DESIGN OF ELECTROMAGNETIC STIRRING CONDITIONS INVOLVING CONTINUOUS CASTING OF STEELS

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A method is proposed to determine effective electromagnetic stirring conditions involving continuous casting which is reduced to an exhaustive search of the sets of the effective impurity diffusion coefficient and melt velocity values and determination of appropriate operating conditions of an inductor.

A mechanism of electromagnetic stirring (EMS) may be explained as a result of interaction of electrodynamic, magnetohydrodynamic, and metallurgical factors. One of the most essential EMS advantages lies in the fact that this process ensures formation of equiaxed crystals during solidification of a continuously cast ingot. This is attributed to the interaction of two main factors. The first factor is that the tops of dendrites undergo failure or fusion and serve as the centers of formation of equiaxial crystals. The second factor consists in removal of metal superheat as a result of high convective heat transfer on the front of solidification and fusion of dendrites. A liquid metal is supercooled because of supercooling the dendrites tops and just from this moment equiaxed crystals begin to grow [1, 2].

A favorable EMS effect on all kinds of axial segregation, including which resulted from formation of bridges, the V-shaping, and the segregation associated with bulging of ingot faces may be attributed to a less pronounced tendencey of the equiaxial structure to form such defects.

When designing EMS units (EMSU) and casting technologies, the problems arise concerning a choice of rational (from the viewpoint of cast metal quality) stirring schemes, layout of a stirring zone, electrotechnical parameters of the units, and their operating conditions. In order to answer these questions, use is often made of indirect quality criteria, i.e., the magnitude of magnetic induction, the density of electromagnetic forces, and the velocity of metal motion at the crystallization front.

To determine effective EMS conditions, it is necessary to take into consideration the following four groups of factors:

a) EMSU electromechanical parameters (the number of pole pairs, pole pitch, the number of turns per an inductor phase);

b) physical characteristics of a test alloy (coefficients of mass density, specific heat, thermal conductivity, viscosity of a melt, etc.);

c) a permissible, as regards item specifications, degree of finite chemical inhomogeneity (ΔC);

d) operating conditions of the stirring unit allowing variation (control) of parameters (voltages and current loads per inductor phase, the direction of an acting electromagnetic force, the current frequency, the reversal period, etc.).

Obviously, the first two groups of factors are given, while the second two groups are interrelated between each other so that a change of the EMS operating conditions (group c) entails a change in the obtained degree of chemical inhomogeneity of a continuously cast ingot. To determine the mentioned interrelation, it is necessary to use some indices of the process of impurity mass transfer in the liquid core of an ingot, namely, the average velocity of a melt flow along the crystallization front v_{av} and effective transfer coefficient of the impurity in the moving melt D_L. Under rather general conditions, the dimensional and similarity theories may be employed to establish the relation of the finite degree of impurity macrosegregation (in a completely solidified ingot) in a dimensionless form

$$\left(\frac{\Delta C}{C_0}\right)^{n_1} \mathrm{Re}^{n_2} = \mathrm{const}, \tag{1}$$

where n_1 and n_2 are some yet unknown numbers.

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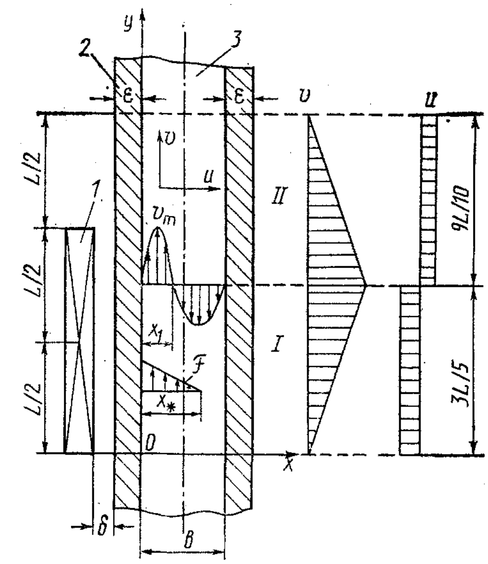

Fig. 1. Velocity distribution of the melt flowing around the crystallization front: 1) inductor of a running electromagnetic field; 2) solid shell of the ingot with thickness ε; 3) liquid core of the ingot.

Extracting the n_1-th root from the both sides of (1) and assuming $n = n_1/n_2$, we obtain

$$\frac{\Delta C}{C_0}\mathrm{Re}^n = A = \mathrm{const}, \tag{2}$$

where the constants A and n are to be determined. On the assumption of the parabolic velocity distribution of the melt flow running about the crystallization front (Fig. 1), it may be assumed that $v_{av} \approx 0.67\, v_m$, then

$$\mathrm{Re} = 0{,}67\,\frac{v_m(R-\varepsilon)}{\nu}, \tag{3}$$

where the melt viscosity coefficient ν and the solid shell thickness ε are considered to be known for the inductor operation zone, while the maximum flow velocity v_m is related with the amplitude of an electromagnetic force F_0 as

$$v_m^2 = EF_0. \tag{4}$$

From the kinematic considerations of a possible melt velocity field in the inductor operation zone (Fig. 1) on sections I and II with an account of the equations of continuity and total energy

$$Э = \int_0^{3L/2}\int_0^{b}\left[2\left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial v}{\partial x}\right)^2\right]dxdy - \frac{A}{\rho\nu}\int_0^{L}\int_0^{x_*}(1 - x/x_*)\,dxdy,$$

we derive the equation for the coefficient E which is representative of the role of physical properties of the melt and the flow kinematics:

$$E = \left\{7{,}93L\left[\left(1 - \frac{b}{5x_*}\right) + \frac{5q}{54}\left(25\frac{x_*^3}{b^3} - 70\frac{x_*^2}{b^2} + 60\frac{x_*}{b} + \right.\right.\right.$$
$$\left.\left.\left. + 64\frac{b}{25x_*} - \frac{104}{5}\right)\right]\right\} \Big/ \left[\rho\left(\frac{b}{L} + \frac{35}{16}\frac{L}{b}\right)\right]. \tag{5}$$

