 15000 W·m⁻²·K⁻¹ in this paper.

(3) All components were isotropic, and the physical properties were only related to temperature.

(4) Since the Sn content of the molten Cu-0.45Sn alloy is 0.45%, only liquid-solid phase transition occurs during the solidification process, and no other phase transitions take place. Except for the latent heat of crystallization, other latent heat of phase transformation was not considered.

(5) The primary cooling zone and secondary cooling zone (air cooling zone) distributed uniformly in circumferential direction, and the cooling intensity remained the same in this direction.

(6) Since the heat transfer in the drawing direction of the billet is much smaller than in the radial direction, the heat transfer in the drawing direction is ignored [19], and only the radial heat transfer is considered. The billet heat transfer was two-dimensional in radial direction.

The billet was selected as the research object under the above assumptions, as shown in figure 1. The simplified two-dimensional heat transfer control equation [20, 21] was as follows:

\[ \frac{\partial T}{\partial t} = \frac{\lambda}{\rho c_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \]  

(1)

\[ c_p = c - L \left( \frac{df_s}{dT} \right) \]  

(2)

where \( \lambda \) is the thermal conductivity of the billet (W·m⁻¹·K⁻¹); \( \rho \) is the density of liquid copper (kg·m⁻³); \( T \) is the temperature of liquid copper (°C); \( c_p \) is the equivalent specific heat capacity of liquid copper (J·kg⁻¹·K⁻¹); \( c \) is the specific heat capacity of liquid copper (W·m⁻³·K⁻¹·°C⁻¹); \( f_s \) is the solid fraction (%); and \( L \) is the latent heat of solidification (J·K⁻¹).
2.2. Geometric model and meshing

The process principle of upward continuous Cu-0.45%Sn alloy casting is shown in figure 1(a). In the process, electrolytic copper and tin ingot are melted and mixed evenly in the melting channel of the induction furnace to form a molten copper alloy, which is kept warm in the furnace body; during the upward continuous casting, the molten copper alloy first enters the graphite mould, and then, copper alloy rod, is obtained from the liquid through the cooling system; material continuously moves upward under the action of a mechanical device. As a result, the molten copper alloy continuously enters into part 8 and finally forms a continuous copper alloy rod of large length.

In the above process, the casting temperature, cooling strength, and casting speed of molten copper alloy affect the quality of the continuous-casting billet. To fully consider the influence of various factors on this material, the region of solidification and cooling temperature change of Cu-0.45%Sn alloy was defined as the research object, while the molten Cu-0.45%Sn alloy and rod, the graphite mould, and the water-cooled copper sleeve were considered as the simulation objects. The 3D geometric model is shown in figure 1(b). The total length of the model was 400 mm, the diameter of the rod billet were 8 mm, 20 mm and 32 mm respectively. The length of the graphite mould was 95 mm, the length of the first cooling water copper sleeve was 65 mm, and the length of the second cooling zone was 305 mm. All models were designed according to the real geometric size of the crystallizer. Firstly, a 3D geometric model was created in Unigraphics NX, and then Meshcast software was used to divide face mesh and volume mesh.

2.3. The physical properties

Table 1 lists the physical properties of Cu-0.45%Sn alloy, where the enthalpy and density are functions of temperature. After importing the composition data of Cu-0.45%Sn alloy into ProCAST, the function curve of enthalpy and density is generated by using its built-in database.

2.4. Setting of initial and boundary conditions

The initial temperatures of the Cu-0.45%Sn alloy rod, the graphite mould, and the copper sleeve are set to the casting temperature, 200 °C, and 30 °C, respectively.

Due to the different characteristics of heat transfer at the different boundary regions of the geometric model of upward continuous casting, the heat conduction in the solidification process of this casting method needs to be analysed. As shown in figure 2 (a), the boundary conditions applied in the temperature field analysis are set as follows. Because the heat conduction of the cross-section of the continuous-casting billet is much lower than
that of the circumferential surface, boundary 1 is set as the adiabatic boundary. Boundary 2 is the constant-
temperature boundary, which the temperature is set as the casting temperature of Cu-0.45%Sn alloy. Boundary 3 is the contact interface between Cu-0.45%Sn alloy billet and air, while the heat transfer coefficient of copper tube, between Cu-0.45%Sn alloy billet and air, as well as the temperature of the copper tube are set. Boundary 4 is the temperature boundary of cooling water, and the primary cooling water temperature and heat transfer coefficient \( h \) are set.

