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THERMAL PROCESSES IN NONSYMMETRIC HEATING OF INGOTS AND BILLETS BEFORE ROLLING

V. I. Timoshpol'skii, I. A. Trusova, and S. M. Kozlov

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The effect of the process of tilting on the dynamics of the temperature field of a solid cylindrical ingot is shown. The selection of the site of location of tilters for annular furnaces that operate in pipe and axle rolling is substantiated.

In the development of technologies of metal heating and the improvement of the structures of high-temperature devices a detailed analysis of the thermophysical processes is required. The regularities of the internal heat transfer in the heating of ingots and billets in annular furnaces are considered in [1-4] and other works.

One factor that makes it possible to have a qualitative effect on the distribution of the temperature field of a steel ingot in metal heating is the tilting (turning over to a prescribed angle) of the billets. The expediency of the process of tilting large-diameter cylindrical bodies and the character of its effect on the furnace capacity in different technological zones are considered in [1].

In this work, an attempt was made to evaluate, based on a numerical experiment, the effect of the tilting process on the temperature drop over the cross section and to provide substantiation for the selection of the location of tilters from the viewpoint of the reduction in the nonuniformity of ingot heating.

In works published earlier [2, 4], the heating of solid cylinders is shown to be nonsymmetric. Furthermore, the results of experimental investigations that were carried out in annular furnaces of the 250 axle-rolling mill at the Dnieper Integrated Iron-and-Steel Works (Ukraine) make it possible to draw the conclusion that heating billets 0.27 m in diameter and 1.75–2 m long is nonsymmetric, too; however in this case the heat exchange from the butt end of the cylinder has practically no effect on the internal heat absorption by the metal.

Taking into account the aforesaid, the temperature problem of the process of heating an infinite cylinder in nonsymmetric heating by radiation and convection can be described by the differential equation

$$c(T)\,\rho(T)\,\frac{\partial T}{\partial t} = \lambda(T)\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \varphi^2}\right) + \frac{\partial \lambda}{\partial r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial \lambda}{\partial \varphi}\frac{\partial T}{\partial \varphi} \tag{1}$$

with the boundary condition

$$\lambda(T)\,\frac{\partial T(R,\varphi,t)}{\partial r} = \sigma(\varphi, T_{\text{furn}}(t))\,(T^4_{\text{furn}}(t) - T^4(R,\varphi,t)) + $$

$$+ \alpha\,(T_{\text{furn}}(t) - T(R,\varphi,t)) \tag{2}$$

and the initial condition

$$T(r,\varphi,0) = T_0(r,\varphi)\,. \tag{3}$$

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The mathematical model of heating (1)-(3) was solved by the grid method with the use of an absolutely stable explicit scheme, to obtain which the Dufore–Frankel method was employed.

Assuming that $T_{i,j,k} = 0.5(T_{i,j,k+1} + T_{i,j,k-1})$, from the differential equation (1) one can obtain a computational scheme of the form

$$T_{i,j,k+1} = \left\{ \left[0.5 - \frac{a_{i,j,k}}{\Delta r^2} \Delta t \left(1 + \frac{1}{r_i^2} \frac{\Delta r^2}{\Delta \varphi^2} \right) \right] T_{i,j,k-1} + \frac{a_{i,j,k}}{\Delta r^2} \Delta t \times \right.$$

$$\times \left[\left(1 + \frac{\lambda_{i+1,j,k} - \lambda_{i-1,j,k}}{4\lambda_{i,j,k}} \right) T_{i+1,j,k} + \left(1 - \frac{\lambda_{i+1,j,k} - \lambda_{i-1,j,k}}{4\lambda_{i,j,k}} \right) T_{i-1,j,k} \right] +$$

$$+ \frac{a_{i,j,k}}{\Delta r^2} \Delta t \frac{1}{r_i^2} \frac{\Delta r^2}{\Delta \varphi^2} \left[\left(1 + \frac{\lambda_{i,j+1,k} - \lambda_{i,j-1,k}}{4\lambda_{i,j,k}} \right) T_{i,j+1,k} + \right.$$

