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Stability condition of semisolid continuous casting process ①

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[Abstract] The major unsteady phenomena in semisolid continuous casting process are the breakage and breakout. The essential reasons for them are the passageway blocking or the solidified shell too thin to endure the withdrawal force because of the remained shell formed at the beginning and its developing afterwards. Through theoretically analyzing the crack filling and the remained shell developing, stability conditions were presented. The essential one of them is that the stress acted on the semisolid slurry must be larger than the yield stress of it. The condition without breakage is to build a balance between the increase of the remained shell resulted in solidifying and the decrease of it resulted in flowing of the semisolid slurry. The condition without breakout is to ensure the solidified thickness larger than the safe thickness. The corresponding mathematical formulas of these conditions were set up and the verification experiments show that these conditions are reliable in applications.

[Key words] semisolid metal; continuous casting; stability condition; breakage; breakout

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1 INTRODUCTION

The semisolid continuous casting, SSCC for short, is a new process with low consumption and high productivity to produce high quality billet for semisolid alloys forming. However, the breakout and breakage often occur in the process because of lacking sufficient research on the steady conditions of the process. It has been experimentally shown that the major factor which limits the process stability is the crack and a remained shell formed at the withdrawal beginning, which results in blocking the slurry passageway so as to produce breakage or breakout[1]. The paper[2] has established a model to predict the dimension and position of the initial crack and remained shell. However, it can not be used to accurately determine whether the process is steady or not, because the dimension of the initial crack is only one essential factor, not the whole ones, to control the process stability.

It has been found that the process stability is also controlled by the crack being filled, welded and the developing of the remained shell[1]. Among the controlling factors, the crack being filled is the first one and is influenced by the dimension of the passageway and the fluidity of the slurry. Therefore, the process stability can be explored by analyzing the conditions of the crack being filled and the development of the remained shell.

2 CONDITION OF CRACK BEING FILLED

2.1 Condition in mechanics

Although the rheological model previously obtained[3~7] are different from each other in some detail forms, there is an identical part, named Binhand Body, in them. So it is clear that there exists a critical stress. If the stress acted on the slurry is larger than the critical one, the semisolid slurry can flow like liquid. However, if the stress acted on it is smaller than the critical one, the slurry can not flow at all. This critical stress is generally named yield stress and remarked by τ_s.

Actually, the stress acted on the slurry is only the static pressure in the SSCC process. Suppose the height of the slurry in the stirring chamber is l_j, the length of the copper mold is l_m, the density and the heat captivity of the slurry are ρ and c respectively, the latent heat of the alloy unit quality is ΔH_m, and the distance of the crack formed at the withdrawal beginning from the top of the copper mold is Z. Then the stress acted on the slurry at the position of the crack equals the static pressure: $\tau_p = \rho g(l_j + Z)$. Thus, the mechanical condition to fill the initial crack is $\tau_p \geqslant \tau_s$, i.e.

$$\rho g(l_j + Z) \geqslant \tau_s \tag{1}$$

The minimum value of Z in formula (1) is zero, so that the condition of any crack being filled is simplified as $\tau_s \leqslant \rho g l_j$.

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Now take steel and aluminum alloy as example, and let $l_j = 0.6\,m$, the yield stress of the slurry is required to be smaller than 0.5 MPa and 0.15 MPa respectively in order to fill any crack from formula (1). However, it is experimentally shown that the actual yield stress of major material in the semisolid state is about $10^2 \sim 10^4$ Pa[4~8], which is obviously smaller than the required one. Consequently the mechanical condition of the crack being filled is easy to meet in the actual process. The key problem to control the breakage and breakout is the slurry passageway.

2.2 Condition of slurry passageway existing

Suppose the initial thickness of the remained shell is δ_0. It will be increased afterward in the SSCC process because of the cooling of copper mold. On the other hand, the thickness of the remained shell will be decreased because of the slurry flowing in which the heat carried by the slurry will be transferred to the remained shell, and an additional stress will act on it and makes it move downward. If the increasing rate is less than the decreasing rate of the remained shell, the slurry passageway can always exist.

Let the time from pouring to withdrawal beginning be t_0. The solidified shell thickness δ_0 formed in the period can be calculated by the square root law:

$$\delta_0 = K\sqrt{t_0}$$

Without considering the thickness decreasing from flowing, the thickness of the solidified shell at any time t after withdrawal beginning can similarly determined by the square root law:

$$\delta = K\sqrt{t + t_0}.$$

Consequently, the increased value $\Delta\delta$ of the thickness of the remained shell can be determined by

$$\Delta\delta = K\sqrt{t + t_0} - K\sqrt{t_0}$$

where K is the solidification coefficient in the copper mold.

Moreover, suppose the temperature in the increased thickness is uniform and equals the solidus temperature T_s, the diameter of the copper mold is D_m. The required heat q_1 to raise the temperature of the newly increased remained shell from T_s to the critical temperature T_{cr}, which is the minimum temperature of the flowing slurry, can be denoted by

$$q_1 = \pi\Delta\delta(D_m - 2\delta_0 - \Delta\delta)\rho Z \cdot [(T_{cr} - T_s)c + \Delta H_m(1 - f_{sc})]$$