2.5. Interfacial heat transfer coefficient

Figure 2(b) is a schematic diagram of the interfaces of the geometric model. Interface I is the contact interface between Cu-0.45%Sn alloy billet and graphite mould. During the solidification process of the molten alloy, the billet shrinks, resulting in an air gap between the billet and the graphite mould. As the temperature of the billet decreases gradually, within a distance from the solidification to the graphite mould outlet, the width of the air gap between the billet and the inner surface of the mould increases in axial direction. As the heat transfer coefficient \( h \) of interface I changes with the solidification time and the heat transfer of the air gap is considered as the heat transfer of air, the heat transfer coefficient \( h \) of interface I decreases significantly in the early stage of solidification and remains relatively stable thereafter [22]. In this paper, based on the actual billet diameter measured at the outlet of the mould, the width of the air gap in the mould [23] is calculated according to equation (3), while the heat transfer coefficient [23] at different temperatures is calculated according to equation (4). The calculation results are listed in table 2.

\[
\Delta T = \frac{\alpha d_0 \Delta T}{2}
\]

where \( d \) is the air gap width (mm); \( \alpha \) is the linear shrinkage coefficient (K\(^{-1}\)); \( d_0 \) is the size before shrinkage (mm); and \( \Delta T \) is the temperature change (K)

| Parameters                          | Value   |
|-------------------------------------|---------|
| Density / (kg·m\(^{-3}\)) at 25 °C | 8924    |
| Density / (kg·m\(^{-3}\)) at 1082 °C | 7993    |
| Specific heat / (J·(kg·°C\(^{-1}\)) | 385     |
| Enthalpy / (kJ·kg\(^{-1}\)) at 25 °C | 13.53   |
| Enthalpy / (kJ·kg\(^{-1}\)) at 1082 °C | 665.41  |
| Melting point / °C                  | 1082    |
| Diameter of rod / mm                | 20      |
| Length of rod / mm                  | 400     |

Figure 2. Schematic diagrams of boundaries (a) and interfaces (b).
Table 2. Values of air gap width and heat transfer coefficient between different diameters Cu-0.45%Sn alloy rod and internal surface of graphite die at different temperatures.

| Temperature (K) | Thermal conductivity of air (W m\(^{-1}\) K\(^{-1}\)) | Width of air gap (mm) | Heat transfer coefficient (W m\(^{-1}\) K\(^{-1}\)) |
|-----------------|---------------------------------|----------------------|----------------------------------|
|                 | \(0.0267\)                       | \(0.043\) \(0.043\) \(0.043\) | \(0.039\) \(0.039\) \(0.039\) |
| 303             |                                 | \(0.108\) \(0.108\) \(0.108\) | \(160\) \(160\) \(160\)     |
| 323             |                                 | \(0.167\) \(0.167\) \(0.167\) | \(160\) \(160\) \(160\)     |
| 373             |                                 | \(0.119\) \(0.119\) \(0.119\) | \(160\) \(160\) \(160\)     |
| 573             |                                 | \(0.186\) \(0.186\) \(0.186\) | \(160\) \(160\) \(160\)     |
| 773             |                                 | \(0.254\) \(0.254\) \(0.254\) | \(160\) \(160\) \(160\)     |
| 873             |                                 | \(0.322\) \(0.322\) \(0.322\) | \(160\) \(160\) \(160\)     |
| 973             |                                 | \(0.405\) \(0.405\) \(0.405\) | \(160\) \(160\) \(160\)     |
| 1073            |                                 | \(0.498\) \(0.498\) \(0.498\) | \(160\) \(160\) \(160\)     |
| 1173            |                                 | \(0.602\) \(0.602\) \(0.602\) | \(160\) \(160\) \(160\)     |
| 1253            |                                 | \(0.717\) \(0.717\) \(0.717\) | \(160\) \(160\) \(160\)     |
| 1273            |                                 | \(0.846\) \(0.846\) \(0.846\) | \(160\) \(160\) \(160\)     |
| 1323            |                                 | \(1.000\) \(1.000\) \(1.000\) | \(160\) \(160\) \(160\)     |
| 1355            |                                 | \(1.165\) \(1.165\) \(1.165\) | \(160\) \(160\) \(160\)     |

\[ h = \frac{\lambda}{d} \]  

where \(h\) is the interfacial heat transfer coefficient (W m\(^{-2}\) K\(^{-1}\)), and \(\lambda\) is the thermal conductivity of air (W m\(^{-1}\) K\(^{-1}\)).

