BRIEF COMMUNICATIONS

NATURAL CONVECTION IN THE MOLTEN CORE OF A KILLED STEEL INGOT

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As we have shown earlier [1-3], the molten steel in the core of an ingot is intensely agitated for a very long time while it is hardening (for a 7 mg killed steel ingot the convection time is 80 min). As the killed steel hardens, the layers of liquid metal at the crystallization front descend; here, in the lower portion of the still molten core of the ingot there is a gradual accumulation of stationary melt and the boundary between the convective metal and the stationary metal moves upward with time.

We can list some causes responsible for the observed mixing of the melt while the ingot is hardening:

1) Agitation of the melt as a result of the mechanical effect of a jet of metal during pouring. However, calculation shows that it is not possible to explain the very long convection time by the effect of a metal jet during pouring.

2) Agitation of the melt as a result of natural heat convection. Here the metal is molten because it is above the liquidus temperature and the colder layers at the crystallization front descend, forcing the lighter metal at the center of the ingot upward [4, 5]. Clearly, when heat is removed, natural convection must cease. According to Ivantsov [6] and the experimental data of Tageev and Gulyaev [7] it takes 10 min for the excess heat to be removed from the center of an ingot weighing 7 mg so that it is quite impossible to explain the very long ingot convection time in terms of this factor.

3) Some researchers [8] assume that the basic principle responsible for convection in a hardening ingot is the shrinkage of the metal during hardening.

To verify this hypothesis a bismuth ingot weighing 13 kg was cast in a steel cylindrical mold. After the ingot was cast, the radioactive isotope thallium-204 was added to the mirror. As is clear from the autoradiograms obtained from this ingot (Fig. 1), the thallium isotope, being entrained by the convective flow, penetrates deeply into the ingot although nothing can be said about shrinkage. In this case, the metal at the side crystallization front ascends. One exception is bismuth, which expands rather than shrinks during hardening.

4. Agitation of the melt as a result of the appearance of concentrated impurity streams during the process which, naturally, can explain the observed descending metal current.

5. Melt convection as a result of the formation of a nucleating solid phase at the crystallization front and the subsequent descent of the enriched melt along the crystallization front.

We shall calculate the change in the volume of the circulating melt with time for a prismatic killed ingot, assuming that in addition to heating the steel above the liquidus line convection is also caused by the presence of solid-phase particles in the boundary layer. To do this the entire hardening period is divided into two stages.

In the first stage of the process when overheating is still present, the melt current descends along the crystallization front because of natural convection. Here flow and heat exchange are turbulent.

After elimination of overheating, there is a descending flow of metal along the crystallization front in the second stage of the process; this is due to the enrichment of the boundary with solid-phase nuclei. Metal flow in this stage is laminar. The melt enriched by solid-phase nuclei accumulates in the lower portion of the ingot; when the concentration of the solid phase passes the metal creep boundary, mixing in this region of the ingot ceases. On the basis of the data of Nekhenedzi [9] and Khvorinov [10] we can assume that the steel is still capable of flowing in the viscous state when up to about 20% of the solid phase is present.

The thermal balance equation for the second stage of the process can be written as

$$\bar{\alpha}\,\theta\, S_{\mathrm{cr}}\, d\tau = -\left(\frac{1}{5}\rho + c\,\theta\right)\gamma\, dV_{\mathrm{cr}}\,. \tag{1}$$

The left side of (1) represents the amount of heat which is transmitted during natural convection to the hardened crust within a time $d\tau$; the right side represents the amount of heat which is lost by an elementary volume dV_{cr} of metal descending into the lower part of the ingot within a time $d\tau$. The latter occurs because of the liberation by the latent heat of crystallization of 20% of the solid phase of volume dV_{cr} (which is responsible for the factor 1/5) and its cooling to a magnitude of θ.

The temperature head θ in this case will be determined by the difference between the liquidus temperature and the equilibrium temperature of steel containing 20% of the solid phase. From the iron-carbon state diagram, we can assume $\theta = 15°$ C for steel 5.

The heat transfer coefficient for convection at a vertical plate in the laminar mode [11] is

$$\bar{\alpha} = 0.7\,\lambda \mathrm{Pr}^{1/2}(0.952 + \mathrm{Pr})^{-1/4}\left(\frac{g\beta}{\nu^2}\right)^{1/4} h^{-1/4}\,\theta^{1/4}. \tag{2}$$

Substituting the value for $\bar{\alpha}$ into (1) and allowing for the fact that for a prismatic ingot whose base is a square with length a,

$$S_{\mathrm{cr}} = 4\,(a - 2k\sqrt{\tau}\,)\,h, \tag{3}$$

$$V_{\mathrm{cr}} = (a - 2k\sqrt{\tau}\,)^2 h, \tag{4}$$

the thermal balance equation becomes

$$-\frac{\alpha V_{\mathrm{cr}}}{V_{\mathrm{cr}}^{3/4}} = A\,\frac{d\tau}{(a - 2k\sqrt{\tau}\,)^{1/2}}\,, \tag{5}$$

$$A = \frac{2.8\,\lambda \mathrm{Pr}^{1/2}(0.952 + \mathrm{Pr})^{-1/4}\left(\dfrac{g\beta}{\nu^2}\right)^{1/4}\theta^{5/4}}{\left(\dfrac{1}{5}\rho + c\,\theta\right)\gamma}\,. \tag{6}$$

After integrating (5) we obtain

$$\left(\frac{V_{\mathrm{cr}}}{V}\right)^{1/4} = 1 + \frac{A}{6k^2V^{1/4}}\times$$

$$\times\left[(a - 2k\sqrt{\tau}\,)^{1/2}(k\sqrt{\tau} + a) - a\sqrt{a}\right]. \tag{7}$$

