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Numerical Simulations of the Ohno Continuous Casting Process for Mg - based Amorphous Alloys

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Abstract: The Ohno continuous casting process for the Mg-based amorphous alloy is simulated using the finite element method. The influences of the temperature in the mold mouth, the cooling distance and the casting rate on the temperature field and the shape of the solid-liquid interface are investigated. It is found that when the temperature in the mold mouth increases from 800°C to 950°C, the convexity of the solid-liquid interface is gradually decreasing and the position of the interface is moving outward along the mold. When the cooling distance is extended from 45 mm to 85 mm, the profile of the solid-liquid interface has little change while its corresponding position is gradually far away from the mold mouth. When the casting rate increases from $1.33 \times 10^{-4} \text{ m} \cdot \text{s}^{-1}$ to $3.33 \times 10^{-4} \text{ m} \cdot \text{s}^{-1}$, the solid-liquid interface is moving back and forth toward the outside and inside of the mold mouth. The optimal process parameters in the Ohno continuous casting process identified in the simulations are 900°C for the temperature in the mold mouth, $2.50 \times 10^{-4} \text{ m} \cdot \text{s}^{-1}$ for the casting rate and 60 mm for the cooling distance. The change in the temperature with the time under the optimum parameters is also obtained and the results indicate that the temperature drops rapidly at the very early process and then keeps almost the constant.

1. Introduction

A Mg-based bulk metallic glass is an amorphous alloy system which possesses the good glass forming ability (GFA), the low density and the high material strength. The Mg-based amorphous alloy is considered an engineering material with a great potential for various applications since abundant Mg resources are readily available and can be cheaply processed. For example, Mg₆₅Cu₂₅Y₁₀ as an amorphous alloy in Mg-Ln-TM has the highest ΔT_x (super-cooled liquid region) and the highest GFA[1]. The alloy has a ternary eutectic component with a melting point of 727.7 °C and the critical cooling rate (R_c) for the glass formation is about 50 K·s⁻¹. [2] The superior properties of this alloy have attracted great attentions from many researchers.

At present, the preparation of amorphous alloys was realized using the continuous preparation[3,4]. The banded amorphous alloys had been used in actual production. The bulk metallic glass alloys could be prepared with a transient production process, such as the water quenching method, the copper mold casting method and the suction casting technique[5-7]. However, the size and the length of the amorphous alloy from those processes limited its wide applications. Those limitations could be overcome using the Ohno continuous casting solidification system. In this system, the sintered body of the master alloy is placed in a graphite crucible and the casting mold is then heated to continuously cast the ingot. The temperature on the mold wall, which contacts with the molten of the Mg-based alloy, needs to be kept above the solidification temperature of the Mg-based alloy to avoid the



formation of crystal nucleus on the mold wall and the heat dissipation in the side of the solidification interface. The reason to keep a strong heat dissipation in the axial direction is that the solidification process occurs only in the front of the ingot. The action of the surface tension in the process of the cooling ingot allows it to maintain the shape of the molten metal[8,9]. Therefore, this method can be used to process the continuous preparation of the bulk metallic glass. However, this process requires a precise control of the process parameters such as the mold temperature, the casting rate and the cooling distance. Numerical simulations have been used to optimize the process parameters. For example, the numerical simulations were used by Zhao *et al.*[5] to simulate the diameter, the wall thickness and the water temperature of the quartz tube. The simulation was also used to optimize the process parameters for the desired microstructure and the phase structure of the amorphous alloy[10,11].

In the Ohno continuous casting process, the position of the solid-liquid interface is important to the amorphous component and surface smoothness of the castings during the Mg-based amorphous solidification process. The excellent mechanical properties can be obtained when an appropriate position of the solid-liquid interface is maintained during the entire casting process. In this study, the change in the temperature in the casting system process is simulated using the finite element method. The effects of key process parameters such as the temperature in the mold mouth, the casting rate and the cooling distance on the casting results are evaluated and the optimal process parameters are then identified. The numerical simulations provide excellent guidelines in the process of the appropriate parameters selection for the experiment in the casting process.