Since, according to previous research [24], the typical value of the heat transfer coefficient between liquid metal and die is found in the range of 10000–20000 W m\(^{-2}\) K\(^{-1}\), the heat transfer coefficient between molten Cu-0.45%Sn alloy and the graphite die is set at 15000 W m\(^{-2}\) K\(^{-1}\) in this paper.

Interface II is the contact interface between the copper sleeve and graphite mould, which are in close contact. Liu et al [22] calculated the heat transfer coefficient of Cu in close contact with the graphite mould as 2400–2600 W m\(^{-2}\) K\(^{-1}\), and, accordingly, the heat transfer coefficient of interface II is set as 2500 W m\(^{-2}\) K\(^{-1}\) in this study.

2.6. Calculation of boundary heat transfer coefficient of primary cooling water

As shown in figure 2(b), interface III is the primary cooling water boundary. The corresponding heat transfer coefficient is calculated according to equation (5) [25]:

\[ h_{Nu} = \frac{\lambda N_{Nu}}{d_e} \]  

where \(h_{Nu}\) is the heat transfer coefficient of the primary cooling water interface; \(N_{Nu}\) is the Nusselt number; \(\lambda\) is the thermal conductivity of water; and \(d_e\) is the equivalent diameter.

\(N_{Nu}\) and \(d_e\) are calculated according to equations (6) and (7) [26]:

\[ N_{Nu} = 0.023 R_e^{0.8} P_r^n \]  

where \(R_e\) is the Reynolds number and \(P_r\) is the Prandtl number; when the fluid is heated, \(n\) equals 0.4.

\[ d_e = \frac{4A}{P} \]  

where \(A\) is the cross-sectional area of the non-circular channel, and \(P\) is the wetted perimeter. In this paper, the difference between the diameter of the inner tube and the outer tube is 10 mm, and the equivalent diameter is 10 mm.

Due to the large number of process parameters for upward continuous casting, many experiments are required to study the relationship between liquid core length and process parameters. Orthogonal experimental design is a design method for studying multi-factor and multi-level problems, in which some representative points from the overall test are selected for testing based on their orthogonality. These representative points exhibit ‘uniform dispersion’, and the characteristics of ‘comparable and neat’ render this method a highly efficient, fast, and economical experimental design method.

In the process of upward continuous casting, the process parameters mainly include casting temperature, upward continuous casting speed, the ratio of stopping time to pulling time, primary cooling intensity, billet diameter, and graphite mould size. In this paper, an orthogonal method is used to design a two-factor two-level experiment. According to actual production experience, two factors are selected, casting temperature and continuous casting speed; two different casting temperatures are selected: 1135 °C and 1215 °C; for the models
with billet diameters of 20 mm and 32 mm, two levels of continuous casting speed are selected: 5 cm min\(^{-1}\) and 25 cm min\(^{-1}\); for the model with a billet diameter of 8 mm, considering the production efficiency, two levels of continuous casting speed are selected: 30 cm min\(^{-1}\) and 160 cm min\(^{-1}\).

3. Simulation and result analysis

To study the influence of the upward continuous casting process parameters on the solidification process of Cu-0.45%Sn alloy rod, the software program ProCAST is used to simulate the solidification process in upward continuous casting of a rod with diameters of 8 mm, 20 mm and 32 mm. The typical proportion of the solid phase is shown in figure 3.

The physical significance of the index representing the simulation results is the liquid core length L: the length in the centre of the billet from the mould liquid level to the liquid phase solidification point, as shown in figure 3.

3.1. Optimization of the upward continuous casting process

The speed and temperature of upward continuous casting are important factors that affect the quality and production rate of a continuous-casting rod. In this paper, the influence of these two factors on upward continuous casting of Cu-0.45%Sn alloy rod is studied using an orthogonal experiment. Table 3 lists the numerical simulation results (liquid core length) of different processing parameters.

