WAYS OF STABILIZING CONTINUOUS UNIDIRECTIONAL SOLIDIFICATION PROCESS AND VERIFICATION TESTS①

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ABSTRACT The relation of parameters concerning the continuous unidirectional solidification process was established by the theoretical analysis of the heat transfer. Based on the relation, the ways of stabilizing the continuous unidirectional solidification process were discussed. For pure aluminium and an Al-1% Cu alloy, when the distance from the spraying position to the solid-liquid interface is smaller than 10 mm, the calculated results determined by the above relation agree with the experimental data on the whole. Therefore the parameters in these cases can match well mutually, consequently the continuous unidirectional solidification process will progress steadily.

Key words unidirectional solidification continuous casting pure aluminium Al-Cu alloy

1 INTRODUTION

As a new type of unidirectional solidification process, the continuous unidirectional solidfication process has been systematically studied from the 1980s, and the continuous casting of nonferrous metals and alloys with unidirectional solidification microstructures has been realized[1-5]. This process is of significant importance to the development of the unidirectional solidification technology and the exploitation of new materials. Although materials of different sections can be obtained, the problem of stability in the solidification process has not been solved yet, for example, the leaking-out of liquid alloy under freezer and inhomogeneous longitudinal microstructures[3]. The main reason responsible for those problems is that the related paramters concerning the continuous unidirectional solidification process cannot match mutually easily. So far, except experimental methods, no ways can be used to determine the relation of the parameters concerning the continuous unidirectional solidification process in advance. As a result, finding out the relation of the related parameters and by which predicting the technological parameters are essential to stabilize the continuous unidirectional solidification process. In this paper, the relation of the related parameters concerning the continuous unidirectional solidification process is derived by means of the theoretical analysis of the heat transfer, the ways of stabilizing the continuous unidirectional solidification process are discussed, the theoretical model is verified by experiments.

2 TEMPERATURE DISTRIBUTIONS IN CONTINUOUS UNIDIRECTIONAL SOLIDFICATION PROCESS

The schematic diagram of the continuous unidirectional solidification process is shown in Fig. 1. The metallic phase in this system can be divided into three sections: forced cooling section (Ⅰ), transition section (Ⅱ) and mold section (Ⅲ).

① Supported by the Basic Research Project BJ96-02-11 of the Metallurgical Industry Ministry of China
Received Jul. 4, 1997; accepted Sep. 9, 1997

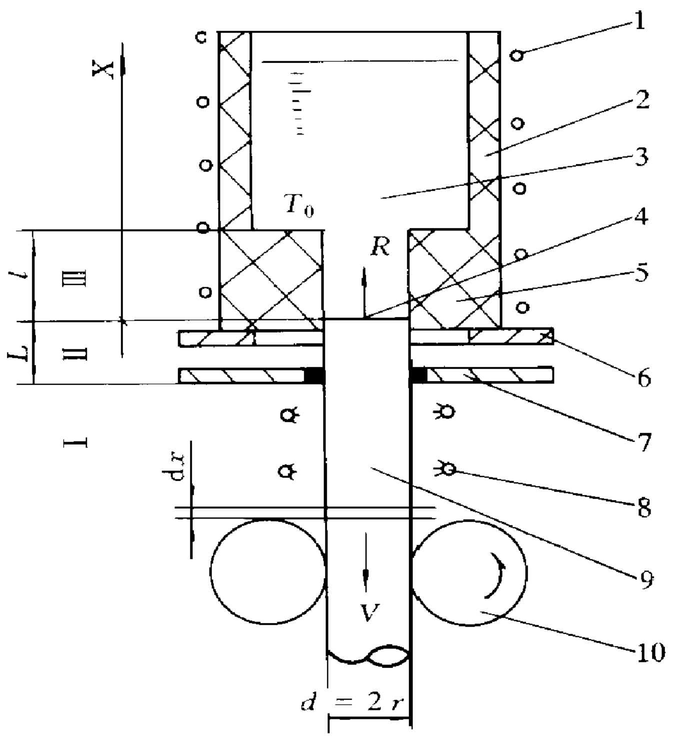

Fig. 1 Schematic diagram of continuous unidirectional solidification

1 —Inductor coil; 2 —Graphite crucible; 3 —Molten metal; 4 —Liquid-solid interface; 5 —Graphite mold; 6 —Mold support; 7 —Water seal; 8 —Water-spraying nozzle; 9 —Ingot; 10 —Pulling device

Ⅰ —Forced cooling section; Ⅱ —Transition section; Ⅲ—Mold section

The following assumptions are made:

(1) The cross-sections of the solid phase and the mold are circles with a radius of r.