Compare the calculation by formulas (4) and (5) with the experimental data obtained by Vives and Perry [3] at $F_0 = 10^3$ N/m^3; b = 0.03 m; L = 0.1 m; $x_* = b$; $\rho = 6950$ kg/m^3.

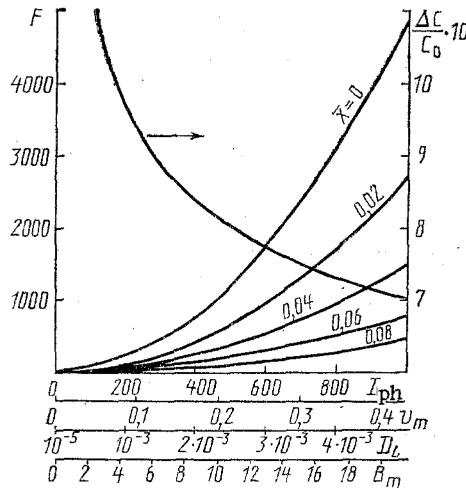

Fig. 2. Nomogram for determination of electromagnetic stirring operating conditions involving casting of carbon steels.

Substituting these data into formulas (4) and (5), we find $v_m = 0.087$ m/sec. In [3], the velocity $v_m = 0.1$ m/sec is obtained that testifies to satisfactory accuracy of the calculations.

Note that the amplitude magnitude of the force F_0 depends on the linear current density and electrotechnical characteristics of the inductor. On the other hand, the melt velocity specifies the mass transfer rate in a liquid ingot core. As is shown in [4, pp. 139, 140] in the case of the turbulent melt flow, the effective diffusion coefficient of an impurity in the melt may be assumed to be equal to:

$$D_L = 0{,}67 a_0^2 (R - \varepsilon) v_m, \tag{6}$$

where $a_0 \approx 0.41$.

Solution of a conjugate system of the heat conduction and impurity diffusion equations at a given D_L allows the degree of the macrosegregation $\Delta C = \bar{C} - C_0$ to be established, i.e., the relation

$$\Delta C = f(D_L). \tag{7}$$

If the empirical coefficients A and n are known, then the procedure of determining the effective electromagnetic stirring conditions involving continuous casting of ingots is reduced to the following sequence of operations:

1) thermophysical characteristics of the test steel grade are determined (with an account of its chemical composition);

2) inductor location and its extension along the ingot axis (L) are chosen;

3) heat transfer coefficients on an external cooled surface of the ingot are specified;

4) the heat conduction problem is solved for a solidifying ingot with the given cross-section at a prescribed casting rate and the thickness of the solid shell ε of the ingot is determined in the inductor zone [5];

5) the value of the effective coefficient of impurity transfer (diffusion) D_L is chosen and the system of the macrosegregation equations is solved to give the finite degree of segregation ΔC;

6) from the formula $v_m = D_L/[0.67 a_0^2 (R - \varepsilon)]$ at the known R, ε, D_L the melt velocity along the crystallization front is determined;

7) the amplitude magnitude of the electromagnetic force is determined by the formula $F_0 = v_m^2/E$;

8) parameters of electric and magnetic fields of the inductor (J, B_x^0, etc.) at the known inductor characteristics and the given amplitude of an electromagnetic force are found.

If the finite degree of macrosegregation obtained in the calculations is unsatisfactory for technological reasons, then the calculation is repeated at a new D_L and new values of the electromagnetic force F_0 and operation conditions of the inductor (J, B_x^0, etc.) are found.

Thus, in the general case the determination of rational operation conditions of electromagnetic stirring is reduced to an exhaustive search for the variants of setting the parameters D_L and v_m and determination of the appropriate operation parameters J, B_x^0 of the inductor. The coefficients A and n in the general relation (2) are to be determined in the course of physical or numerical experiments.

The described procedure has been used when designing the induction EMS technology on a blooming continuous casting machine. The study of the design and characteristics of the inductor has allowed determination of the magnetic induction B_m, diffusion coefficient D_L, and finite degree of inhomogeneity of carbon distribution $\Delta C/C_0$ as a function of the phase current of the inductor I_{ph}. These results are generalized in the form of a nomogram (Fig. 2) and permit us to offer EMS operation conditions for attaining the required $\Delta C/C_0$. In particular, for casting the high-carbon steel at 70 K we propose I_{ph} = 600 A that ensures the degree of chemical inhomogeneity ΔC no more than 0.05%.

NOTATION

ΔC, degree of finite chemical inhomogeneity, %; A, n, constants; v_m, melt flow velocity, m/sec; D_L, effective diffusion coefficient, m^2/sec; R, ε, b, geometric parameters of the ingot, m; L, length of the active inductor zone m; x_*, depth of electromagnetic force penetration into the liquid ingot core, m; F, electromagnetic force, N/m^3; I_{ph}, phase current of the inductor, A; B_m, field intensity, mT.

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