The liquid core length is the distance from the liquid level of the mould to the solidification point of the liquid phase in the centre of the billet [27], which is a very important parameter in continuous casting production. It directly reflects the cooling condition of the billet and the rationality of upward continuous casting speed. Research on the liquid core length is of great significance for increasing the continuous casting speed and improving the quality of the billet. Increasing the liquid core length can prolong the heating time of
the billet in the casting mould, increase the casting mould temperature, reduce the temperature difference between the billet and the casting mould, effect a slower temperature drop of the billet, reduce the thermal stress of the billet, and improve its quality [28]. For the upward continuous casting process, the molten copper mainly flows upwards by the pressure difference formed by the depth of the mould inserting the copper liquid. When the liquid core length exceeds the height from the inlet liquid level of graphite mould to the liquid level of copper alloy [29], the stable working conditions of upward continuous casting are interrupted, resulting in billet defects. Referring to table 4, at the same casting temperature, the liquid core length is still relatively small although the continuous casting speed of the model with a diameter of 8 mm is much higher than that of the model with a diameter of 20 mm or 32 mm. Consequently, for the 8 mm diameter billet, other parameters such as the shape of the mould and cooling water flow must be adjusted to ensure the quality of the cast billet and save water resources. In addition, for a billet with a diameter of 32 mm, when the continuous casting speed is 25 cm min$^{-1}$, the liquid core length even exceeds the length of the graphite mould (95 mm, that is, the height from the inlet liquid level of graphite mould to the liquid level of copper alloy), which will lead to casting defects, porosity, and shrinkage.

The range analysis results are listed in table 4, in which $k_1$ and $k_2$ are the averages of the experimental results (liquid core length) of the respective factors at different levels, and $R$ is the difference between $k_1$ and $k_2$. A greater value of $R$ corresponds to a greater influence of the level change of this factor on the experimental results. According to the magnitude of $R$, the priority of the factors can be judged.

The numerical simulation results (liquid core length) of the geometric models with the diameters of 8 mm, 20 mm and 32 mm show that $R_8$ is 6.99 mm, 16.45 mm and 25.45 mm; $R_{20}$ is 17.28 mm, 36.34 mm and 50.38 mm, respectively. This shows that under the otherwise same conditions, with increasing rod diameter, the influence of the casting temperature and the upward continuous casting speed on the length of the liquid core increases. In addition, the value of $R_k$ under different rod diameters is twice that of $R_{14}$, indicating that the upward continuous casting speed is the main factor, and the casting temperature is the secondary factor. For a better presentation of the influence of process parameters on the simulation results, the range value is drawn into the effect curve. Figure 4 illustrate the main effect diagram of liquid core length for different rod diameters. The steeper upward continuous casting speed line implies a greater impact on liquid core length than that of casting temperature.

| Diameter of rod (mm) | No. | Casting temperature ($^{\circ}$C) | Upward continuous casting speed (cm-min$^{-1}$) | Liquid core length (mm) |
|----------------------|-----|---------------------------------|-----------------------------------------------|------------------------|
| 8                    | 1   | 1135                            | 30                                            | 20.06                  |
|                      | 2   | 1215                            | 30                                            | 24.03                  |
|                      | 3   | 1135                            | 160                                           | 34.32                  |
|                      | 4   | 1215                            | 160                                           | 44.34                  |
| 20                   | 1   | 1135                            | 5                                             | 32.28                  |
|                      | 2   | 1215                            | 5                                             | 45.16                  |
|                      | 3   | 1135                            | 25                                            | 65.05                  |
|                      | 4   | 1215                            | 25                                            | 85.06                  |
| 32                   | 1   | 1135                            | 5                                             | 58.79                  |
|                      | 2   | 1215                            | 5                                             | 73.02                  |
|                      | 3   | 1135                            | 25                                            | 97.96                  |
|                      | 4   | 1215                            | 25                                            | 134.62                 |