Expanding $(\alpha - 2k[\tau]^{1/2})^{1/2}$ in powers of τ and limiting ourselves to the first three terms, we obtain

$$\frac{V_{\mathrm{cr}}}{V} = \left(1 - \frac{A}{4V^{1/4}a^{1/2}}\,\tau - \frac{Ak}{12V^{1/4}a^{3/2}}\,\tau^{3/2}\right)^4. \tag{8}$$

To numerically calculate convection for the specific case of a 7 mg killed steel ingot we use the following parameters [6]: $\gamma = 7000$ kg/m^3; $c = 837$ J/kg · deg; $\rho = 2.68 \cdot 10^5$ J/kg; $\mathrm{Pr} = 0.125$; $\lambda = 23.3$ J/m · sec · deg; $\nu = 0.5 \cdot 10^{-6}$ m^2/sec; $a = 0.66$ m; $k = 3.4 \cdot 10^{-3}$ m//sec$^{1/2}$. Then,

$$\frac{V_{\mathrm{cr}}}{V} = (1 - 0.47\,\tau - 0.05\,\tau^{3/2})^4, \tag{9}$$

if the time is measured in hours.

To experimentally study the mixing kinetics of the metal zone boundary contributing to convective motion additives of the radioisotope Fe^{59} were introduced onto the metal mirror of five test killed

Fig. 1. Autoradiogram of bismuth ingot activated by thallium-204. The indicator was introduced on the metal surface immediately after casting.

steel ingots each weighing 7 mg, at various times after casting. The hardened ingots were then rolled into a square billet of cross section 120 × 120 mm^2. Autoradiograms (using the method described previously [1-3]) of the transverse templets selected at 5% intervals along the length of the billet were taken; from these autoradiograms the depth of penetration of the isotope into the ingot was determined. The depth of penetration of the isotope as a function of the time the additive was introduced is linear throughout the range studied [12].

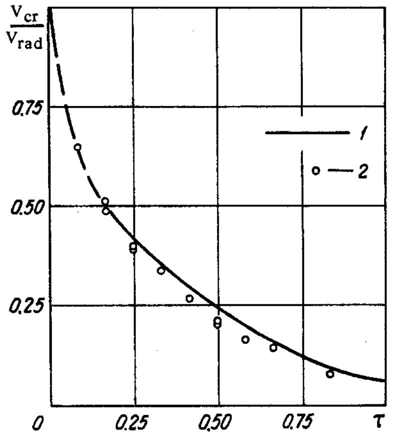

Fig. 2. Change in time of convective metal volume (τ is the time (beginning from the time casting begins) in hours): 1) theoretical curve; 2) experimental data obtained by the radioactive indicator method.

By knowing the change in depth of penetration of the isotope with time we can calculate the change in volume of the convective metal V_{cr}. The theoretical curve (9) is compared with the experimental data obtained for the change in time of the volume of convective metal V_{cr} (Fig. 2). There is almost complete agreement. The solution corresponding to (9) at the boundary in Fig. 2 begins 10 minutes after casting is ended; the dashed line represents the change in the ratio of the liquid-metal volume V_{cr} to the volume of the mold V_{rad} during the first stage of the process when the ingot is still overheated.

NOTATION

$\bar{\alpha}$ is the heat transfer coefficient averaged over the height of the ingot; θ is the temperature head in a horizontal ingot cross section and is equal to the difference in temperature at the center of the ingot and at the boundary of the hardened crust; S_{cr} is the surface area common to the circulating metal and hardened crust; V_{cr} is the volume of circulating metal; c is the specific heat of the melt; γ is the specific gravity of the melt; ρ is the heat of crystallization; τ is the time; h is the height of the circulating-metal zone; β is the coefficient of thermal expansion; g is the gravitational acceleration; ν is the kinematic viscosity; and λ is the coefficient of heat conductivity.

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POLYTROPIC EXPONENT OF COMPRESSION OF A MOIST GAS

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Papers [1-4] dealt with the effect of moistening of air on the characteristics of compression in the absence of external heat transfer and on the following assumptions: The evaporated moisture and the air have the same specific heat; the heating of the liquid during compression is negligible; and the exponent n is constant during compression. The vapor formed by evaporation of the moisture is assumed to be saturated.

We consider a thermally homogeneous thermodynamic system composed of an ideal gas and a liquid uniformly dispersed throughout the volume of the system. The liquid drops are internal heat sinks. The system interacts thermally and mechanically with the surrounding medium. We write the heat balance for the elementary polytropic compression of the system with the instantaneous value of the exponent n:

$$\delta Q_n = \delta Q_r + \delta Q' + \delta Q_0, \tag{1}$$

where $\delta Q_n = (M_1 c_{V_1} + M_2'' c_{V_2})(k - n/n - 1)dT$ is the heat of the polytropic process.

Assuming that the dispersed moisture does not significantly affect heat exchange with the surrounding medium we write the expression for δQ_0 in terms of the polytropic exponent of compression n_0 of the dry gas

$$\delta Q_0 = (M_1 c_{V_1} + M_2'' c_{V_2}) \frac{k_0 - n_0}{n_0 - 1} dT,$$

where k_0 is the adiabatic exponent of the dry gas.

Substituting the expressions for δQ_n, δQ_r, $\delta Q'$ and δQ_0 in (1) and introducing the symbols $x = M_2''/M_2$, the relative concentration of evaporated moisture, $\mu = M_2/M_1$, the initial moisture content of the gas, we obtain