$$\left. \left. + \left(1 - \frac{\lambda_{i,j+1,k} - \lambda_{i,j-1,k}}{4\lambda_{i,j,k}} \right) T_{i,j-1,k} \right] + \frac{a_{i,j,k}}{\Delta r^2} \Delta t \frac{1}{2r_i} (T_{i+1,j,k} - T_{i-1,j,k}) \right\} \times$$

$$\times \left[0.5 + \frac{a_{i,j,k}}{\Delta r^2} \Delta t \left(1 + \frac{1}{r_i^2} \frac{\Delta r^2}{\Delta \varphi^2} \right) \right]^{-1} .$$

This computational equation makes it possible to determine the value of the temperature field at the cylinder nodes at the instant $(k+1)\Delta t$ from the known temperatures at the instants $k\Delta t$ and $(k-1)\Delta t$. At the initial instant we assume that $T_{i,j,-1} = T_{i,j,0}$.

To calculate the temperatures of the cylinder's axial layer with the use of a four-point template, we write

$$T_{i,j,k+1} = \left\{ \left(0.5 - \frac{2a_{i,j,k}}{\Delta r^2} \Delta t \right) T_{i,j,k-1} + \frac{a_{i,j,k}}{\Delta r^2} \Delta t \times \right.$$

$$\times \left[\left(1 + \frac{\lambda_{i+1,j,k} - \lambda_{i-1,j,k}}{4\lambda_{i,j,k}} \right) T_{i+1,j,k} + \left(1 - \frac{\lambda_{i+1,j,k} - \lambda_{i-1,j,k}}{4\lambda_{i,j,k}} \right) T_{i-1,j,k} + \right.$$

$$\left. \left. + \left(1 + \frac{\lambda_{i,j+1,k} - \lambda_{i,j-1,k}}{4\lambda_{i,j,k}} \right) T_{i,j+1,k} + \left(1 - \frac{\lambda_{i,j+1,k} - \lambda_{i,j-1,k}}{4\lambda_{i,j,k}} \right) T_{i,j-1,k} \right] \right\} \times$$

$$\times \left(0.5 + \frac{2a_{i,j,k}}{\Delta r^2} \Delta t \right)^{-1} .$$

In calculations the number of nodes along the coordinate φ on the interval $[0, 2\pi]$ was taken to be a multiple of four. The values of $a = a(T)$ and $\lambda = \lambda(T)$ correspond to the temperatures at the nodes of the grid region at the beginning of each calculational time interval. Their numerical values were determined from empirical formulas proposed in [5].

Allowance for the boundary condition (2) was made by introduction of a fictitious semilayer at the cylinder surface by analogy with the above algorithm. The temperature of the fictitious semilayer T_{fict} was found using the Newton method of successive approximations.

TABLE 1. Numerical Values of the Coefficients n_i as Functions of the Relative Value of the Interaxial Distance

n_i	S/D					
	1.0	1.25	1.5	2.0	4.0	∞
n_0	0.4320	0.4840	0.5370	0.6130	0.7100	0.7380
n_1	0.4222	0.4060	0.3910	0.3600	0.3330	0.3350
n_2	0.1640	0.1230	0.0830	0.0170	–0.0530	–0.0810
n_3	0.0120	0.0600	–0.0050	0.0170	0.0110	0.0140
n_4	–0.0330	–0.0240	–0.0150	–0.0170	–0.042	–0.0082
n_5	–0.0025	–0.0030	–0.0040	–0.033	–0.0015	0.010
n_6	0.0053	0	–0.0050	0.0120	–0.0004	0.0008