### Table 4. Ranges of simulation results shown in table 3.

| Diameter of rod (mm) | Factor                          | Casting temperature ($^{\circ}$C) | Upward continuous casting speed (cm-min$^{-1}$) | Assessment index of results: liquid core length (mm) |
|----------------------|---------------------------------|---------------------------------|-----------------------------------------------|---------------------------------------------------|
|                      |                                 |                                  |                                               | $k_1$ | $k_2$ | $R$ |
| 8                    | Casting temperature A ($^{\circ}$C) | 27.18                           | 34.14                                         | 6.99  |
|                      | Upward continuous casting speed B (cm-min$^{-1}$) | 22.04                           | 39.32                                         | 17.28 |
| 20                   | Casting temperature A ($^{\circ}$C) | 48.66                           | 65.11                                         | 16.45 |
|                      | Upward continuous casting speed B (cm-min$^{-1}$) | 38.71                           | 75.05                                         | 36.34 |
| 32                   | Casting temperature A ($^{\circ}$C) | 78.36                           | 103.81                                        | 25.45 |
|                      | Upward continuous casting speed B (cm-min$^{-1}$) | 65.9                            | 116.28                                        | 50.38 |
For higher production efficiency, it is necessary to improve the billet drawing speed and casting temperature during upward continuous casting. Higher drawing speed can enhance the billet surface quality. However, the drawing speed has an important impact on the heat transfer and solidification process, and the liquid core length is directly proportional to the drawing speed [30]. When the drawing speed increases, the residence time of liquid copper in the graphite mould decreases, the liquid core length of the billet increases, the temperature of the billet shell increases, and the fracture strength of the billet shell decreases. Once the friction between graphite mould and billet is greater than the fracture strength of the billet shell, cracks and other defects will appear in the billet shell. In addition, excessive drawing speed will also increase impurity segregation and microstructure porosity in the billet [31]. Therefore, there is a maximum drawing speed [32] under certain mould length, temperature gradient, and cooling conditions. Casting temperature has an important influence on the billet quality, and higher casting temperature is beneficial for improving drawing speed and production efficiency. At low casting temperatures, the alloy liquid at the front end of crystallization easily solidifies after cooling, fluidity becomes poor, and filling is difficult. With the increase in casting temperature, fluidity of the alloy improves, and atomic spacing attraction as well as melt viscosity decrease. Furthermore, an increased casting temperature improves the superheat of the alloy solution, prolongs alloy solidification time, and is conducive to the improvement of melt fluidity [33]. However, excessive casting temperature increases the shrinkage of the alloy as well as the solubility of gas in liquid metal and the number of defects such as porosity, which easily forms inside the casting [34, 35]. While the casting temperature of oxygen-free copper and high copper alloy in upward continuous casting is generally about 1150 °C–1180 °C [36, 37], the casting temperature should be as high as possible within a certain range considering the viscosity of Cu–Sn alloy melt and upward feeding resistance.

Based on the above analysis, the liquid core length is relatively short for the 8 mm billet. The selected boundary conditions, casting temperature, and upward continuous casting speed of the model in the numerical simulation are obviously not the optimal combination. Thus, the cooling conditions and geometric model parameters need to be further adjusted. For a 20 mm billet, the optimal casting temperature is 1175 °C, and the upward continuous casting speed is 25 cm min$^{-1}$. After setting the optimal parameters, a simulation is performed to obtain a liquid core length of 71.3 mm. For a 32 mm billet, the optimal casting temperature and
upward continuous casting speed are 1175 °C and 15 cm min\(^{-1}\), respectively. After setting the optimal parameters, the simulation results show that the liquid core length is 88.3 mm.

3.2. Effect of the ratio of stopping time to pulling time on the upward continuous casting process

Drawing speed, the ratio of stopping time to pulling time, and stop-draw period are important process parameters of upward continuous casting, as shown in equations (8)–(10).

\[ t_s + t_p = t \]  \hspace{1cm} (8)
\[ \frac{t_s}{t_p} = n \]  \hspace{1cm} (9)
\[ v = \frac{u}{1 + n} \]  \hspace{1cm} (10)

In these equations, \( t_s \) is the stop time, \( t_p \) is the pull time, \( t \) is the stop-draw period, \( n \) is the ratio of stopping time to pulling time, \( v \) is the upward continuous casting speed, and \( u \) is the drawing speed. Therefore, if the upward continuous casting speed is set to a fixed value, the ratio of stopping time to pulling time will determine the other two parameters.

In this paper, the upward continuous casting speed is set at 25 cm min\(^{-1}\), casting temperature is 1175 °C, billet diameter is 20 mm, and stop-draw period is 1s. ProCAST is used to simulate the upward continuous casting process of Cu-Sn alloy under different ratios of stopping time to pulling time. The results, shown in figure 5, demonstrate that the liquid core length of the Cu-0.45%Sn alloy billet increases with increasing ratio of stopping time to pulling time. Furthermore, when this ratio is less than 2.13, the liquid core length increases from 52 mm to 72 mm. As the reason for this result, with increasing ratio of stopping time to pulling time, the drawing time becomes shorter in the same stop-drawing cycle, and to maintain the constant continuous casting speed, the instantaneous speed of drawing increases, resulting in the decrease of cooling intensity and the increase of liquid core length. At ratios greater than 2.13, the liquid core length increases from 72 mm to 112 mm, which exceeds the length of the mould, resulting in the increase of quality defects on the surface and inside the billet.

