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PROCEDURE OF CALCULATION OF THE AXIAL CHEMICAL INHOMOGENEITY OF SOLIDIFYING STEEL INGOTS

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A physicomathematical model and a procedure of calculation of the basic indices of axial chemical inhomogeneity in continuously-cast steel billets have been developed. The influence of the processes of convective transfer in the two-phase zone of the alloy on the occurrence and development of axial chemical inhomogeneity has been shown.

Keywords: *physicomathematical model, axial chemical inhomogeneity, pressure pulse.*

Introduction. Steel ingots crystallize to form a two-phase zone representing the interlacing of dendritic crystallites with the mother melt. There is reason to believe that the latter moves within the two-phase zone with velocities much higher than the velocity of molecular diffusion of impurities [1–4]. The assumption of convective impurity transfer has been used in [5, 6], when the process of occurrence of off-center chemical inhomogeneity in steel ingots was explained. A physicomathematical model of the process of occurrence of axial chemical inhomogeneity in continuously-cast steel billets has been proposed in [7]; the model is based on the idea of impurity transfer in the two-phase zone under the influence of the pressure difference due to the presence of negative pressures in the shrinkage zone of the billets. Below, we give the basic propositions of a semiempirical procedure of evaluation of the basic indices of axial chemical inhomogeneity.

Analysis of Procedures of Calculation of Axial Chemical Inhomogeneity in Continuously-Cast Billets. Figure 1 gives the simplest diagram for determination of the pressure field in the axial zone of continuously-cast billets, in accordance with which the liquid core of a solidifying billet is separated into two zones, as far as the degree of mobility of a melt is concerned: in the upper zone of height H, the melt moves relatively freely under the action of a nonuniform temperature field (thermogravitational convection), whereas the lower zone of height L is formed by the interlacing of dendritic crystallites and the movement of the melt in this zone obeys the laws of filtration theory. In accordance with Darcy's empirical formula, the velocity of melt flow in the filtration zone is related to the pressure gradient by the linear relation

$$v = -\frac{K}{\mu}\,\mathrm{grad}\,P\,. \tag{1}$$

Under the assumption of the stationary regime of melt flow, the local value of pressure at a distance x from the bottom part of the liquid core is determined by the expression [3]

$$P = P_{\mathrm{a}} + \rho g H - \frac{\beta}{1-\beta}\,\frac{\mu}{2K}\,\frac{d\psi}{dt}\,(L^2 - x^2)\,. \tag{2}$$

In [8, Chapter 3], A. V. Veinik has given results of the experiments on determination of the permeability of model alloys (Al–Sn and Pb–Sn) and has generalized experimental data of other researchers for 35L-grade steel and AL7 alloy. According to [8], the average values of the permeability coefficient for the above alloys vary within comparatively narrow limits ($K = 10^{-11}$–10^{-12} m^2). Calculations from formula (2) require that the function $d\psi/dt$, i.e., the local rate of rise of the solid phase in the shrinkage zone of a solidifying ingot, be prescribed. In the simplest case

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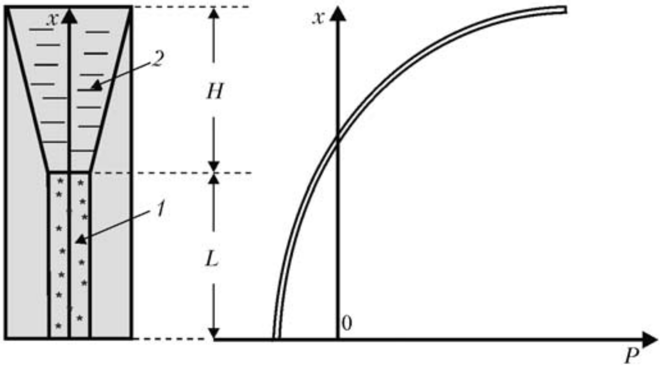

Fig. 1. Diagram of internal-pressure distribution along the axial zone of a solidifying billet: 1) shrinkage zone; 2) feed zone.

