DIAGNOSIS OF THERMAL REGIMES ON CONTINUOUS STEEL-CASTING MACHINES

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UDC 536.024:666.76:669.046

This article examines questions related to the use of inverse problems for diagnosing the thermal regimes of steel-casting machines, using slide gates and nozzle-feeders as an example.

The serviceability of refractory steel-casting machinery is determined in part by the thermal stresses and strains which develop during use in the interaction of the molten metal with the refractory structure. A thin layer of refractory adjacent to the surface of contact with the metal typically undergoes thermal cracking and phase transformations for several minutes after the beginning of teeming, and these processes to a large extent determine the heat resistance and durability of the refractories.

To evaluate the intensity of the thermal action of the molten metal and calculate the temperature fields and stresses in the refractory structure, investigators often use empirical relations to determine the heat-transfer coefficient on the working surface [1]:

$$\mathrm{Nu} = 5 + 0{,}21\,\mathrm{Pe}^{0.75}, \tag{1}$$

$$\mathrm{Nu} = 0{,}7\,\mathrm{Pe}^{0.33}, \tag{2}$$

$$\mathrm{Nu} = 1{,}1\,[(1-\mathrm{Pr})^{1/3}\,\mathrm{Pe}]^{0.5}, \tag{3}$$

$$\mathrm{Nu} = 0{,}75\,[(1-\mathrm{Pr})^{1/3}\,\mathrm{Pe}]^{0.5}. \tag{4}$$

However, these relations were for the most part obtained in experimental studies of relatively low-temperature metallic liquids: sodium, lithium, zinc, etc. When Eqs. (1)-(4) are used for steel-casting machinery, the values of the heat-transfer coefficients α and the heat fluxes turn out to be excessively large: $\alpha = 0.5\cdot10^4$-$5\cdot10^4$ W/(m$^2\cdot$K), $q = 0.75\cdot10^7$-$7.5\cdot10^7$ W/m^2.

Assuming a thermal load of this intensity, we find that temperature gradients within the range from $1\cdot10^3$ to $5\cdot10^3$°C/mm would develop within the surface layer of the refractory. Such gradients would be a hundred times greater than the values corresponding to failure of the product. However, experience shows that the fracture of refractories during steel-teeming is usually not catastrophic in character. This means that when a cold (T = 100-500°C) refractory is washed by molten steel which is only slightly hotter (by 20-50°C) than the crystallization temperature, Eqs. (1)-(4) give clearly overstated values of the heat-transfer coefficient. Such unreliable information naturally complicates the study of the performance of refractory steel-casting machinery in order to improve their design.

To improve the accuracy and informativeness of the results of studies focusing on thermal loading rates, we examined an inverse boundary-value problem of heat conduction (ICP). As it turned out, this is the only approach that can be taken to diagnosing heat transfer, since it is nearly impossible to directly measure heat flow or the temperature of the surface of a refractory washed by molten steel without some distortion and deterioration of the service characteristics of the equipment.

The inverse problem for the wall of a refractory structure of finite thickness b was examined in the following formulation [2, 3]:

$$\rho c(T)\frac{\partial T(x,\tau)}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T(x,\tau)}{\partial x}\right),\ x\in(0,\ b],\ \tau\in(0,\ \tau_m]. \tag{5}$$

All-Union Institute of Refractories, Leningrad. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 3, pp. 404-408, March, 1989. Original article submitted April 18, 1988.

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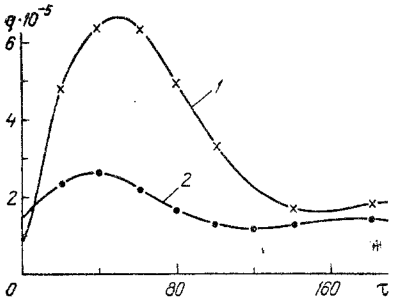

Fig. 1

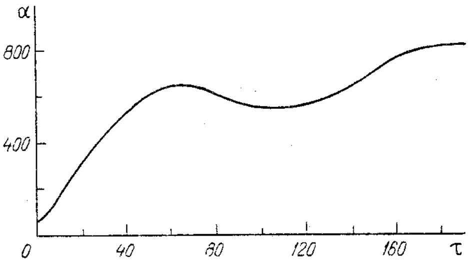

Fig. 2

Fig. 1. Results of determination of nonsteady heat flux q, W/m², from the solution of the ICP: 1) for the slide gate; 2) for the nozzle-feeder; τ, sec.

Fig. 2. Calculated dependence of the heat-transfer α, W/(m²·K) on teeming time.

