TEMPERATURES, STRESSES, AND STRAINS IN ASYMMETRIC RADIATIVE AND CONVECTIVE HEATING OF FLAT OBJECTS

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The article presents calculations of nonsteady temperature, stress, and strain fields in flat blanks heated in a continuous furnace. The calculated temperatures agree satisfactorily with the experimental data.

For designing reheating furnaces and improving their operating regimes, reliable and sufficiently accurate methods of determining the thermal and mechanical state of the objects placed in these furnaces are indispensable. The heating of flat bodies with radiative and convective heat supply was examined by a number of authors. For instance, in [1, 2] the temperature fields in prismatic and round blanks were calculated. Taits et al. [3] used approximate relations of thermoelasticity and determined the stresses corresponding to the temperature gradient in the cross section of the body, measured in the experiments. Analytical investigation of thermoelastic stresses and strains was carried out by Samoilovich [4]. In the present work the calculations of temperatures, stresses and strains in blanks take into account the change of temperature of the environment, the asymmetric heat supply, and also the real dependences of the thermophysical and mechanical characteristics of the material on the temperature. The calculation of stresses and strains was carried out on the basis of the theory of nonisothermal plastic flow by the method developed in [5] and used by us previously for calculating the hardening process [6]. The usual assumption for problems of this kind was made, viz., that temperature and mechanical fields are unconnected (see, e.g., [7]), and after the temperature field for the corresponding instant had been calculated, the thermal stresses and strains were determined. Since prismatic blanks are usually fed into the furnace continuously, with their lateral sides touching, the temperature field was considered approximately unidimensional. Since the length of the blanks was much greater than the transverse dimensions, they were treated as free lying beams in the calculation of stresses and strains.

If we proceed from the above-said, the heat-conduction problem has the form

$$C(\vartheta)\rho(\vartheta)\frac{\partial\vartheta}{\partial\tau}=\frac{\partial}{\partial z}\left[\lambda(\vartheta)\frac{\partial\vartheta}{\partial z}\right] \tag{1}$$

with the initial and boundary conditions:

$$\vartheta=\vartheta_0,\ \tau=0, \tag{2}$$

$$-\lambda\left(\frac{\partial\vartheta}{\partial z}\right)_{sb}=\alpha(\vartheta_{gb}-\vartheta_{sb})+\sigma_{glm}\left[\left(\frac{\vartheta_{gb}}{100}\right)^4-\left(\frac{\vartheta_{sb}}{100}\right)^4\right], \tag{3}$$

$$\lambda\left(\frac{\partial\vartheta}{\partial z}\right)_{st}=\alpha(\vartheta_{gt}-\vartheta_{st})+\sigma_{glm}\left[\left(\frac{\vartheta_{gt}}{100}\right)^4-\left(\frac{\vartheta_{st}}{100}\right)^4\right]. \tag{4}$$

The radiant heat flux in Eqs. (3) and (4) is determined by the simplified method of [8] on the assumption that the local values of the flux are proportional to the local difference between the fourth degrees of the effective temperature of the radiation and of the temperature of the metal surface. It is assumed that the temperature of the lining surface is approximately equal to the temperature of the gases. If necessary, the boundary conditions can be refined on the basis of recommendations available in the literature [8].

For a beam free of surface forces, and with a change of its temperature only across its

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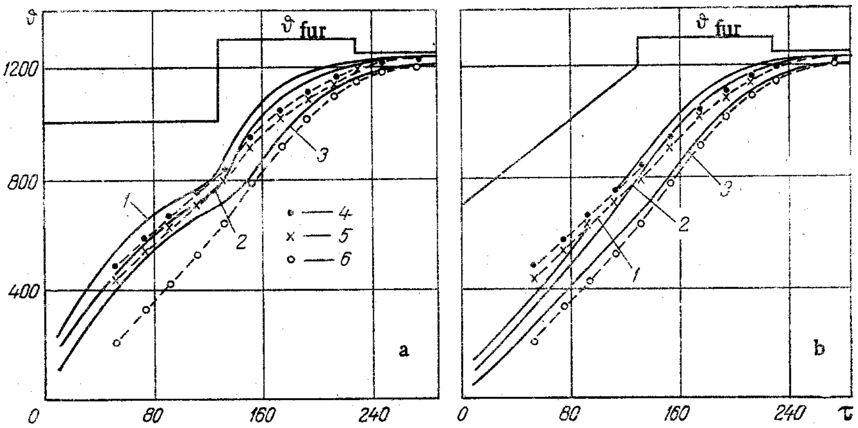