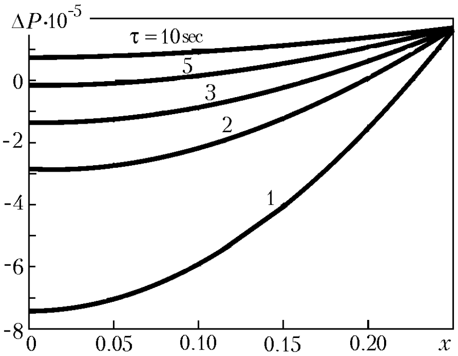

Fig. 2. Internal-pressure distribution along the billet axis for different values of the "time of solidification of the melt in the shrinkage zone" τ. ΔP, Pa; x, m.

we use the assumption of a constant rate of solidification of a melt in the axial zone of a continuously-cast billet and introduce the arbitrary "time of solidification of a melt in the shrinkage zone:"

$$\tau = (\partial\psi/\partial t)^{-1} . \tag{3}$$

Figure 2 gives the pressure-difference distribution along the portion of the axial zone of the billet of height L (see Fig. 1):

$$\Delta P = -\frac{\beta}{1-\beta}\frac{\mu}{2K}\frac{d\psi}{dt}(L^2 - x^2)$$

with the prescribed physical properties of the molten steel $\beta = 0.045$, $\rho = 6900\ \text{kg/m}^3$, and $\mu = 0.0062$ Pa·sec and values of a number of parameters: $K = 10–11\ \text{m}^2$, $L = 0.25$ m, $H = 1$ m, and $\tau = (\partial\psi/\partial t)^{-1} = 1, 2, ..., 10$ sec. It follows from the figure that a major part of the zone of the continuously-cast billet (from $x = 0.11$ m to $x = 0.24$ m) is exposed to negative pressure, which contributes to the development of porosity and to convective impurity transfer to the axial zone of solidifying billets [7]. In a more general case we must find the rate of solidification of a melt on the basis of numerical solution of the corresponding heat-conduction problem for a solidifying billet.

Modeling of the Process of Formation of Axial Chemical Inhomogeneity in Continuous Casting of Steel. Today's description of thermophysical processes in a solidifying steel billet is based on the idea of crystallization of steel in the temperature interval between the liquidus and the solidus and inevitable occurrence of a two-phase zone representing the interlacing of dendrites and the melt and separating the portions of a completely solidified crust and the liquid core of the billet. A fairly complete theoretical description of this phenomenon has been presented in [9, 10].

The release of the heat of aggregate transformation in the above works is allowed for by introduction of the heat source into the equation of nonstationary heat conduction, whose parameters are dependent on the form of a transformation (alloy-state) diagram and the specific heat of transformation Q:

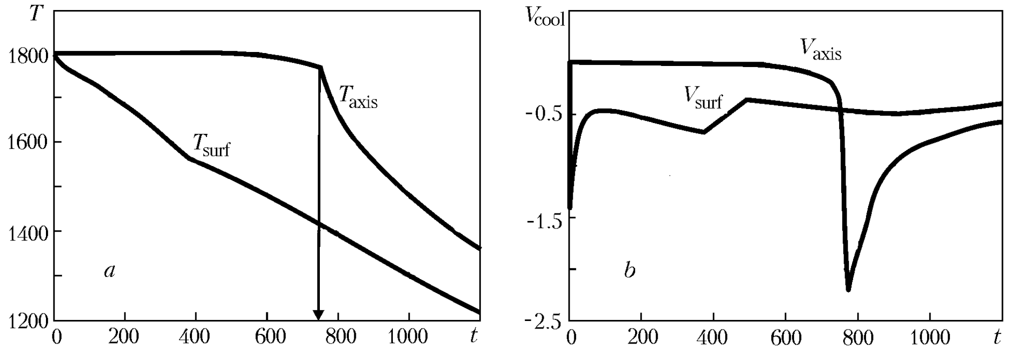

Fig. 3. Time change in the temperatures (a) and the cooling rates (b) on the axis and surface of a continuously-cast steel billet of diameter 0.2 m. T, K; t, sec.