Let the longitudinal temperature gradient of the slurry be G_t, the corresponding gradient of the solid volume fraction be G_f and the critical solid volume fraction be f_{sc}. If we make an assumption that the temperature is uniform in the radial direction in the newly increased solidified shell, the heat released from the slurry flowing through the remained shell zone can be determined by

$$q_2 = \frac{1}{4}\pi(D_m - 2\delta)^2\rho Z^2(G_t c + \Delta H_m G_f)$$

With another assumption that this heat q_2 is completely transferred to the newly increased remained shell and used to make its temperature increase, it is clear that if the heat q_2 is larger than the heat q_1, the newly increased remained shell from solidification will become fluid so as to decrease the thickness of it and keep the slurry passageway exist always. Thus, the condition of the slurry passageway existing is

$$\frac{1}{4}D_m^2 Z(G_t c + \Delta H_m G_f) > \Delta\delta(D_m - 2\delta_0 - \Delta\delta)[(T_{cr} - T_s)c + \Delta H_m(1 - f_{sc})]$$

Putting the expression of $\Delta\delta_1$ into the above formula, we obtain a quadratic inequality about time t:

$$K^2\left[\sqrt{t - t_0} - \sqrt{t}\right]^2 - (D_m - 2\delta_0)K \cdot \left[\sqrt{t - t_0} - \sqrt{t}\right] + A > 0$$

where $A = D_m^2 Z(G_t c + \Delta H_m G_f)/[4(T_{cr} - T_s)c + \Delta H_m(1 - f_{sc})]$.

According to the properties of a quadratic inequality, when $\Delta = (D_m - 2\delta_0)^2K^2 - 4AK^2 < 0$, the quadratic inequality is true in the real number range. Consequently, it also means that the thickness of the remained shell will not continuously increase. By substituting A and Δ into it, the condition of the crack being filled in time can be obtained as

$$\frac{Z(G_t c + \Delta H_m G_f)}{(T_{cr} - T_s)c + \Delta H_m(1 - f_{sc})} > \left[\frac{D_m - 2\delta}{D_m}\right]^2 \quad (2)$$

From condition (2), it is clear that:

1) the smaller the diameter of the copper mold and the longitudinal temperature gradient of the slurry are, the more easily the crack is filled;

2) the longer the initial remained shell is, the more easily the crack is filled;

3) the larger the critical solid volume fraction is, or the lower the critical temperature is, the easier the crack is filled;

4) the smaller the solidification temperature range is, the more easily the crack is filled;

5) the latent heat and heat capacity of the alloy have not significant effect on the crack filling due to the same power in the formula's numerator and denominator.

3 CONDITION OF CRACK BEING WELDED

Similar to the traditional continuous casting, the crack being welded sufficiently is the key to prevent the breakout in the SSCC process. If every crack can be welded sufficiently in time and a critical thickness of the welded shell has been formed before the crack moves downward to the bottom of the copper mold, the SSCC process can be continuously carried on without breakout. This critical thickness is generally called safe thickness in the continuous casting process, and remarked by δ_{min}. The values of it change with the kind of alloy and the microstructure of the billet. Thus, it is natural that the semisolid slurry has a different critical thickness corresponding to that of the traditional continuous casting. However, the difference is only in values, the idea of the critical thickness is also useful in the SSCC process[9].

Let the safe thickness of the semisolid slurry be remarked by δ_{min}, the time t_1 to form it can be determined by the square root law: $t_1 = (\delta_m/K)^2$.

On the other hand, let the time from the crack forming to its moving downward to the bottom of the copper mold be t_2, which is controlled by the withdrawal rate v_p and the length l_m of the copper mold, and can be determined by $t_2 = (l_m - Z)/v_p$.

In order to make the welded thickness larger than the safe thickness, the following inequality must be true: $t_1 < t_3$, i.e. $(\delta_{min}/K)^2 < (l_m - Z)/v_p$, or

$$l_m > v_p(\delta_{min}/K)^2 + Z \tag{3}$$

Inequality (3) is just the condition of the crack being welded sufficiently in time. From the formula it is seen that the length l_m of the copper mold must be larger than a critical value related with the withdrawal rate v_p, the solidification coefficient K and the safe thickness of the semisolid slurry δ_{min}. In detail, the required length of the copper mold to prevent from breakout is proportional to the withdrawal rate, the square of the safe thickness and the remained shell length, but inversely proportional to the solidification coefficient.

4 VERIFICATION EXPERIMENTS AND DISCUSSION

The SSCC process is steady if both the breakage and breakout do not occur. Therefore, the stability conditions of the SSCC can be obtained as follows by summarizing the above results.

Condition 1: the stress acted on the slurry must be larger than the yield stress, shown as formula (1);

Condition 2: the remained shell does not continuously increase in the process, shown as formula (2);

Condition 3: the welded thickness of the crack must be larger than the safe thickness, shown as formula (3).

If condition 1 cannot be satisfied, the SSCC process cannot be carried out at all because the slurry cannot flow. Thus, condition 1 is an essential condition for the process stability. If condition 2 is not satisfied, the breakage will be seen after some time because of the slurry passageway being blocked by the remained shell step by step. If condition 3 is not satisfied, the breakout will occur because the welded thickness is too thin to bear the slurry's pressure acted on it. Only if the three conditions are simultaneously satisfied, the SSCC can continuously and steadily carry on without breakage and breakout.

In order to verify the availability of the stability conditions, a series of test has been designed and carried out with the SSCC machine made in China. The tested alloy is A356 aluminum alloy. The obtained results show that all the SSCC process satisfying the continuous conditions could be continuously and steadily carried on, but those not satisfying the conditions cannot be steady because of breakage or breakout (as shown Table 1).

Table 1 Example of testing results

Test number	Stability conditions			Result
	Condition 1	Condition 2	Condition 3	
1	Yes	Yes	Yes	Breakout
2	Yes	No	Yes	Breakage
3	Yes	Yes	Yes	Steady

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