(2) The radial temperature gradient is very small, and it can be ignored.

(3) The heat transfer from the system to the environment is carried out by the forced cooling of spraying water in section Ⅰ.

(4) The temperature of the melt at the entrance of the casting mold, T_0, is kept constant.

(5) No heat transfer occurs between the system and the environment in sections Ⅱ and Ⅲ

(6) When the pulling speed equals the solidification rate, the stability of the continuous unidirectional solidification process reaches its limiting point, and the corresponding pulling speed is called the critical pulling speed.

The coordinate system with the origin on the solid-liquid interface is shown in Fig. 1. Take a microelement $\pi r^2 dx$ and let the distance from this microelement to the solid-liquid interface be constant, then the heat balance equation of this microelement is as follows[6]:

(Heat change of transfer) +
(Heat change of boundary movement) +
(Heat change of loss to environment) = 0 (1)

2.1 Temperature distribution in section Ⅰ

Following eq. (1), the heat balance equation of microelement $\pi r^2 dx$ can be written as

$$\alpha_S \frac{d^2 T^{(1)}}{dx^2}(C_S \rho_S \pi r^2 dx) + R\frac{dT^{(1)}}{dx}(C_S \rho_S \pi r^2 dx) - h(T^{(1)} - T_a) 2\pi r dx = 0 \quad (2)$$

where x is the distance from the microelement to the solid-liquid interface, cm; C_S is the specific heat of the solid metal, 4.18 J·g^{-1}·K^{-1}; r is the radius of the solid metal, cm; h is the heat exchange coefficient between the solid phase and the environment, 4.18 J·cm^{-2}·s^{-1}·K^{-1}; $T^{(1)}$ is the temperature at x, K; T_a is the ambient temeprature, K; ρ_S is the density of the solid metal, g·cm^{-3}; α_S is the thermal diffusivity of the solid phase, cm^2·s^{-1}; K_S is the heat conduction coefficient of the solid metal, $K_S = \alpha_S \cdot \rho_S \cdot C_S$, 4.18 J·cm^{-1}·s^{-1}·K^{-1}; R is the solidification rate, cm·s^{-1}.

The boundary conditions are:

$$x = -L,\ T^{(1)} = T_L \quad (3a)$$

$$x = -\infty,\ T^{(1)} = T_a \quad (3b)$$

Substituting the boundary conditions eqs. (3a) and (3b) into eq. (2) and solving eq. (2) yields the temperature distribution of section Ⅰ:

$$\frac{T^{(1)} - T_a}{T_L - T_a} = \exp\{-[\frac{R}{2\alpha_S} - \sqrt{(\frac{R}{2\alpha_S})^2 + \frac{2h}{K_S r}}(L + x)]\} \quad (x \leqslant L) \quad (4)$$

2.2 Temperature distributions in sections Ⅱ and Ⅲ

According to the treatment method in 2.1, the heat balance equation of microelements in sections II and III can be expressed by

$$\frac{d^2T}{dx^2}+\frac{R}{\alpha}\frac{dT}{dx}=0 \quad (5)$$

where α is thermal diffusivity, $cm^2\cdot s^{-1}$.

(1) The boundary conditions of section II are:

$$x=0,\ T^{(2)}=T_m+mC_0/k \quad (6a)$$

$$x=-L,\ T^{(2)}=T_L \quad (6b)$$

where T_m is the melting point of pure metal, K; m is the slope of the liquidus of alloy; C_0 is the concentration of solute, %; k is the distribution coefficient.

(2) The boundary conditions of section III are:

$$x=0,\ T^{(3)}=T_m+mC_0/k \quad (7a)$$

$$x=l,\ T^{(3)}=T_0 \quad (7b)$$

where l is the height of the casting mold, cm.

Substituting the boundary conditions eqs. (6a) and (6b), and eqs. (7a) and (7b) respectively and solving eq. (5) yield the temperature distributions in sections II and III as follows:

$$\frac{T^{(2)}-(T_m+mC_0/k)}{T_m+mC_0/k-T_L}=-\frac{1-\exp(-\frac{R}{\alpha_S}x)}{1-\exp(\frac{R}{\alpha_S}L)} \quad (-L\leqslant x\leqslant 0) \quad (8)$$

$$\frac{T^{(3)}-(T_m+mC_0/k)}{T_m+mC_0/k-T_0}=-\frac{1-\exp(-\frac{R}{\alpha_L}x)}{1-\exp(-\frac{R}{\alpha_L}l)} \quad (x\geqslant 0) \quad (9)$$