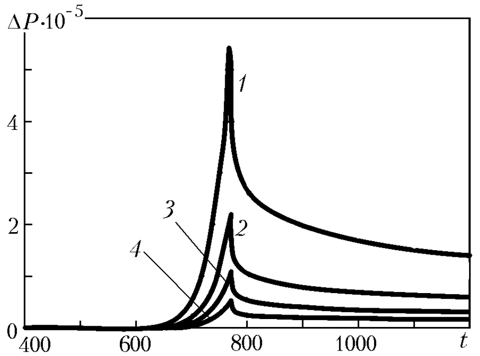

Fig. 4. Time change in the pressure difference on the axis of a billet of diameter 0.2 m in accordance with formula (6) for a few values of the permeability coefficient of the two-phase zone: 1) $K = 10^{-12}$, 2) $0.25{\cdot}10^{-11}$, 3) $0.5{\cdot}10^{-11}$, and 4) 10^{-11} m^2. ΔP, Pa; t, sec.

$$\rho c \frac{\partial T}{\partial t} = \mathrm{div}\,(\lambda\ \mathrm{grad}\ T) + \rho Q \frac{\partial \psi}{\partial t}\,. \tag{4}$$

With the corresponding boundary conditions, Eq. (4) is solved by a numerical method and offers information on the temperature field of the solidifying ingot and on the cooling rates on its individual portions to the researcher. Figure 3 shows, as the simplest example, the time change in the temperatures and cooling rates on the axis and surface of a steel billet with a circular cross section (diameter $d = 0.2$ m) with the following prescribed parameters of the process: $\rho = 7000$ kg/m^3, $c = 650$ J/(kg·K), $\lambda = 40$ W/(m·K), and $Q = 2.65{\cdot}10^5$ J/kg.

The calculation has been carried out for 30KhGSA-grade steel possessing a wide crystallization interval ($T_{liq} = 1788$ K and $T_{sol} = 1658$ K) with the prescribed initial temperature $T_{in} = 1800$ K and conditions of convective heat exchange on the cooled billet surface $T_s = 773$ K and $\alpha = 250$ W/(m^2·K)).

Such calculations of the solidification of castings with numerical methods has now become the practice of investigations of casting and ingot solidification [11]. The found quite substantial growth in the cooling rate on the billet axis in the final period of crystallization plays an important role in analyzing the pressure field in the billet's axial zone. As is clear from Fig. 3b, the cooling rate on the billet axis rapidly rises from 0.01 to 2.2 deg/sec during the crystallization interval (about 160 sec).

Let us assume that the solidification rate $d\psi$ appearing in the Flemings solution (2) is in direct proportion to the cooling rate $V_{cool} = \partial T/\partial t$:

$$\frac{d\psi}{dt} = \mathrm{const}\ (\partial T/\partial t)\,. \tag{5}$$

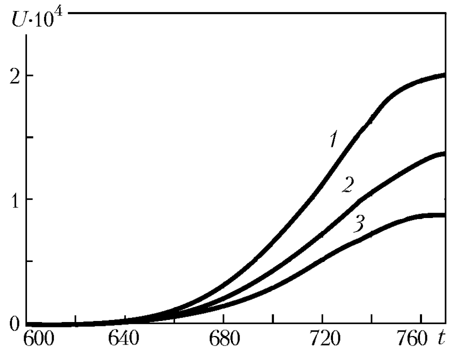

Fig. 5. Time change in the melt-flow velocity in the shrinkage zone for the following values of the permeability coefficient of the two-phase zone: 1) $K = 10^{-11}$, 2) $0.5 \cdot 10^{-11}$, and 3) 10^{-12} m^2. U, m/sec; t, sec.