Fig. 1. Dependence of the temperature of the blank on time [a) temperature of the methodological zone of the furnace is constant, b) variable; solid lines) calculated values; dashed lines) experimental data]: 1-3) calculated temperatures at the upper, lower surfaces, and at the center of the blank, respectively; 4-6) experimental values of the temperatures on the upper, lower surfaces, and at the center of the blank, respectively. ϑ, °C; τ, min.

thickness, Geller and Parnas [6] presented an expression for the stresses σ_{xx}:

$$\sigma_{xx} = \frac{3}{2\psi + \gamma} (\Delta\varepsilon_{xx} + b_{xx}). \tag{5}$$

where

$$\psi = \frac{1}{2G}, \quad \sigma_i^2 - \sigma_y^2 < 0; \tag{6}$$

$$\psi = \frac{1}{2G} + \Delta\eta, \quad \sigma_i^2 - \sigma_y^2 = 0; \tag{7}$$

$$b_{xx} = \left(\frac{\sigma_{xx} - \sigma}{2G}\right)^* + (\gamma\sigma)^* - \Delta\varphi. \tag{8}$$

For the given problem

$$\varphi = \beta(\vartheta - \vartheta_0). \tag{9}$$

As in [6], the strain increment $\Delta\varepsilon_{xx}$ may be considered linearly dependent on the coordinate z:

$$\Delta\varepsilon_{xx} = C_1 z + C_2. \tag{10}$$

The coefficients C_1 and C_2 are found from the condition of equilibrium of the beam:

$$\int_0^\delta \sigma_{xx}\, dz = 0, \tag{11}$$

$$\int_0^\delta \sigma_{xx} \left(z - \frac{\delta}{2}\right) dz = 0. \tag{12}$$

The deflection R of a freely supported beam can be calculated by the known formula [9]

$$R = \frac{\varkappa l^2}{8}, \tag{13}$$

where the curvature of the beam $\varkappa$ is equal to the coefficient C_1 in formula (10).

Equations (1)-(12) were solved numerically on an ES-type computer. At first the temperature field in the blank was determined from Eqs. (1)-(4) by the finite difference method. Then from the obtained temperatures at each step in time the stresses, strains, and deflection were found from Eqs. (5)-(12) by the iteration method.

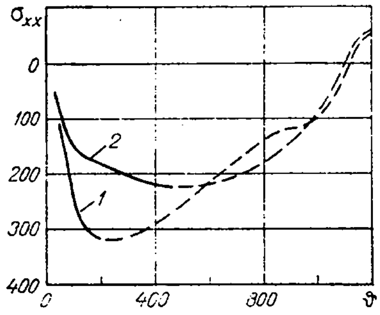

Fig. 2.

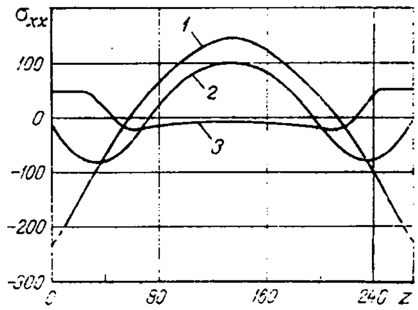

Fig. 3.

Fig. 2. Dependence of the stresses on the upper surface of the blank on the temperature of the surface: 1, 2) calculations with constant and with variable temperature, respectively, in the methodological zone of the furnace. σ_{xx}, MPa.

Fig. 3. Stress distribution across the thickness of the blank (variable temperature of the methodological zone). Dashed lines indicate the zones of plasticity: 1, 2, 3) τ = 94, 165, 285 min, respectively. z, mm.