2. Physical and Mathematical Model

2.1 Model and Assumptions

For different air velocities, the larger the air flow is, the more uneven the temperature field is[12]. In order to simplify the calculation, the mathematical model needs to be established to describe the temperature field. The schematic of Ohno continuous casting solidification system is illustrated in Figure 1. The following assumptions in the mathematical model are made:

- (1) The temperature of the crystallizer inner wall is constant during the continuous casting process.
- (2) The metal liquid in the mold is kept in a laminar steady state and there is no axial heat transfer in the mold.
- (3) The possible physical properties difference is not considered in the interface region between the solid and liquid metals.
- (4) The constitutional super cooling of the metal in the solidification dynamics is not considered.

The coordinate system of the physical model[13,14] is also shown in Figure 1. The center of the export surface of the mold is defined as the origin of the coordinate. The specific boundary conditions are described as:

- (1) The temperature in the boundary is equal to the melting point of the alloys
- (2) The mold is always heated.
- (3) Cooling water is passing through in the boundary.
- (4) The casting rate is constant.

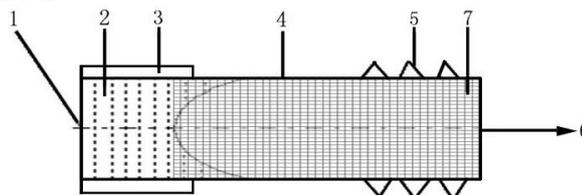


Figure 1 Physical model

- 1.Constant temperature heat source; 2. Molten metal; 3. Heated mold; 4. Ingot; 5. Cooling water;
- 6.Casting direction; 7. The finite element mesh of the calculation.

2.2 Heat Transfer Equation of the Temperature Field

The heat transfer equation of the temperature field can be expressed as

$$\lambda \frac{\partial^2 T}{\partial Z^2} + \lambda \frac{\partial^2 T}{\partial R^2} - \rho C_p v \frac{\partial T}{\partial Z} + q = 0 \dots\dots\dots(1)$$

where λ is the thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$); T is the temperature (K); R is the radius (m); ρ is the density ($\text{kg}\cdot\text{m}^{-3}$); C_p is the specific heat capacity ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$); v is the speed ($\text{m}\cdot\text{s}^{-1}$) and q is the endogenous heat (the latent heat of the crystallization released per unit time, $\text{W}\cdot\text{m}^{-3}$).

2.3 Thermal Physical Parameters

2.3.1 Thermal Conductivity in the Mold

In the mold, the temperature in the molten metal is higher than the metal melting point, which forces the heat transfer by convection between the metal and the casting mold. Its thermal conductivity[15] is expressed in the form of:

$$\lambda_1 = N_u \times \lambda / d \dots\dots\dots(2)$$

In the above equation, λ is the material melt thermal conductivity; d is the diameter of the casting; and N_u can be written as

$$N_u = 5.0 + 0.025(P_r \cdot R_e)^{0.8} \dots\dots\dots(3)$$

and

$$P_r = C\mu / \lambda \dots\dots\dots(4)$$

$$R_e = vd\rho / \mu \dots\dots\dots(5)$$

where C is the specific heat capacity ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$); μ is the material melt kinematic viscosity ($\text{m}^2\cdot\text{s}^{-1}$) and ρ is the density of the material ($\text{kg}\cdot\text{m}^{-3}$).

2.3.2 Water-Cooled Heat Exchange Coefficient

The heat exchange coefficient for water-cooling is influenced by the water quantity and the water temperature. It can be empirically expressed[15] as

$$\lambda_2 = \frac{(35.9 + 4.9W) \times T_s}{e^{\frac{T_s}{100}}} \dots\dots\dots(6)$$

where W is the water flow rate ($\text{L}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and T_s is the casting surface temperature ($^{\circ}\text{C}$).

2.3.3 The Center of the Axis

The center of symmetry is taken as the center of the axis, in which an adiabatic heating condition is assumed and thus the heat exchange coefficient is zero at this location.

2.3.4 Specific Heat Capacity

The relationship between the specific heat capacity of the amorphous metal and the temperature could be expressed by the following equations[16]:

$$C_{p,s} = 30.5 + 8 \times 10^{-10}(T - 570) + 0.04(T - 570) \dots\dots\dots(7)$$

when $570 \leq T \leq 690$ and

$$C_{p,s} = 51.2 + 0.05(T - 690) - (T - 690)^{0.5} \dots\dots\dots(8)$$

when $690 \leq T \leq 760$ in the super-cooled liquid region.

The thermal physical parameters and thermal properties parameters of the alloy are listed in Table 1 and Table 2, respectively.

Table 1 The thermal physical parameters by calculating.

