Application of inoculators-macrochillers at electroslag remelting

Ilia CHUMANOV

Faculty of Metallurgy, South Ural State University, Zlatoust, Russia

Abstract: Usage of inoculators-chillers (macrochillers) at electroslag remelting can significantly increase the attraction of the process (especially at getting large-scale castings) concerning both cost saving and quality improvement. The cost is reduced due to less power consumption and increase in productivity at the expense of increase of vertical speed of metal crystallization. The quality of obtained metal is improved in the following parameters: the macrostructure is more dispersed and disoriented; the sharp increase in isotropy of mechanical properties; reduction of intergranular fractures and increase of impact toughness value; suppression of development of channel-type macrosegregation defects (cords); lessening of ingots top scrap. At the same time the fulfillment of the electroslag process with usage of inoculators-chillers demands not just additional equipment (dosers) and preparation of chillers themselves (grinding them to the demanded size) but also the development of the technological modes. For that the following were calculated: fall time of macrochiller through slag bath; the dynamics of skull freezing; burn-off time of skull and macrochiller; macrochiller delivery rate. It is established, that while passing through the slag bath the macrochiller and the skull melt down totally and reach the metal bath as a drop of liquid metal.

Keywords: Electroslag smelt, Inoculators-macrochillers, Steel, Mathematic modeling

1. Introduction

Usage of inoculators-chillers (macrochillers) at electroslag remelting can significantly increase the attraction of the process (especially at getting large-scale castings) concerning both cost saving and quality improvement. The cost is reduced due to less power consumption and increase in productivity at the expense of increase of vertical speed of metal crystallization. The quality of obtained metal is improved in the following parameters:

- the macrostructure is more dispersed and disoriented;
- the sharp increase in isotropy of mechanical properties;
- reduction of intergranular fractures and increase of impact toughness value;
- suppression of development of channel-type macrosegregation defects (cords);
- lessening of ingots top scrap.

At the same time the fulfillment of the electroslag process with usage of inoculators-chillers demands not just additional equipment (dosers) and preparation of chillers themselves (grinding them to the demanded size) but also the development of the technological modes. For that the following calculations are needed.

2. Calculation of the fall time of macrochiller through slag bath

Let us deduce the formula connecting the distance passed by the macrochiller and the fall time (passage time) of macrochiller in slag. In order to make it easier we conduct the calculation for a spherical macrochiller. Also we accept that the influence of electrodynamic and convective forces on the macrochiller motion is insignificant, so the fall time can be defined from the solution of differential equation of motion of sphere in viscous liquid [1]:

$$V_М \rho_М \frac{d\omega}{dt} = V_М g(\rho_М - \rho_{ШЛ}) - 0{,}5 c_0 F \rho_М \omega^2, \tag{1}$$

where: ω - rate of fall of macrochiller (sphere);

c_0 – hydrodynamical resistance coefficient;

F – section of macrochiller (sphere).

Introducing the notations D_1, D_2 , D_3 we transform the equation (1) into the following:

$$D_1 \frac{d\omega}{dt} = D_2^2 - D_3^2\omega^2 \tag{2}$$

Integrating the equation (2) two times, in the range from t_0 till t, we find the correlation connecting the distance Z passed by the macrochiller with the fall time at c0 = const [2]:

$$Z = -\frac{D_2}{D_3}(t - t_0) + \frac{D_1}{D_3^2}\ln\frac{1+y}{1+y_0}, \tag{3}$$

where:

$$y = \frac{D_2 + D_3\omega_0}{D_2 - D_3\omega_0}\exp[2D_2D_3(t - t_0)], \tag{4}$$

$$y_0 = \frac{D_2 + D_3\omega_0}{D_2 - D_3\omega_0} \tag{5}$$

The obtained equation due to its nonlinearity is solved with application of software package. The calculation is conducted with the following initial data:

R=0.003 m – macrochiller radius; ε=0.0006 m – thickness of the forming skull [2]; $\rho_м$=7800 kg/m^3 – metal density; $\rho_{шл}$=2400 kg/m^3 – slag density; c_0=1 – hydrodynamical resistance coefficient of slag [2];ω_0=8.3 m/sec – initial rate of macrochillers input;t_0=0.85 sec – time of macrochiller free fall before falling in slag bath.