3 RELATION OF PARAMETRS CONCERNING CONTINUOUS UNIDIRECTIONAL SOLIDIFICATION PROCESS

The heat balance equation at the solid-liquid interface in the continuous unidirectional solidification process is[6]

$$K_SG_S-K_LG_L=\rho_SHR \quad (10)$$

where K_L is the heat conduction coefficient of the melt, $4.18\ J\cdot cm^{-1}\cdot s^{-1}\cdot K^{-1}$; G_S is the temperature gradient at the solid-liquid interface on the solid side, $K\cdot cm^{-1}$; G_L is the temperature gradient at the solid-liquid interface on the liquid side, $K\cdot cm^{-1}$; H is the melting heat, $4.18\ J\cdot g^{-1}$.

Differentitating eqs. (8) and (9) yields

$$G_L=\left.\frac{dT^{(3)}}{dx}\right|_{x=0}=[T_0-(T_m+mC_0/k)]\times[1-\exp(-\frac{R}{\alpha_L}l)]^{(-1)}\frac{R}{\alpha_L} \quad (11)$$

$$G_S=\left.\frac{dT^{(2)}}{dx}\right|_{x=0}=-[(T_m+mC_0/k)-T_L]\times[1-\exp(\frac{R}{\alpha_S}L)]^{(-1)}\frac{R}{\alpha_S} \quad (12)$$

Assuming at $x=-L$,

$$G_S^{(1)}=G_S^{(2)} \quad (13)$$

From eqs. (4) and (8), one can obtain

$$G_S^{(1)}=\left.\frac{dT^{(1)}}{dx}\right|_{x=-L}=(T_a-T_L)[\frac{R}{2\alpha_S}-\sqrt{(\frac{R}{2\alpha_S})^2+\frac{2h}{K_Sr}}] \quad (14)$$

$$G_S^{(2)}=\left.\frac{dT^{(2)}}{dx}\right|_{x=-L}=[T_L-(T_m+mC_0/k)]\times[1-\exp(\frac{R}{\alpha_S}L)]^{(-1)}\frac{R}{\alpha_S}\exp(\frac{R}{\alpha_S}L) \quad (15)$$

Substituting eqs. (14) and (15) into eq. (13) yields

$$T_L=(T_m+mC_0/k)\times[1-\exp(\frac{R}{\alpha_S}L)]^{(-1)}\times\frac{R}{\alpha_S}\exp(\frac{R}{\alpha_S}L)+(\frac{R}{2\alpha_S}-\sqrt{(\frac{R}{2\alpha_S})^2+\frac{2h}{K_Sr}})T_a/\{[1-\exp(\frac{R}{\alpha_S}L)]^{(-1)}\frac{R}{\alpha_s}\times\exp(\frac{R}{\alpha_S}L)+[\frac{R}{2\alpha_s}-\sqrt{(\frac{R}{2\alpha_S})^2+\frac{2h}{K_Sr}}]\} \quad (16)$$

Substituting eq. (16) into eq. (12) and then substituting eqs. (12) and (11) into eq. (10), using the critical pulling speed V to replace the growth rate R following assumption (6), one can obtain the relation between the related parameters and the melt temperature T:

$$T_0 = \frac{K_S \alpha_L}{K_L}[1 - \exp(-\frac{V}{\alpha_L}l)] \times (T_m + mC_0/k - T_a)[\frac{V}{2\alpha_S} - \sqrt{(\frac{V}{2\alpha_S})^2 + \frac{2h}{K_S r}}] / \{[\frac{V}{2\alpha_S} - \sqrt{(\frac{V}{2\alpha_S})^2 + \frac{2h}{K_S r}}] \times [\exp(\frac{V}{\alpha_S}L) - 1]\alpha_S - V\exp(\frac{V}{\alpha_S}L)\} - H\rho_S\frac{\alpha_L}{K_L} \times [1 - \exp(-\frac{V}{\alpha_L}l)] + (T_m + mC_0/k) \quad (17)$$

4 WAYS OF STABILIZING CONTINUOUS UNIDIRECTIONAL SOLIDIFICATION PROCESS

The meaning of the steady continuous unidirectional solidification process lies in that, first, no leaking-out of liquid alloy under freezer occurs; second, the longitudinal microstructures must be homogeneous. The key to achieve these two goals is to keep the solid-liquid interface steady in the continuous unidirectional solidification process.

Eq. (17) relatively fully describes the intrinsic relations of the related parameters concerning the continuous unidirectional solidification process at a steady state; it is also the theoretical model for the steady progress of the continuous unidirectional solidification process. Therefore, Eq. (17) can be used to find the ways of stabilizing the continuous unidirectional solidification process.