Temperature (°C)	570	600	630	660	690	720	750
Specific heat capacity (J·kg ⁻¹ ·K ⁻¹)	30.5	31.7	32.9	34.1	35.3	47.2	46.45
Thermal conductivity of materials (W·m ⁻¹ ·K ⁻¹)	640.5	665.7	690.9	716.1	741.3	991.2	975.5
Thermal conductivity in the mold (W·m ⁻¹ ·K ⁻¹)	810.6	842.4	874.3	906.2	938.1	1254.4	1234.5

Table 2 Mg₆₅Cu₂₅Y₁₀ alloy parameters.

Density (kg·m ⁻³)	Melting point(°C)	Critical cooling rate (K·s ⁻¹)	Super-cooled liquid region (K)	Bar Diameter(mm)	Latent heat (J·kg ⁻¹)
2270	727.7	50	61	4-7	269059.7

3. Results and Discussions

The temperature in the casting mold was calculated by the finite element analysis (FEA) method and the process parameters[17-19] affecting the temperature field in Ohno Continuous Casting process were obtained including the mold temperature, the cooling distance, the casting rate, the molten metal temperature and the pressure head. Because the molten metal temperature and the pressure head in the continuous casting process were relatively stable, they were excluded in this study. In order to single out the effect of a given parameter on the temperature field, only the selected parameter was allowed to change while all other parameters were fixed during the process of the casting rate increased from the lowest rate until the connection broken between melt and solidification. The parameters studied in this process included the temperature in the mold mouth, the cooling distance and the casting rate. The results from the FEA can be summarized as follows:

3.1 The Effects of the Temperature in the Mold Mouth on the Solid Liquid Interface

When the temperature in the mold mouth is lower than the melting point of the metal, the solid-liquid interface would be in the deep position of the mold mouth. In this case, the friction between the casting alloy and the mold wall would be very high and thus it becomes difficult to cast the casting alloy out. When the mouth temperature is more than 10°C higher than the melting point of the metal, the solid-liquid interface position would be close to the mold mouth. In this case, the ingot surface would be smoother and continuous casting would be easier. When the mouth temperature is just above the melt point of the metal, the solid-liquid interface would still be inside the mold mouth. In this case, the interface of the casting would become very rough, which could even lead the amorphous alloy to be broken during casting. However, when the mouth temperature is too high, the leakage would outflow. Therefore, the quality of the casting process would be affected when the temperature in the mold mouth is either too high or too low. When the temperature is too high, there is not enough time for the overheated liquid to be cooled, which leads to the melt to be cut and results in a leakage phenomenon. When the temperature was too low, the solid-liquid interface is moved to the inside of the mold mouth and the untimely solidification of the internal molten metal occurs, which is hard to cast out. Therefore, an appropriate mouth temperature is very critical for the high quality of the casting

process.

The temperature field in the mold was simulated using the FEA for various temperatures in the mold mouth with the cooling distance at 65 mm and the casting rate at $2.33 \times 10^{-4} \text{ m} \cdot \text{s}^{-1}$. The temperature distributions in the mold and the corresponding profile and location of the solid-liquid interface are shown in Figures. 2 and 3, respectively, for mold mouth temperatures at 820°C, 850°C, 900°C, 920°C.