Inserting the initial data in the equations (3), (4) and (5) we find the fall time of a macrochiller with radius 0.003 m in a slag bath with thickness 0.269 m. The time is t=0.86 c.

In truth the macrochiller melts while passing the slag bath so its radius decreases and consequently the rate of its fall through the slag reduces. Hereby the fall time of macrochiller through slag is slightly longer than 0.86 sec. The precise time can be defined by solving the equation (3) with the assumption that the macrochiller radius tents to zero. Approximately the time is equal to 1.02 sec.

The fall time of macrochiller is limited with the thickness of the slag bath. In order to calculate the fall time of macrochiller with radius 0.003 m through the slag bath with depth 0.269 m the value of freezing skull is taken. According to data [2] this value equals to 0.0006 m for macrochiller with radius 0.003 m. In truth while macrochiller is falling through slag the skull first grows, then at balancing the thermophysical properties of the macrochiller and the slag bath the growth stops and the skull starts to melt quickly. After it has melted down the macrochiller itself starts to melt.

3. Calculation of dynamics of skull freezing

Let us deduce the rated correlation for analysis of dynamics of skull freezing on a macrochiller. The thickness of the skull freezing on a macrochiller can be estimated if we know the quantity of heat taken for its heating-up. Then the macrochiller temperature is increasing due to picking up the heat of slag superheat, removal of the slag crystallization heat and heat of solidifying skull. Consequently, the heat balance equation can be written down in this way:

$$dQ = dQ_{AK} + dQ_{KP}, \tag{6}$$

where: dQ – quantity of heat absorbed by the macrochiller; dQ_{AK} – quantity of heat removed from solidified skull into the macrochiler; dQ_{KP} – heat of superheat and slag crystallization.

We define the value dQ from the condition that all the heat passing through the surface of the macrochiller during the time dt is used for its heating:

$$dQ = V_M \rho c d\bar{T}, \tag{7}$$

where: V_M – volume of macrochiller;
ρc – density and specific heat capacity of metal;
$d\bar{T}$ – change of average temperature during the time dt.

In case of spherical macrochiller we define the value $d\bar{T}$ from the solution of sphere heating problem with boundary condition of the third type [2]. We have:

$$d\bar{T} = (T_C - T_0)\sum_{n-1}^{\infty} B_n \mu_n^2 \frac{a}{R^2}\exp(-\mu_n^2 \frac{dt}{R^2})dt, \tag{8}$$

where: T_C, T_0 – temperature of medium and initial temperature of chiller; R – macrochiller radius;

$$a = \frac{\lambda}{c\rho}, \quad B_n = \frac{6Bi^2}{\mu_n^2(\mu_n^2 + Bi^2 - Bi)}, \quad Bi = \frac{\alpha R}{\lambda},$$

where: Bi – Biot number; λ = 25 kcal/m· h·°C – thermal conduction of metal; μ – roots of characteristic equation; α = 4000 kcal/m^2·h·°C – coefficient of heat-transfer by convection between macrochiller and medium.

We find the values μ and B_n according to [3]. Thus, for a spherical macrochiller:

$$dQ = \frac{4}{3}\pi R^3 \rho c(T_C - T_0)\sum_{n-1}^{\infty} B_n \mu_n^2 \frac{a}{R^2}\exp(-\mu_n^2 \frac{dt}{R^2})dt \tag{9}$$

To define the values dQ_{AK} and dQ_{KP} from the right part of the equation (6) we use the solutions obtained for the solidification of ball casting on the outside. In our example a layer of slag has to freeze on the spherical macrochiller. Taking into regard that the thickness of that layer is small we can accept the linear temperature distribution over the radius of the freezing coverage (n=1), then:

$$dQ_{AK} = 2\pi R^2 (\rho c \Delta T)^* (1 + \frac{4}{3}\delta^2) d\varepsilon, \tag{10}$$

$$dQ_{KP} = 4\pi R^2 \rho^* [\eta + c^* (T_C^* - T_{KP}^*)](1 + 2\delta + \delta^2) d\varepsilon \tag{11}$$

The values marked with asterisk relate to the medium in which the macrochiller moves that is to the slag bath.

$$\Delta T^* = T_П^* - T_{КР}^*, \tag{12}$$

where: $T_{КР}^*$ - slag crystallization temperature; $T_П^*$ - slag temperature in the points of contact with the chiller;

$\delta = \frac{\varepsilon}{R}$; ε – thickness of skull; T_C^* - temperature of medium.