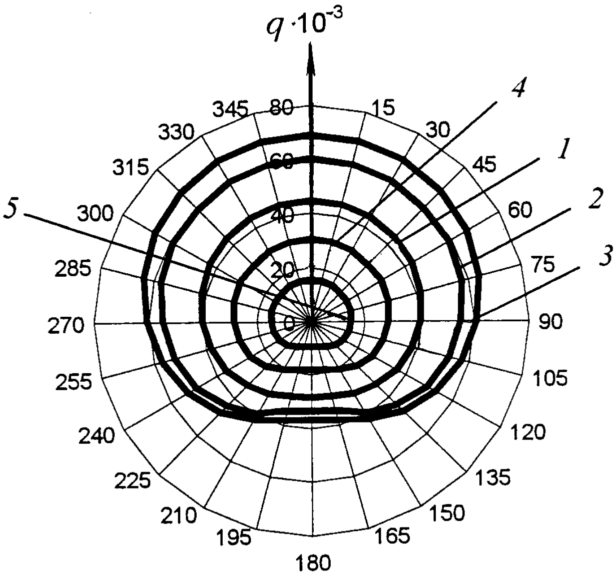

Fig. 1. Heat-flux distribution along the perimeter of the cross section of a 0.27-m-diameter billet for $S/D = \infty$ at the end of each technological heating zone of the annular furnace: 1) unheated zone; 2) methodological zone; 3) first welding zone; 4) second welding zone; 5) soaking zone. q, W/m^2.

The magnitude of the emissivity changed along the perimeter of the billet cross section with allowance for the effect of the relative position of the billets S/D by the formula

$$\sigma(\varphi, T_{\text{furn}}(t)) = \sigma_{\max}(T_{\text{furn}}(t)) \sum_{i=0}^{6} n_i \cos i\varphi \,.$$

The value of $\sigma_{\max}$ was determined as a function of the furnace temperature from a plot that was obtained based on experimental investigations of the heating of cylindrical billets in an annular furnace [1], while the coefficients n_i were determined as functions of the relative position of the billets from Table 1.

Figure 1 presents, as an example, diagrams of the heat-flux distribution along the perimeter of the cross section of a 0.27-m-diameter billet for $S/D = \infty$ at the end of each technological heating zone of the annular furnace.

To determine the adequacy of the mathematical model (1)-(3) for actual processes, we carried out parametric identification according to the data of a full-scale experiment that was conducted under the conditions of the annular furnace of the 250 mill at the Dnieper Integrated Steel-and-Iron Works (Fig. 2). It is seen from the figure that the average disagreement of the temperatures at the characteristic points of the billet cross section obtained in the experiment and according to the data of numerical calculations amounts to 2–4%. This

TABLE 2. Effect of the Angle and Instant of Tilting on the Maximum Temperature Drop

Angle of tilting, deg	Tilting time from the onset of heating, h									
	0.84	1.31	1.51	1.61	1.7	1.71	1.72	1.81	1.91	2.5
0	182	182	–	–	–	–	–	–	182	182
45	182	182	–	–	–	–	–	–	182	182
90	182	180	–	–	–	–	–	–	182	182
180	180	174	162	156	151	150	151	159	169	182

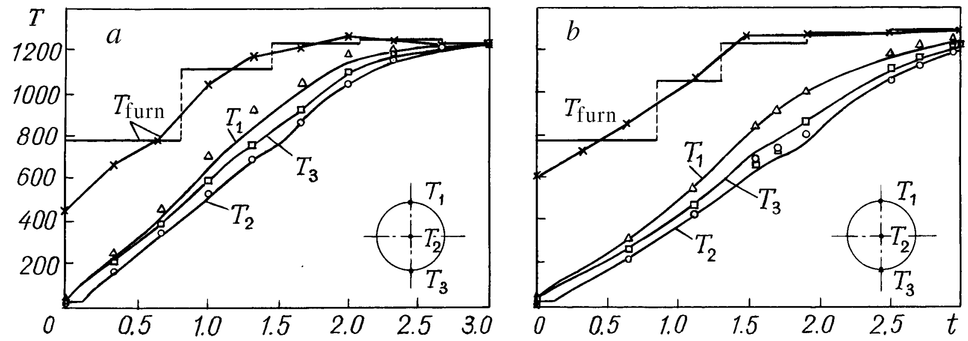

Fig. 2. Comparison of calculated (curves) and experimental (points) data on the heating of cylindrical billets: a) D = 0.23 m; b) 0.27. T, ^{o}C; t, h.