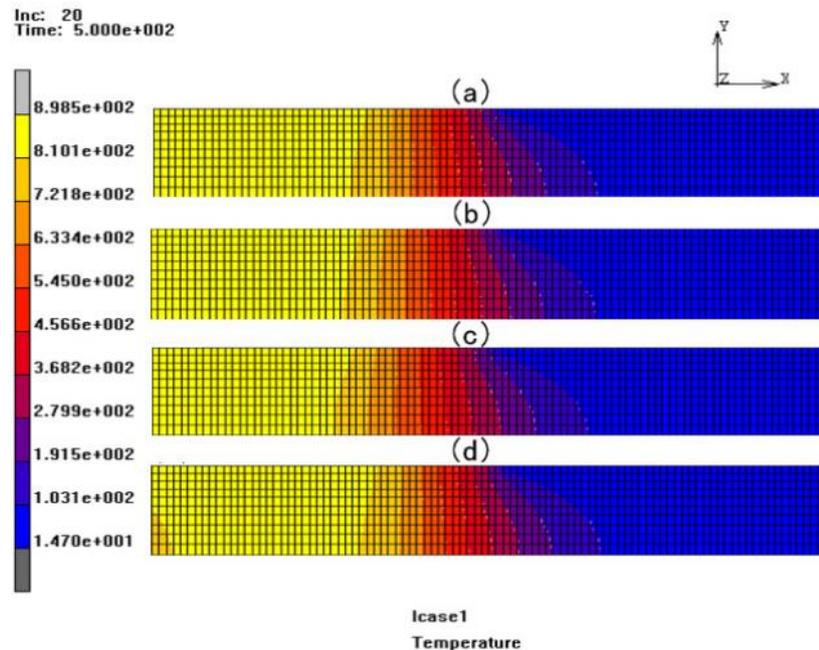


Figure 2 Temperature distribution in the mold for the mold mouth temperature at (a) 820 °C, (b) 850 °C, (c) 900 °C and (d) 920 °C.

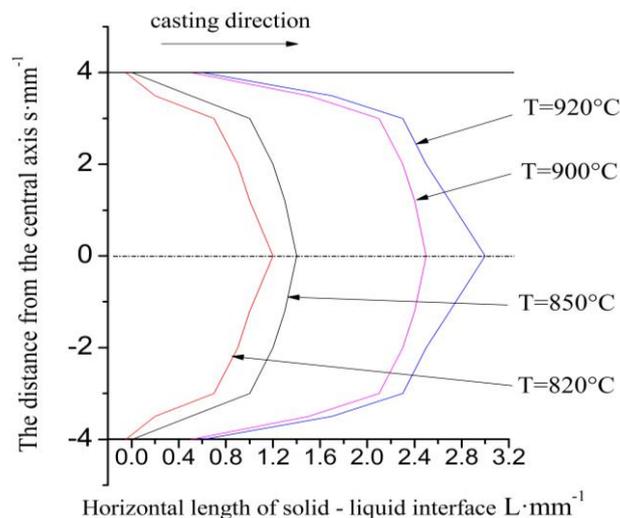


Figure 3 The influence of temperature on the solid - liquid interface profile and location.

It is seen from Figure 3 that the solid-liquid interface is gradually moving outward when the temperature in the mold mouth continues increasing. When the temperature in the mold mouth is low at 820°C, the solid-liquid interface is located in the deep inside of the mold mouth, which makes the casting surface very rough and makes the metal casting more difficult. When the temperature in the mold mouth is 920°C, the solid-liquid interface is almost out of the mouth, which results in a casting

leakage. Therefore, it is demonstrated from the above results that 900°C is the most appropriate temperature in the mold mouth to ensure the smoothness of the casting surface and to allow the casting process to be carried in an appropriate rate.

3.2 The Effects of the Cooling Distance on the Solid-Liquid Interface

The more appropriate the cooling distance is, the better the quality of the ingot is. The cooling distance is one of the critical factors to determine the content of amorphous components. The temperature field in the mold was obtained for various cooling distances at the mouth temperature at 900°C, the casting rate at $2.33 \times 10^{-4} \text{ m} \cdot \text{s}^{-1}$ and the water flow rate at $1.990456 \text{ l} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. The temperature distributions in the mold and the corresponding profile and location of the solid-liquid interface are shown in Figures. 4 and 5, respectively, for the cooling distances at 50 mm, 60 mm, 70 mm, 80 mm.