In this case the pressure difference at the beginning of the shrinkage zone on the billet axis is found, according to the Flemings formula, as

$$\Delta P = -\frac{\beta}{1-\beta}\frac{\mu}{2K}\frac{AV_{\text{cool}}}{\delta T_{\text{cr}}}, \tag{6}$$

where we have taken const $= A/(T_{\text{liq}} - T_{\text{sol}}) = A/\delta T_{\text{cr}}$.

Figure 4 gives the time change in the pressure difference on the axis of a steel billet of diameter 200 mm, when a few values of the permeability coefficient and $A = 3.3852$ are prescribed; the time change in the rate of cooling of the metal on the billet axis is taken in accordance with Fig. 3b. From a comparison of Figs. 3b and 4, we may infer that the pressure pulse in the billet's shrinkage zone changes in synchronism with the cooling rate; the maximum value of the pressure difference is in inverse proportion to the value of the permeability coefficient of the two-phase zone.

The pulse occurrence of the pressure difference in the shrinkage zone of a solidifying billet inevitably leads to an inflow of the mother melt from adjacent regions of the two-phase zone. Where the concentration of the impurity (sulfur, phosphorus) or any component of the alloy (carbon, manganese, silicon) in the mother melt exceeds the initial concentration of this component under the action of the process of dendritic liquation, the pulse change in the pressure difference on the billet axis will inevitably lead to an enrichment of the axial zone with this component. This is how one possible explanation for the occurrence of chemical inhomogeneity in continuously-cast steel billets looks like.

Change in the concentration of the impurity in the shrinkage zone under the influence of the inflow of the impurity excess from adjacent regions can be described with the use of the following system of equations:

$$\frac{\partial C}{\partial t} + \nabla (C\mathbf{U}) = \nabla (D \nabla C), \tag{7}$$

$$\rho \frac{\partial U}{\partial t} - \mu \nabla^2 U + (\mu/K)\, U + \nabla P = \mathbf{F}. \tag{8}$$

Here Eq. (7) describes the process of convective diffusion in the shrinkage zone and (8) determines the velocity of movement of the melt in this zone. Both equations are integrated by the finite-element method with the specified initial conditions

$$C = C_{\text{in}}, \quad P = 0 \quad \text{at} \quad t = 0. \tag{9}$$

For Eq. (7), we use the boundary condition $C = C_{\text{exc}}$ at the boundary of the zones (for $x = L$), where C_{exc} is the excess concentration in the interdendritic space of the feed zone, which is a result of the process of dendritic liquation. In [22], in investigating the dendritic liquation of manganese and sulfur in continuously-cast 09G2S-steel bil-

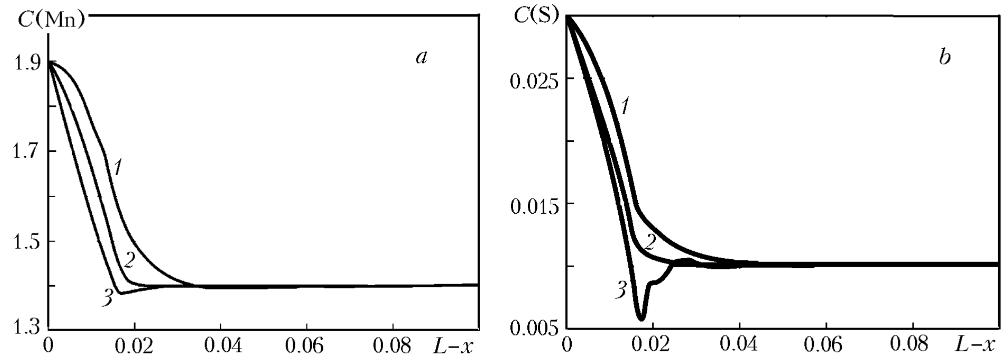

Fig. 6. Distributions of manganese (a) and sulfur (b) along the shrinkage zone of a 09G2S-steel billet of diameter 200 mm for the final instant of the process of solidification (t = 770 sec), obtained by calculation for different values of the volume-shrinkage coefficient: 1) $\beta = 0.045$, 2) 0.03, and 3) 0.02, $D = 0.38 \cdot 10^{-8}$ m^2/sec, and $K = 10^{-12}$ m^2. C, %; L–x, m.