We proceeded with the assigned initial condition

$$T(x,\ 0) = T_0,\ x \in [0,\ b], \tag{6}$$

and the measured temperature data $f_1(\tau)$, $f_2(\tau)$ at two wall-thickness points x_1 and x_2

$$T(x_1,\ \tau) = f_1(\tau),\ x_1 \in [0,\ x_2),\ \tau \in (0,\ \tau_m]; \tag{7}$$

$$T(x_2,\ \tau) = f_2(\tau),\ x_2 \in (x_2,\ b],\ \tau \in (0,\ \tau_m]. \tag{8}$$

We needed to determine the heat flux on the heated surface (x = 0)

$$q(\tau) = -\lambda(T) \cdot \frac{\partial T(0,\ \tau)}{\partial x},\quad \tau \in (0,\ \tau_m]. \tag{9}$$

In the given ICP, it is evident that the heat conduction process has smoothing properties for refractory materials with low transport properties and small values of $\lambda(T)$. Thus, the sensitivity of temperature measurements made over the wall thickness will vary relative to the external thermal load, decreasing sharply with increasing distance from the heated surface. As a result, to increase the accuracy of the ICP solution, the coordinates of the thermocouples x_1 and x_2 must be placed near the outside surface of the heated wall.

The ICP was solved in linear [4] and nonlinear formulations [5]. In the linear ICP, the change in the thermal conductivity $\lambda(T)$ of the refractory was considered by introducing a model temperature with the use of the Kirchhoff transform $\theta = \frac{1}{\lambda} \int_0^T \lambda(T)\, dT$. A comparative analysis of the results of methodological calculations showed that both formulations of the ICP are sufficiently accurate and efficient. The thermal load created during steel-teeming was diagnosed experimentally on the working surface of slide gates and nozzle-feeders. Temperature was measured during the first 200 sec after the beginning of teeming. The measurements were made 0.02 and 0.05 m from the heat-receiving surface on the slide gate and 0.0035 and 0.0185 m from this surface on the nozzle-feeder.

The results of determination of the nonsteady heat flows are shown in Fig. 1. Analysis of the results indicates that the maximum heat fluxes are 10-100 times lower than the data obtained from criterional relations (1)-(4). As far as describing the overall pattern of the process is concerned, this means that a certain degree of thermal resistance may develop on the heat-receiving surface of the refractory in the initial seconds after its contact with the molten metal. This resistance would reduce heat transfer to the wall of the channel from the metal. The dynamics of change in heat flux (Fig. 1) are similar for the slide gate and nozzle. The thermophysical process of contact of the metal with the refractory can be divided into three stages: 1) increase in heat flux; 2) reduction in heat flux; 3) relative stabilization of heat transfer. The dynamics of the change in heat flux in the initial stage suggests that a shielding layer of solidified metal is formed on the surface of the refractory beginning with the moment of contact. The rate of the buildup of this layer

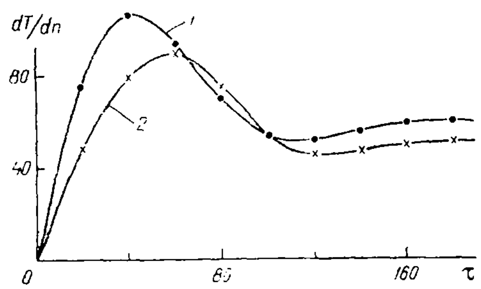

Fig. 3. Dependence of the temperature gradient on the refractory-metal contact surface dT/dn, °C/mm, on teeming time: 1) in the slide gate; 2) in the nozzle-feeder.

will obviously have an indirect effect on the rate of change of heat flux, i.e., it will diminish the thermal load. A subsequent increase in the temperature of the surface of the working channel leads to gradual erosion of the metal skin, thus decreasing the temperature gradient and stabilizing heat transfer. The values of the heat-transfer coefficient α (Fig. 2) calculated for the measured heat flux confirm the variable character of the heat transfer process, which is the result of the formation and subsequent removal of the metal skin.

The data obtained on the change in the thermal load was used to calculate the temperature gradients on the contact surface of the channels of the slide gate and nozzle-feeder (Fig. 3). The maximum values of temperature gradient are 88.0°C/mm for the slide gate and 107.5°C/mm for the nozzle-feeder. These figures are considerably lower than the values obtained from Eqs. (1)-(4). The largest temperature gradient is reached not at the moment of contact but 40-70 sec after teeming begins. The gradient remains high until τ = 100 sec, afer which it gradually decreases and stabilizes.