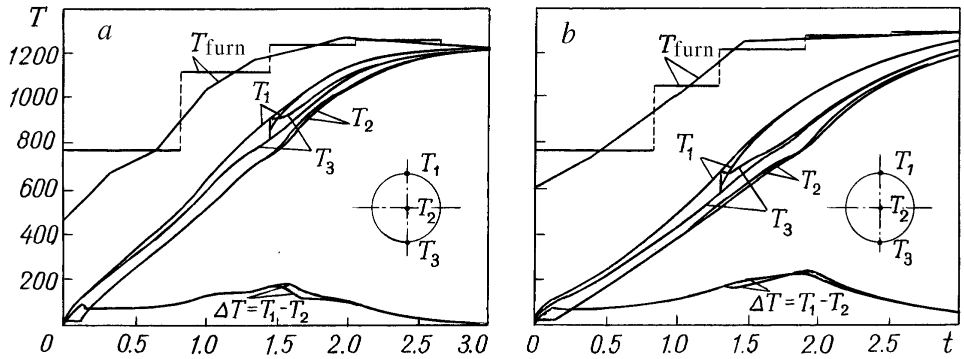

Fig. 3. Dynamics of nonsymmetric heating of the metal at characteristic points of the cross section of a cylindrical billet for $S/D = \infty$ and the largest temperature drop: a) D = 0.23 m; b) 0.27.

disagreement occurs primarily in a billet-temperature range that falls in the zone of phase transformations of the metal, which can be considered to be quite satisfactory.

Subsequently, to solve the problem of the effect of tilting on the temperature drop over the cross section of a cylindrical billet, we carried out a number of calculations of heating the metal both without tilting and with tilting to a certain angle at different heating times. The calculation results are accumulated in Table 2.

An analysis of the results of the temperature distribution over the billet cross section confirmed the initial assumption of the highest efficiency of tilting to an angle of 180^{o}. The smallest temperature drop over the billet cross section is attained in the second half of the first welding zone of the annular furnace. In a specific case, the decrease in the maximum temperature drop amounts to 18% as compared to the process of heating without tilting. However from the viewpoint of the technological and production features of axle and pipe rolling, it is appropriate to recommend that tilters be used at the beginning of the first welding zone.

Figure 3 gives the dynamics of the process of heating the metal at characteristic points of the cross section of cylindrical billets 0.27 and 0.23 m in diameter in nonsymmetric heating and also the values of the largest temperature drop in tilting of the billets at the beginning of the first welding zone. A computational analysis of the position of isotherms over the cross section of the cylindrical billet at the end of each technological zone of the annular furnace shows a displacement of the thermal center in relation to the geometric one.

The maximum temperature drop over the billet cross section for a specific version of tilting decreased by 7%. In turn the decrease in the temperature drop over the billet cross section involves a decrease in thermal stresses, which makes it possible to recommend that tilting be used in heating of steels that are prone to considerable thermal deformations or cracking.

NOTATION

$T(r, \varphi, t)$, metal temperature at the point of the billet cross section prescribed by the polar coordinates r and φ at the instant t; $T_{furn}(t)$, temperature of the heating medium (furnace) at the instant t; $T_0(r, \varphi)$, distribution of the temperature field over the billet cross section at the initial instant; T_{fict}, temperature of the fictitious semilayer; t, time; R, cylinder radius; $c(T)$, $\rho(T)$, and $\lambda(T)$, heat capacity, density, and thermal conductivity of the steel, respectively; $a(T) = \frac{\lambda(T)}{c(T)\rho(T)}$, thermal-diffusivity coefficient; $\sigma(\varphi, T_{furn}(t))$, radiant heat-transfer coefficient that changes along the perimeter of the billet cross section; α, convection heat-transfer coefficient; S, distance between the cylinders' axes; D, cylinders' diameters; Δ, increment. Subscripts: i, j, and k, numbers of the layers with respect to the radius, angle, and time; furn, heating medium (furnace); fict, fictitious; 0, initial; max, maximum value.

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