In addition to ratios of stopping time to pulling time, the process conditions for setting the billet were consistent with the numerical simulation conditions, and the samples shown in figure 6 were prepared. Figures 6(a) and (b) show the surface of billets and the tensile fracture morphology of the upward continuous-casting billets at different ratios of stopping time to pulling time. The ratio of stopping time to pulling time of the upper sample in figures 6(a) and (b) is 2.13. This ratio is 3.54 for the lower sample in figure 6(a), and transverse cracks appear at the red mark. Because the surface of the billet can be rapidly cooled and solidified when the drawing speed is fast while the internal cooling and solidification are slower, the surface of the billet is subjected to shrinkage stress, and surface transverse cracks appear.

The ratio of stopping time to pulling time of the lower sample in figure 6(b) is 7.33, shrinkage holes appear in the red circle in the centre of the billet, the instantaneous speed of pulling is too fast, and the rising speed of the copper alloy liquid entering the graphite mould under the upward pressure will not keep up with the drawing.

\[ \text{Figure 5. Effect of stopping time to pulling time ratio on the liquid core length in continuous casting.} \]
In summary, under this process condition, when the liquid core length is greater than 86 mm, the billet will exhibit quality defects.

3.3. Influence of primary cooling water flow on the continuous casting process

At an upward continuous casting speed of 25 cm·min⁻¹, a casting temperature of 1175 °C, and a billet diameter of 20 mm, ProCAST is used to simulate the upward continuous casting process of Cu–Sn alloy while the primary cooling water flow is set at 0.09 m³·h⁻¹, 0.27 m³·h⁻¹, 0.45 m³·h⁻¹, 0.63 m³·h⁻¹, 0.9 m³·h⁻¹, and 1.35 m³·h⁻¹. The results, shown in figure 7, indicate that with increasing flow of cold water the liquid core length of the Cu–Sn alloy billet decreases. When the flow of cooling water is less than 0.45 m³·h⁻¹, the liquid core length decreases. Above a flow rate of 0.45 m³·h⁻¹, the change of liquid core length is small, which indicates that increasing the cooling water flow leads to only little improvement on the cooling intensity when the flow exceeds a certain value.

In addition to cooling water flow, the process conditions for casting the billet were consistent with the numerical simulation conditions, and representations of the macrostructure of samples shown in figure 8 were recorded. The left and right sides of figure 8 are the longitudinal cross-sectional structure diagrams of the billets at cooling water flow rates of 0.09 m³·h⁻¹ and 0.63 m³·h⁻¹, respectively. The left side depicts a large-sized columnar crystal with a large penetrating crystal grain in the centre, which length exceeds 27 mm. The crystal grains on the right side are more uniform and fine. For these two different cooling water flows, the liquid core

**Figure 6.** Cu-0.45%Sn alloy rod produced at different ratios of stopping time to pulling time (a) surface of billets (b) fracture of billets.

**Figure 7.** Effect of cooling water flow on liquid core length in continuous casting.
length obtained by the numerical simulation is 76.8 mm and 69.5 mm, respectively, which also verifies that the liquid core length has a great influence on the quality of the billet.

4. Conclusions

(1) Three geometric models of upward continuous casting of Cu-0.45%Sn alloy are developed, and the boundary conditions and interface conditions of the numerical simulation are determined for the simulation of the upward continuous casting process using ProCAST. Based on the results, the upward continuous casting speed has a great influence and the casting temperature only little influence on the liquid core length. Casting temperature, upward continuous casting speed, cooling conditions, other process parameters, and mould shape should be adjusted to ensure the quality of billets with different diameters.

(2) The simulation results show that the ratio of stopping time to pulling time should not be higher than 2.13 at a casting temperature of 1175 °C, a billet diameter of 20 mm, and an upward continuous casting speed of 25 cm·min⁻¹. If the ratio exceeds the value of 2.13, the surface quality of the billet will become poor, and external and internal defects will increase.

(3) According to the simulation results with a casting temperature of 1175 °C, a billet diameter of 20 mm, and an upward continuous casting speed of 25 cm·min⁻¹, the liquid core length decreases with increasing flow of the primary cold water. When the flow of the cooling water exceeds the threshold of 0.45 m³⋅h⁻¹, the liquid core length change only slightly.

(4) The appropriate upward continuous casting process parameters are determined as 1175 °C for the casting temperature and an upward continuous casting speed is 25 cm·min⁻¹, the ratio of stopping time to pulling time should not be higher than 2.13, the flow of the cooling water is not less than 0.45 m³⋅h⁻¹.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.
ORCID iDs

Siming Hua @ https://orcid.org/0000-0001-5586-957X
Pingze Zhang @ https://orcid.org/0000-0001-6198-7759
Zili Liu @ https://orcid.org/0000-0003-2543-5249

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