The experimental data on the temperature gradients corresponding to failure of the refractory lie within the range 20-80°C/mm for a broad range of products, according to the literature. Comparing this data with the results in Fig. 3, we can conclude that cracks form on the surface of the refractory and extend a short distance into the material.

It is important to note that the surface of the refractory is heated to 1300°C 100 sec after the beginning of teeming. At this temperature, the low-melting constituents of the refractory become liquid. In the presence of a temperature gradient, acting as a driving force, the low-melting compounds are moved deeper into the refractory into colder material along capillary pores. Thus, based on the action of these two physical mechanisms, it can be estimated that a surface layer of refractory 1-3 mm thick is loosened within 20-100 sec after the beginning of teeming. The appearance of numerous capillary paths and a reduction in the concentration of the binder near the surface have two consequences: impregnation of the refractory with steel to a depth of 1-3 mm; erosion and entrainment of a certain layer of material by the flow of steel due to the rupture of bonds between grains of the principal phase. The impregnation of the refractory with steel naturally results in a sharp increase in the thermal conductivity of the material in the surface layer. This increase in thermal conductivity in turn leads to an increase in heat flow and the heat-transfer coefficient – as is seen in the interval 110-180 sec (see Figs. 1 and 2).

The results of the studies completed here permit the following conclusions.

1) The use of inverse heat-conduction problems to diagnose the thermal regimes of slide gates and nozzle-feeders makes it possible to determine the dynamics of the thermal loads during the initial period of the nonsteady operation of steel-teeming.

2) Analysis of the character of change in thermal loading during the initial period of teeming made it possible to propose a model of boundary phenomena in the region of contact between the refractory and molten metal.

3) The data obtained can be used as a basis for studying physicochemical processes which take place in the failure of refractories in contact with steel.

NOTATION

Nu, Nusselt number; Pe, Peclet number; Pr, Prandtl number; α, heat-transfer coefficient; q, heat flux; T, temperature; ρ, density; C, heat capacity; λ, thermal conductivity; x, coordinate; b, wall thickness; τ, time; τ_m, duration of the process; x_1, x_2, coordinates of the thermocouples; T_0, initial temperature; θ, model temperature.

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A PROGRAMMABLE SUITE FOR IDENTIFYING THERMAL PARAMETERS IN ENGINEERING PROCESSES

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UDC 62.50:536.2

A system is described for identifying thermophysical characteristics and boundary conditions for heat transfer in pulsed processes.

Heat-treatment and strengthening techniques are often pulsed ones, with cycles lasting about 10^{-2}-10^{-4} sec, such as multipass grinding, laser hardening, and plasma treatment, or electrohydraulic pulse hardening. The same applies to rapid pulse methods of determining thermophysical characteristics.

Models may be written for such processes if they can be identified by solving interior and exterior inverse thermal-conduction problems. Short realization times impose special requirements on the identification system, which is a distinction from steady-state or slow nonstationary processes.

The coefficients in the conduction equation may be determined by an efficient pulse method involving laser heating [1], where a single experiment gives all the thermophysical characteristics: thermal diffusivity $a(T)$, specific heat $c(T)$, and thermal conductivity $\lambda(T)$, together with the latent heat of fusion, the emissivity, and the total emission. The method is a very convenient one and sometimes the only one for materials and composites such as powder steels, ceramics, evaporated thin films, multilayer systems, bimetals, molten metals, and heat-resistant protective coatings. The errors in determining $a(T)$, $c(T)$, and $\lambda(T)$ are [2] comparable with the errors in measuring the temperatures, while the method is readily automated.

One can determine the boundary conditions in heat transfer: heat flux densities $q(\tau)$, heat-transfer coefficients $\alpha(\tau)$, and the concentrations q_S and q_W of surface and bulk heat sources, by nonstationary methods with model systems and pilot plants.

This methodology in solving the interior and exterior boundary-value problems is based on nonlinear parametric optimization [3, 4]; one minimizes a functional

$$I = \int_0^{\tau} [T(r, \tau) - T_{\mathbf{e}}(r, \tau)]^2 d\tau \Rightarrow \min$$

and uses a combination of iterative gradient and search optimization methods.

This suite for identifying thermal parameters includes the following:

1) a GOR-100M laser with nominal output up to 90 J, pulse length 1 msec, wavelength 0.6940 μm, and spot diameter 0.1 mm, together with fast temperature sensors, an S13-1 stor-

Izhevsk Mechanics Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 3, pp. 408-411, March, 1989. Original article submitted April 19, 1988.