After substitution of expressions (9) – (11) into the heat balance equation (6) and integration we obtain the following equation:

$$A_1\delta + A_2\delta^2 + A_3\delta^3 + \sum_{n=1}^{\infty} B_n \exp(-\mu_n^2 \frac{dt}{R^2}) - c = 0,$$

where: $A_1 = 3k(L_1 + \frac{\theta_H}{2})$; $A_2 = 3k(L_1 + \frac{\theta_H}{3})$; $A_3 = 3k(L_1 + \frac{\theta_H}{4})$; $c = A_1\delta_1 + A_2\delta_1^2 + A_1\delta_1^3 + \sum_{n-1}^{\infty} B_n \exp(-\mu_n^2 \frac{dt}{R^2})$

$$k = \frac{(\rho c)^*}{\rho c};\ \theta_H = \frac{\Delta T^*}{\Delta T_0};\ L_1 = \frac{\eta^*}{c^*\Delta T_0} + \frac{\Delta T_{ПЕР}^*}{\Delta T_0};$$

$$\Delta T_{ПЕР}^* = T_C^* - T_{КР}^*;\ \Delta T_0 = T_П^* - T_0;\ T_П^* = T_{(X)}^* = T_{КР}^* + (T_C^* - T_{КР}^*)(1 - \frac{\varepsilon}{x}),\ \text{with } x \geq \varepsilon.$$

The equation (13) connects the thickness of the skull freezing on the macrochiller with the time during which the skull acquires its maximal value and starts to melt. The equation (13) is solved with the application of software package. The following values are taken as the initial data:

ρ* = 2400 kg/m^3 – slag density;

c* = 0.3 kcal/(kg · °C) = 1260 joule /(kg · K) – specific heat capacity of slag;

ρ = 7800 kg/m^3 – metal density;

c = 0.165 (kcal/kg · °C) = 693 joule /(kg · K) – specific heat capacity of metal;

$T_{КР}^*$ = 1573 K – slag crystallization temperature;

T_C^* = 2048 K – slag temperature;

$T_П^*$ – slag temperature next to the macrochiller;

ε = 0.0006 m – thickness of the skull;

x = 0.0007 m – vicinity of the macrochiller for calculating the temperature next to the macrochiller;

T_0 = 20 °C = 293K – the initial temperature of the macrochiller;

η^* = 0.015 kg/m · sec – dynamic viscosity of slag.

B_n = 0.9959 – constant depending on the Biot number;

μ_n = 1.1656 – roots of the characteristic equation

$$B_n = \frac{6Bi^2}{\mu_n^2(\mu_n^2 + Bi^2 - Bi)}$$

After insertion of the initial data into the equation (13) we obtain the value of time during which the skull acquires its maximal value ε = 0.0006 m while the macrochiller is falling in slag (t = 0.31 sec). After that the skull starts to melt quickly and then the macrochiller itself starts to melt down.

4. Discussion (10 pt bold Times New Roman)

After the total heating of the macrochiller if it continues to move in the superheated melt the skull and the macrochiller itself start to melt down.

For quantitative assessment of the process let us assume that the heat of superheat is supplied to the macrochiller with the help of thermal conduction and convection. The condition on the melting surface of the macrochiller corresponds to it [2]

$$\rho^* \eta \frac{d\varepsilon}{dt} = \lambda^* \left(\frac{\partial T}{\partial x} \right)^*_{x=\varepsilon} + \alpha_K \left(T_C^* - T_{KP}^* \right) \tag{14}$$

In addition let us assume that in the small vicinity of the macrochiller the slag temperature field is defined with the following formula:

$$T_{(X)}^* = T_{KP}^* + \left(T_C^* - T_{KP}^* \right) \left(1 - \frac{\varepsilon}{x} \right) \tag{15}$$

with $x \geq \varepsilon$.