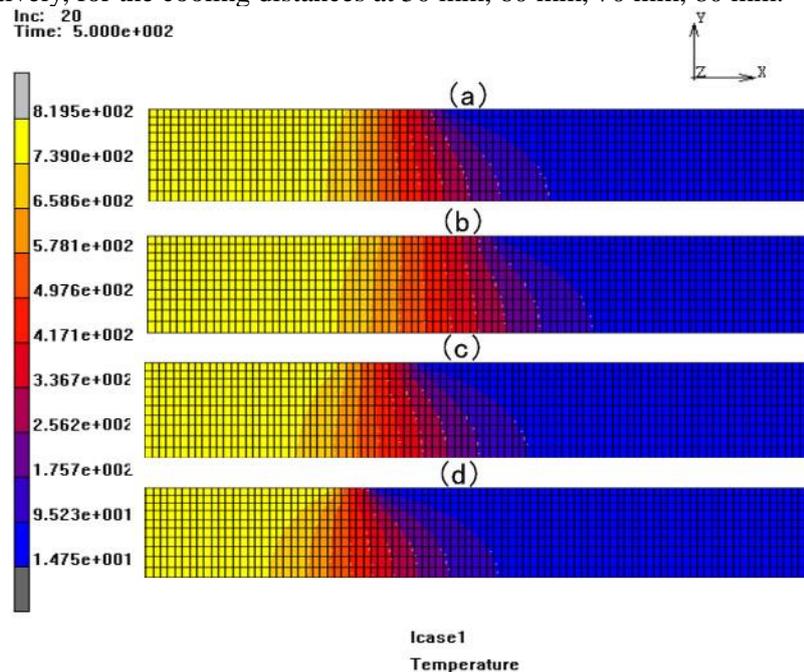


Figure 4 Effect of the cooling distance on the temperature field for the cooling distance at (a) 80 mm, (b) 70 mm, (c) 60 mm, and (d) 50 mm.

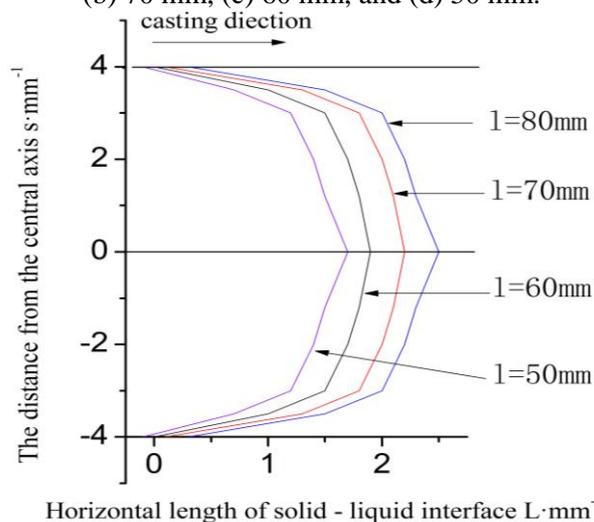


Figure 5 Effect of the cooling distance on the solid-liquid interface profile and location ($v=2.33 \times 10^{-4} \text{ m} \cdot \text{s}^{-1}$, $T=900^\circ\text{C}$, $W=1.990456 \text{ l} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$).

It is observed from Figure 5 that the horizontal position of the solid-liquid interface is far away from the crystallizer at 80 mm cooling distance, which would result in a leakage accident. It is also seen from Figure 5 that the use of the cooling distance at 50 mm results in a shallow solid-liquid interface position, which indicates that the cooling distance is too short and it is not conducive to casting metal out. As demonstrated in Figure 5, the cooling distance of 60 mm is the most appropriate cooling distance considering the quality of continuous casting and casting rate.

3.3 The effect of the casting rate on the solid-liquid interface

The temperature field in the mold was obtained for various casting rates at the mouth temperature at 900°C, the cooling distance at 60 mm and the water flow rate at 1.990456 l·m⁻²·s⁻¹. The temperature distributions in the mold and the corresponding profile and location of the solid-liquid interface are shown in Figures. 6 and 7, respectively, for the casting rate at 1.50×10⁻⁴ m·s⁻¹, 2.00×10⁻⁴ m·s⁻¹, 2.50×10⁻⁴ m·s⁻¹ and 3.00×10⁻⁴ m·s⁻¹.