Concrete calculations were carried out for blanks of steel 45, 270 × 350 × 6000 mm in size, heated in a rolling mill furnace. The thermophysical and mechanical properties of steel 45 were taken from [10], and we approximated them by piecewise linear functions for the calculations:

$$\lambda = -0{,}0214\,\vartheta + 48{,}1 \text{ W/m}\cdot{}^\circ\text{C}, \tag{14}$$

$$\begin{cases} C = 0.4\,\vartheta + 448 \text{ J/kg}\cdot{}^\circ\text{C}, \; 50^\circ\text{C} \leqslant \vartheta \leqslant 700^\circ\text{C}, \\ C = 14.1\vartheta - 9124.3 \text{ J/kg}\cdot{}^\circ\text{C}, \; 700^\circ\text{C} \leqslant \vartheta \leqslant 750^\circ\text{C}, \\ C = -17.1\vartheta + 14289 \text{ J/kg}\cdot{}^\circ\text{C}, \; 750^\circ\text{C} \leqslant \vartheta \leqslant 800^\circ\text{C}, \\ C = 0.166\vartheta + 441.6 \text{ J/kg}\cdot{}^\circ\text{C}, \; 800^\circ\text{C} \leqslant \vartheta \leqslant 1200^\circ\text{C}, \end{cases} \tag{15}$$

$$G = -41\vartheta + 79200 \text{ MPa}. \tag{16}$$

The dependence of the yield strength of steel 45 on the temperature was taken according to the data for steels with similar composition presented in [5], and it was taken equal in the temperature range 50-1220°C:

$$\sigma_y = -0.299 + 400 \text{ MPa}. \tag{17}$$

On the basis of measurements carried out on an industrial furnace, the following values were adopted for our calculations: α = 30 W/m^2·°C, σ_{glm} = 3.15, 2.9, and 3.05 in the methodological, welding, and soaking zones of the furnace, respectively, ϑ = 1300 and 1245°C, ϑ = 1250 and 1245°C in the welding and soaking zones, respectively. Because of insufficient experimental data on the methodological zone, the calculations were carried out with some approximations of its temperature. Initially it was taken constant along the zone and equal to 1000°C at the top and 900°C at the bottom of the chamber.

The results of these calculations are presented in Fig. 1a. The figure also contains plots of the experimental data. The temperatures at several points of the blank were measured with Chromel–Alumel thermocouples whose emf was recorded by an instrument type PP-63 during the entire heating cycle of the blanks in the furnace. Copper chips were put on the bottom of the holes into which the thermocouples were then caulked.

It can be seen from Fig. 1a that the calculated temperatures in the blank are considerably higher than the experimental data. This difference is particularly great in the first (methodological) heating zone. The best agreement of experimental and calculated data was obtained when a linear change of temperature in the methodological zone was specified (Fig. 1b).

A comparison of the stresses in the upper surface of the blank at constant and at variable temperature in the methodological zone of the furnace (Fig. 2) shows that in the latter case the stress level in the methodological zone is lower than in the former case, and the stresses in the subsequent zones are approximately equal to each other. The investigation of the stress distribution over the cross section of the blank (Fig. 3) showed that the stresses are greatest in the methodological zone, and then, as the metal becomes hotter, they decrease.

Calculations showed that the deflection of the blanks, as was to be expected, changes during the heating process. When the temperature gradient between the top and the bottom of the blank is maximal, the deflection is directed upward and attains 20-22 mm. This indicates that there is a considerable gap between the blank and the hearth of the furnace, which in turn improves convective heat exchange on the lower surface of the blank. Toward the end of the heating, the deflection decreases to 1-2 mm and changes its sign.

The obtained results proved useful in the analysis of the technology of heating blanks in a rolling mill furnace. On the other hand, they also indicate that further experimental investigations are indispensable, especially in the methodological zone where the heating rates and temperature gradients over the cross section of the blank are particularly great. The method of calculating temperatures, stresses and strains, used in the present work, may also be applied to investigations of the heating of articles in other technological processes.

NOTATION

ϑ, temperature; τ, time; x and z, coordinates along the length and thickness of the plate (beam); C, heat capacity; ρ, density; λ, thermal conductivity; α, heat-transfer coefficient between the surface of the blank and the heating medium of the furnace; $\sigma_{gl m}$, reduced radiation factor in the system gas—laying—metal; ε_{xx}, relative deformation; σ_{xx}, normal stress in the direction x; σ_i, stress intensity; $\Delta\eta$, proportionality factor between stresses and strains in the plastic zone; σ_y, yield strength; G, shear modulus; γ, bulk modulus of elasticity; β, mean value of the coefficient of thermal expansion in the temperature range $(\vartheta - \vartheta_0)$; l, length of the blank. Subscripts: b, t, bottom, top of the furnace, respectively; s, surface of the blank; o, initial value; *, values of physical magnitudes relating to the instant $\tau - \Delta\tau$; g, gas.

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