With account of the expression (15) the melting dynamic equation (14) is the following:

$$\eta \rho^* \frac{d\varepsilon}{dt} = \left(\frac{\lambda^*}{\varepsilon} + \alpha_K \right) \left(T_C^* - T_{KP}^* \right) \tag{16}$$

After integration of it (under the condition that $\left(T_C^* - T_{KP}^* \right)$ = const) we obtain:

$$\left(t_0 - t \right) \left(T_C^* - T_{KP}^* \right) = \eta \rho^* \left(\varepsilon - \varepsilon_0 - \frac{\lambda^*}{\alpha_K} \cdot \ln \frac{\lambda^* + \alpha_K \varepsilon}{\lambda^* + \alpha_K \varepsilon_0} \right) \alpha_K, \tag{17}$$

where: ε_0 = 0.0006 м – thickness of the skull in the moment t_0 = 0 sec;

η = 0.015 kg/m · sec – slag viscosity;

ρ^* = 2400 kg/m^3 – slag density;

λ^* = 7 joule /m · sec · ºC – slag thermal conduction;

α_K = 4667 joule /m^2 · sec · ºC – coefficient of heat-transfer with convection.

Inserting the initial data into the formula (17) we discover that the skull will melt down within 0.03 sec while the macrochiller is passing through the slag bath. Inserting the values of metal density, macrochiller radius in the moment t_0 = 0 sec and metal thermal conduction we can define the time during which the macrochiller itself melts down in the slag bath. This time is equal to 0.63 sec [4]. Thus, while passing through the slag bath the macrochiller and the skull melt down totally and reach the metal bath as a drop of liquid metal. It can be shown as a diagram (figure 1).

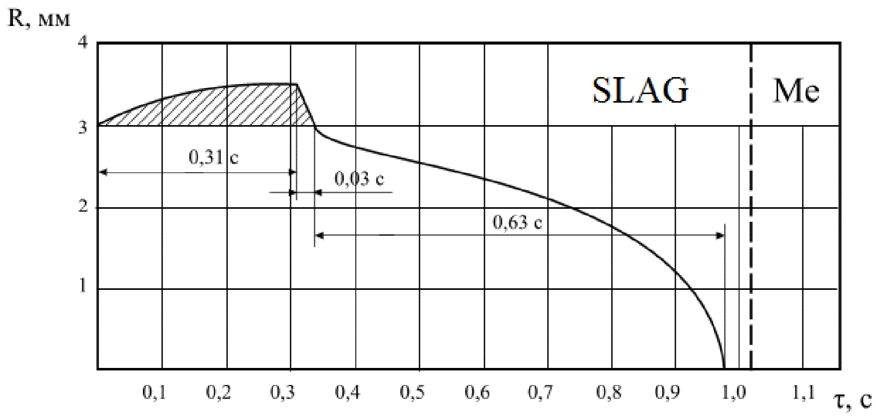

Fig. 1 Freezing and melting of slag on the macrochiller with diameter 6 mm and further melting of the macrochiller (the skull is hatched)

5. Calculation of macrochiller delivery rate

Let us calculate the volume and mass of one cylindrical macrochiller:

$$V_i = \pi R^2 \cdot l, \tag{18}$$

where: R – radius of the base of cylindrical macrochiller;

l – length of the macrochiller;

$$m_i = \rho \cdot V_i, \tag{19}$$

where:

V_i – volume of the macrochiller;

ρ – density of the macrochiller metal;

According to the formulas (18) and (19) we obtain:

$$V_i = 3{,}14 \cdot 0{,}003^2 \cdot 0{,}006 = 1{,}7 \cdot 10^{-7}\,\text{м}^3,$$

$$m_i = 7800 \cdot 1{,}7 \cdot 10^{-7} = 1{,}326 \cdot 10^{-3}\,\text{кг}$$

As during the remelting period (τ=15504sec=4,31hours, pilot melting) it is possible to input 233 kg of macrochillers we can calculate the rate of macrochiller delivery into the slag bath:

$$\upsilon_{M/X} = \frac{m_i \cdot \tau}{233}$$

We obtain:

$$\upsilon_{M/X} = \frac{1{,}326 \cdot 10^{-3} \cdot 15504}{233} \approx 0{,}1\,\text{c} \tag{20}$$

Thus, the rate of macrochiller delivery into the slag bath is 1 macrochiller per 0.1 sec. If we use two dosers the delivery rate is 1 macrochiller per 0.2 sec for each doser. On the basis of the obtained results some specific technological recommendations can be elaborated.

References

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