In the continuous unidirectional solidification process, if the pulling speed v is larger than the critical pulling speed V, then the solid-liquid interface will move towards the outlet of the casting mold at a speed of $(v - V)$ until there occur pull cracks; if $v < V$, i.e. $v < R$, then the solid-liquid interface will move inwards the casting mold at a speed of $(R - V)$, but the moving speed will become smaller gradually, and finally the solid-liquid interface will be stable at some position in the casting mold, consequently the solidification process reaches a steady state and the longitudinal microstructures will be homogeneous. It can be seen that the pulling speed is very important to the stability of the continuous unidirectional solidification process. In addition, all other parameters indirectly affects the position of the solid-liquid interface through affecting the critical pulling speed V.

The larger the pulling speed V, the easier the steadiness that the continuous unidirectional solidification process will become. Therefore, the most efficient way of stabilizing the continuous uni-directional solidification process is to obtain a critical pulling speed V as larger as possible by adjusting the related parameters. Using the data in Table 1, the calculated T_0 vs V relations for pure aluminium and an Al-1% Cu alloy determined by Eq. (17) are presented in Figs. 2 and 3, in which T_0 varies with V almost linearly. It can be derived that lower melt temperature is beneficial to obtain higher pulling speed without consideration of the solidification quality. The relations between other parameters with the pulling speed V can also be calculated using Eq. (17). Based on these curves, the largest critical pulling speed V can be obtained.

Besides the internal factors, the external factors also affect the stability of the continuous unidirectional solidification process. In order to obtain high surface quality Ref. [5] managed to control the position of solid-liquid interface outside the casting mold and make the molten metal solidify at the moment when it leaves the casting mold[3]. In this case, not only the internal factors of the system must match mutually, but the temperautre of the melt at the outlet of the casting mold must be precisely measured, and high-precision pulling device is needed, then the solidification process will progress steadily.

Table 1 Physical parameters

Material	T_i/K	ρ_S, ρ_L/(g·cm^{-3})	α_S, α_L/(cm^2·s^{-1})	K_S, K_L/(4.18 J·cm^{-1}·s^{-1})	H/(4.18 J·g^{-1})
Aluminium	933.7	2.71, 2.32[7]	0.916[7], 0.634*	0.57, 0.274[8]	95[6]
Copper	1356	9.0[6], 7.9[7]	1.16[6], 0.88*	0.94[6], 0.635[7]	51[6]

* Calculated values.

5 VERIFICATION TESTS

5.1 Experimental method

The continuous unidirectional solidification tests were performed with pure aluminium and an Al-1% Cu alloy on the apparatus as shown in Fig. 1. In this apparatus, an induction furnace is used to melt metals, spraying water is used for forced cooling and a pulling device can change speed steplessly. The tests were carried out under different T_0 and L; they didn't stop until there were leaking-out of molten alloy under freezer by adjusting the pulling speed. The pulling speed at this moment is called the critical pulling speed of the continuous unidirectional solidification process. The diameter of the specimens is 10 mm.

5.2 Experimental results and discussion

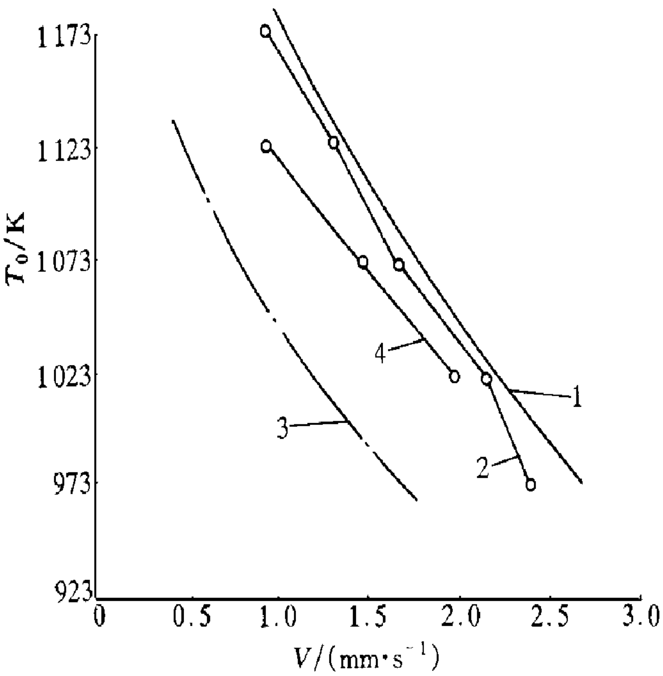

Fig. 2 Relationship between T_0 and V for pure Al

1 —Calculated(L = 10 mm);
2 —Experimental(L = 10 mm);
3 —Calculated(L = 30 mm);
4 —Experiemntal(L = 10 mm);