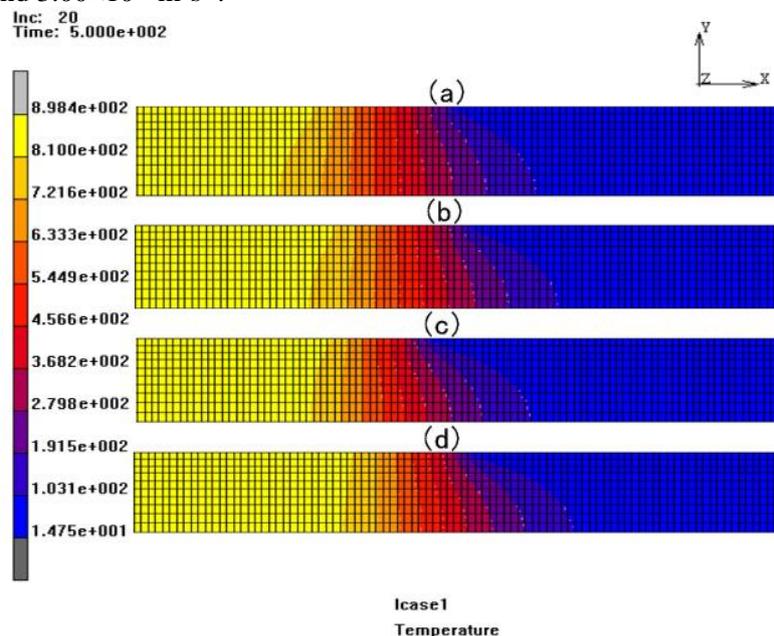


Figure 6 The effect of the casting rate on the temperature distribution for the casting speed at (a) 1.50×10⁻⁴ m·s⁻¹, (b) 2.00×10⁻⁴ m·s⁻¹, (c) 2.50×10⁻⁴ m·s⁻¹ and (d) 3.00×10⁻⁴ m·s⁻¹

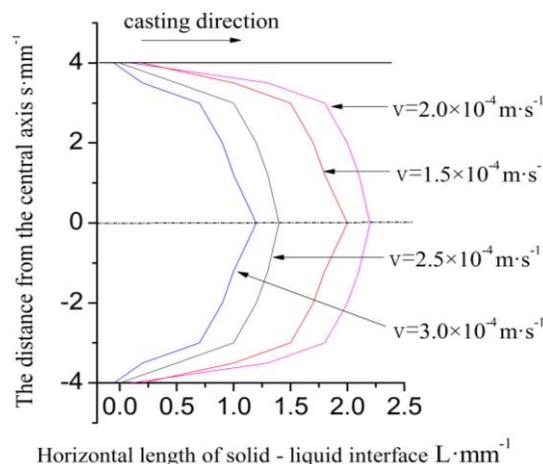


Figure 7 Effect of traction speed on the solid-liquid interface profile and location ($T_s=900\text{ }^\circ\text{C}$, $l=60\text{ mm}$, $W=1.990456\text{ l}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$).

The distance between the solid-liquid interface and the exit of the crystallizer should be kept in an appropriate distance to obtain good quality casting. When the solid-liquid interface is located in the deep inside of the crystallizer, casting can fail due to the broken alloy. When the solid-liquid interface is located just in the inside of the crystallizer, the interface of the casting ingot can be rough and the amorphous content in the alloy can be low[20]. The best position of the solid-liquid interface should be about 1.24 mm inside the crystallizer which comes through simulation test. It is clearly demonstrated from the interface profile shown in Figure 7 that the use of the casting rate at $2.50 \times 10^{-4} \text{ m} \cdot \text{s}^{-1}$ results in a smoother surface of the product.

3.4 Temperature Field Optimization

The simulation was carried out using ideal process parameters identified above: 900°C for the temperature in the mold mouth, $2.50 \times 10^{-4} \text{ m} \cdot \text{s}^{-1}$ for the casting rate and 60 mm for the cooling distance. The resulting temperature distributions in the mold at various times are shown in Figure 8.