lets, Kumanin has recorded the following values of concentrations in the interdendritic space: $C_{\text{exc}}(\text{Mn}) = 1.9\%$ ($C_{\text{in}} = 1.4\%$) and $C_{\text{exc}}(\text{S}) = 0.03\%$ ($C_{\text{in}} = 0.01\%$).

Let us assume that the temperature field of solidifying 09G2S-steel billets of diameter 0.2 m can be described by the plots of Fig. 4 and evaluate the degree of enrichment of the shrinkage zone of such billets by solution of the above equations of melt motion and convective diffusion. Figure 5 gives results of the solution of Eq. (8) in the form of the time change in the melt-flow velocity at the point $x = L/2 = 0.125$ m for three values of the shrinkage coefficient β and with allowance for the pressure pulse in accordance with Fig. 4. The obtained plots of the change in the melt velocity with time have been used in numerical solution of the equation of convective diffusion (7).

Figure 6 gives calculation results for the instant of completion of the solidification of the alloy on the billet axis for different values of the shrinkage coefficient of the alloy. In the calculations, we have used the above values of the concentration of the component of steel (manganese) and the impurity (sulfur) from [12].

Conclusions. The calculation results enable us to draw certain conclusions on the influence of a pressure pulse on the impurity distribution in the shrinkage zone. First of all, we emphasize that the velocities of movement of the melt in the shrinkage zone are comparatively low (fractions of millimeters a second), which is consistent with the calculation results in [7].

Also, noteworthy is the fact that the depth of penetration of the excess-concentration front of the impurity within the shrinkage zone L^* does not exceed 4–5 cm, which determines the length of corresponding defects of the V-segregation type in the axial zone of continuously-cast billets [6]. As follows from Fig. 6, the change in the shrinkage coefficient within $\beta = 0.03$–0.045 is accompanied by a change of no more than 1–1.5 cm in the index L^*, which confirms the possibility of evaluating the indicated index with a known uncertainty in the coefficient of volume shrinkage of the alloy.

The presented physicomathematical model confirms the substantial influence of the possess of convective transfer in the two-phase zone of a solidifying alloy on the development of the axial chemical inhomogeneity of continuously-cast steel billets.

NOTATION

A, pouring-out ability; C, concentration of the impurity, %; c, heat capacity, kJ/(kg·K); D, diffusion coefficient, m^2/sec; d, diameter, m; $\mathbf{F}$, external-force vector; g, free-fall acceleration, m/sec^2; H, melt height in the upper zone, m; K, permeability coefficient of the dendritic net, m^2; L, melt height in the lower zone, m; Q, specific heat of transformation, J/kg; P, pressure, Pa; T, temperature, K; t, time, sec; U, velocity; $\mathbf{U}$, velocity vector; V_{cool}, cooling rate, deg/sec; v, melt-flow velocity, m/sec; x, running coordinate, m; α, heat-exchange coefficient, W/(m^2·K^4); β, coefficient of volume shrinkage in solidification; λ, thermal conductivity, W/(m·K); μ, dynamic viscosity of the melt, Pa·sec; ρ, mass density of the melt, kg/m^3; ψ, fraction of the solid phase at a distance x from the bottom part of the liquid core; τ, arbitrary solidification time, sec. Subscripts: a, atmospheric; exc, excess; cr, crystallization; liq, liquidus; in, initial; axis, axis; cool, cooling; surf, surface; sol, solidus; s, surroundings, medium.

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