The T_0 vs V curves of the pure aluminium and the Al-1% Cu after continuous unidirectional solidification under different L values are also presented in Figs. 2 and 3. The curves show that when the pulling speed is smaller than the critical pulling speed V, the continuous unidirectional solidification process will reach a steady state. The left sides of the curves are steady regions, in which the related parameters can match well each other. It can be seen from Fig. 2 that when L = 10 mm, the calculated results are very close to the experimental ones for the pure aluminium, while when L = 30 mm, the deviation is relatively large. This is believed to be caused by assumption (5). Because when L is large, there exist thermal radiation and convective heat transfer between the solid metal and the enviroment in the region from the solid-liquid interface to the spraying position, consequently the practical pulling speed is larger than the calculated one.

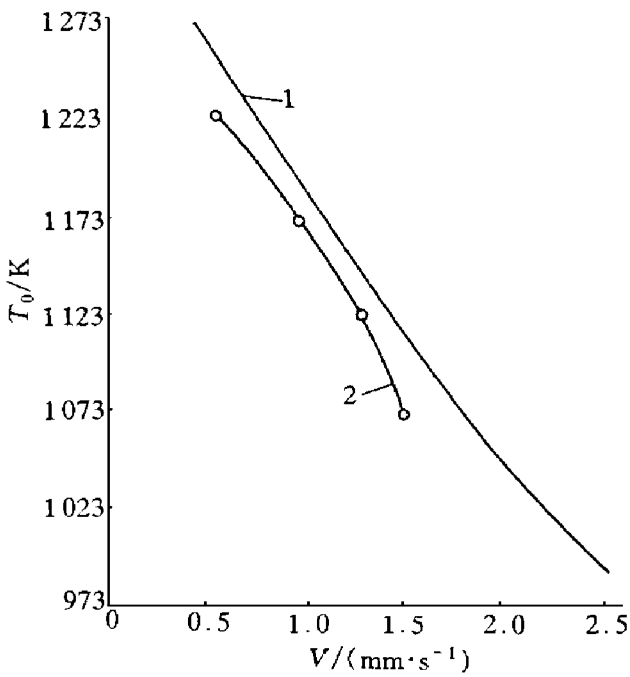

Fig. 3 Relationship between T_0 and V for Al-1% Cu alloy(L = 10 mm)

1 —Calculated; 2 —Experimental

When $L = 10$ mm, the comprehensive effects of the heat-proof of the water seal and the mold support and the radiative heating of this part by the bottom of the casting mold make the heat exchange between the system and the enviroment ignored. When $L = 10$ mm, the calculated results also agree well with the experimental ones for the Al-1% Cu alloy, as shown in Fig. 3. Therefore, if $L < 10$ mm, the results calculated using Eq. (17) will be more correct.

Eq. (17) is verified to be reliable by the continuous unidirectional solidification tests of a pure aluminium and an Al-1% Cu alloy, thus the technological parameters determined can ensure the steady progress of the continuous unidirectional solidification process.

6 CONCLUSIONS

(1) The key to stabilize the continuous unidirectional solidification process is to make the related parameters match mutually; the most effective way of achieving steady solidification is to increase the critical pulling speed of the solidification process.

(2) The relation of the related parameters concerning the continuous unidirectional solidification process can be expressed by

$$T_0 = \frac{K_S \alpha_L}{K_L}[1 - \exp(-\frac{V}{\alpha_L}l)] \times (T_m + mC_0/k - T_a)[\frac{V}{2\alpha_S} - \sqrt{(\frac{V}{2\alpha_S})^2 - \frac{2h}{K_S r}}]/\{[\frac{V}{2\alpha_S} - \sqrt{(\frac{V}{2\alpha_S})^2 + \frac{2h}{K_S r}}] \times [\exp(\frac{V}{\alpha_S}L) - 1]\alpha_S - V\exp(\frac{V}{\alpha_S}L)\} - H\rho_S\frac{\alpha_L}{K_L} \times [1 - \exp(-\frac{V}{\alpha_L}l)] + (T_m + mC_0/k)$$

When $L \leqslant 10$ mm, the results calculated using this equation basically agree with the experimental results for a pure aluminium and an Al-1% Cu alloy. The parameters thus determined can match well each other, and can make the solidification progress steadily. This equation can provide a basis for determining the related technological parameters.

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(Edited by Peng Chaoqun)