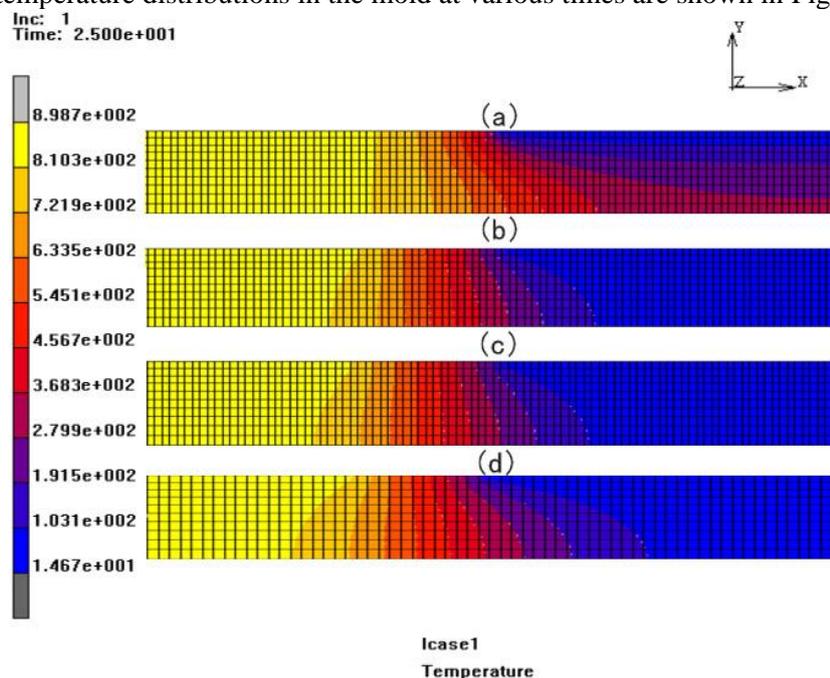


Figure 8 (a) The temperature distribution at 100 s
 (b) The temperature distribution at 250 s
 (c) The temperature distribution at 500 s
 (d) The solid-liquid interface after stabilization.

It can be seen from the figure that the temperature field trends gradually to be smooth and stable as casting progressing and it reaches a stable state after 500s. When the solid-liquid interface is located at about 1.24 mm inside the crystallizer, the shape of the solid-liquid interface becomes a smooth circular incurve, as shown in Figure 8 (d). The variation in the temperature at the central axis location with the casting time is shown in Figure 9. It is seen that the temperature quickly reaches to the steady state after a short period of time. The maximum temperature change rate is calculated to be about $60 \text{ K} \cdot \text{s}^{-1}$. This cooling rate could be achieved by the Ohno Continuous Casting experiment for the amorphous alloy preparation.

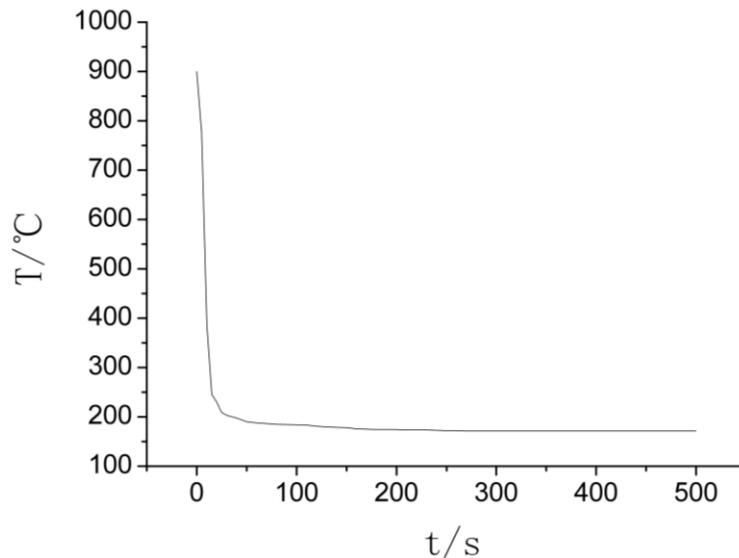


Figure 9 Relationship between temperature and time at solid-liquid interface.

4. Conclusions

Based on the above results from the finite element analysis, some conclusions can be made:

(1) The maximum temperature change rate of $Mg_{65}Cu_{25}Y_{10}$ was determined to be about $60\text{ K}\cdot\text{s}^{-1}$ and this cooling rate can be achieved by the Ohno Continuous Casting.

(2) When the mold mouth temperature rose from 800°C to 950°C , the high-convexity shape of the solid-liquid interface was gradually decreasing and its corresponding position was gradually moving from the inside of the mold toward the outside of the mold. When the temperature was at 900°C , the solid-liquid interface was kept in an appropriate distance from the mouth, which prevented the casting alloy from casting out of the mouth and eliminated the potential leakage accident. Therefore, 900°C is an optimal temperature in the mold mouth in preparing the $Mg_{65}Cu_{25}Y_{10}$ amorphous alloy by the Ohno Continuous Casting.

(3) The profile of the solid-liquid interface was almost independent of the cooling distance but the position of the interface was gradually departing from the mold mouth with an increased cooling distance from 45 mm to 85 mm. The optimal cooling distance is 60 mm, at which high content of amorphous alloy can be easily cast out.

(4) When the casting rate rose from $1.33\times 10^{-4}\text{ m}\cdot\text{s}^{-1}$ to $3.33\times 10^{-4}\text{ m}\cdot\text{s}^{-1}$, the solid-liquid interface position was moving back and forth toward the outside and inside of the mold as the solidification process was progressing. The optimal casting rate is $2.50\times 10^{-4}\text{ m}\cdot\text{s}^{-1}$, at which the solid-liquid interface is stable and robust.

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