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ANALYSIS OF THERMAL STRESSES IN MASSIVE STEEL INGOTS IN THE PROCESS OF THEIR HEATING IN A FURNACE PRIOR TO THEIR TREATMENT BY PRESSURE

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A method of estimating the thermally stressed state of massive steel ingots heated in a combustion furnace has been developed. The rate of heating of these ingots as permitted by their technological parameters (admissible thermal stresses), was estimated.

Continuous steel casting is among the dominant high technologies developed in modern ferrous metallurgy. However, massive steel ingots of weight from 10–15 tons to 250–300 tons used for production of unique machineries in modern machine building (rotors of the turbines of electric power stations, large rolls) cannot be obtained by the continuous-casting method. At present, for the purpose of obtaining such ingots, along with the traditional casting of steel into ingot moulds, different methods of remelting (electroslag, vacuum-arc, electron-beam remelting, and others) are extensively being developed.

In the process of formation of massive steel ingots, in their cast structure there arise specific defects, the removal of which decreases the output of the finished metal, which substantially influences the cost of the products obtained. Among the above-indicated defects of massive cast-steel ingots are cracks in the cast steel. In many cases, such ingots are broken down at the stages of cooling after the casting or in the process of their heating in chamber furnaces prior to their treatment by pressure.

The aim of the present work is to analyze the thermally stressed state of massive steel ingots in the process of their heating in a chamber furnace prior to their treatment by pressure with consideration for the residual stresses arising in these ingots at the stage of their cooling after the casting. In the earlier publications of the authors of the present work [1–3], methods and results of empirical investigations of the temperature field of massive ingots as well as some regularities of the failure of steel ingots under the action of thermal stresses are presented.

It should be noted that the study of the temperature field of massive steel ingots presents significant methodical difficulties; because of this, experimental investigations of such fields number in the units. Of importance are the results obtained by V. I. Zalesskii and G. A. Pimenov [4–6] in the process of investigating the failure of 60KhN-steel ingots of weight 38 tons under the action of residual stresses. In the present work, the empirical data of these authors are used for analysis of the thermal stresses arising in a cylindrical steel ingot in the process of its nonsymmetric heating in a chamber furnace; this analysis is carried out with consideration for the dependence of the thermophysical and mechanical characteristics of the steel on its temperature.

The problem on the thermally stressed state of steel ingots heated in a chamber furnace is solved in the following mathematical formulation:

1) a cylindrical ingot with a cross section of diameter $2R$ is considered in the Cartesian coordinate system x, y, the origin of which $x = 0$, $y = 0$ is at the point of tangency of the ingot with the furnace bottom, as is shown in Fig. 1a;

2) the equation of nonstationary heat conduction in the Cartesian coordinate system has the form

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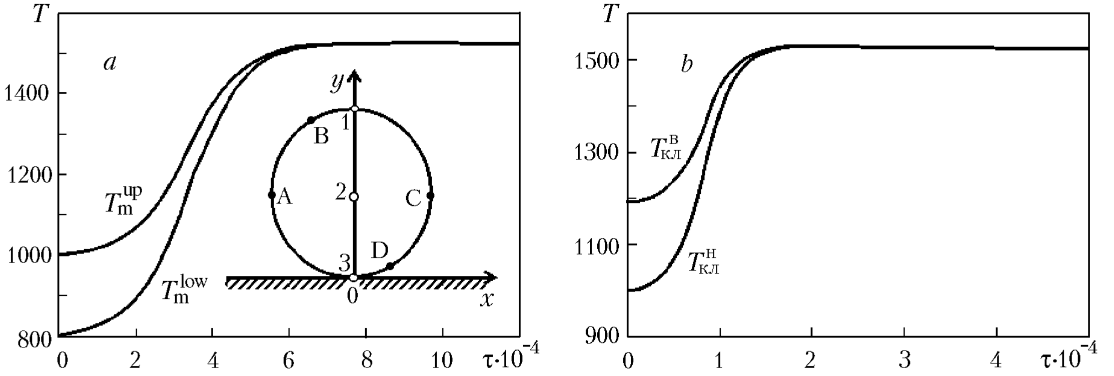

Fig. 1. Time dependences of the temperatures of the heating medium of a furnace (furnace setting) operating under the "soft" (a) and "hard" (b) heating conditions and scheme of disposition of control points (1–3) in the cross section of an ingot. T, K; τ, sec.

$$\rho(T)\, c_p(T) \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left[\lambda(T) \frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda(T) \frac{\partial T}{\partial y}\right]; \tag{1}$$

3) the heat exchange on the surface of the ingot is defined by the Stefan–Boltzmann law; in this case, the heating medium is the masonry (the inner surface of the furnace setting), whose temperature changes with time;

4) the following boundary conditions are set at the surface of the ingot:

$$-\lambda(T)\left[\frac{\partial T}{\partial n}\right]_{\text{sur}} = \chi_{\text{up}}\left\{[T_{\text{m}}^{\text{up}}(\tau)]^4 - [T_{\text{sur}}(\tau)]^4\right\}, \tag{2}$$

$$-\lambda(T)\left[\frac{\partial T}{\partial n}\right]_{\text{sur}} = \chi_{\text{low}}\left\{[T_{\text{m}}^{\text{low}}(\tau)]^4 - [T_{\text{sur}}(\tau)]^4\right\}; \tag{3}$$

5) it is assumed that the temperature of the masonry on the side of the furnace arch exceeds the temperature of the furnace bottom, which is due to the cooling of the bottom as a result of the charging of a cold ingot into the furnace; in the process of heating of the furnace, the temperatures of the arch part of the masonry and the furnace bottom equalize gradually, as is shown in Fig. 1 (time dependences of the temperatures $T_{\text{m}}^{\text{low}}$ and T_{m}^{up});

6) the difference between the conditions of radiative heat exchange at the upper and lower surfaces of the ingot is taken into account in the simplest way: the coefficient of radiative heat exchange at the upper surface region ABC is assumed to be $\chi_{\text{up}} = 2.5 \cdot 10^{-8}$ W/(m^2·K^4), and this coefficient for the lower region CDA is taken to be $\chi_{\text{low}} = 0.5 \cdot 10^{-8}$ W/(m^2·K^4);

7) the problem on the nonlinear thermoelasticity of the ingot is solved on the assumption that the ingot is subjected to a plane deformation; in this case, the components of the stress tensor (σ_x, σ_y, τ_{xy}) and the deformation tensor (ε_x, ε_y, γ_{xy}) are related as

$$\begin{bmatrix}\sigma_x \\ \sigma_y \\ \tau_{xy}\end{bmatrix} = D\left\{\begin{bmatrix}\varepsilon_x \\ \varepsilon_y \\ \gamma_{xy}\end{bmatrix} - \begin{bmatrix}\alpha \\ \alpha \\ 0\end{bmatrix}(1+\mu)(T - T_0)\right\}, \tag{4}$$

where

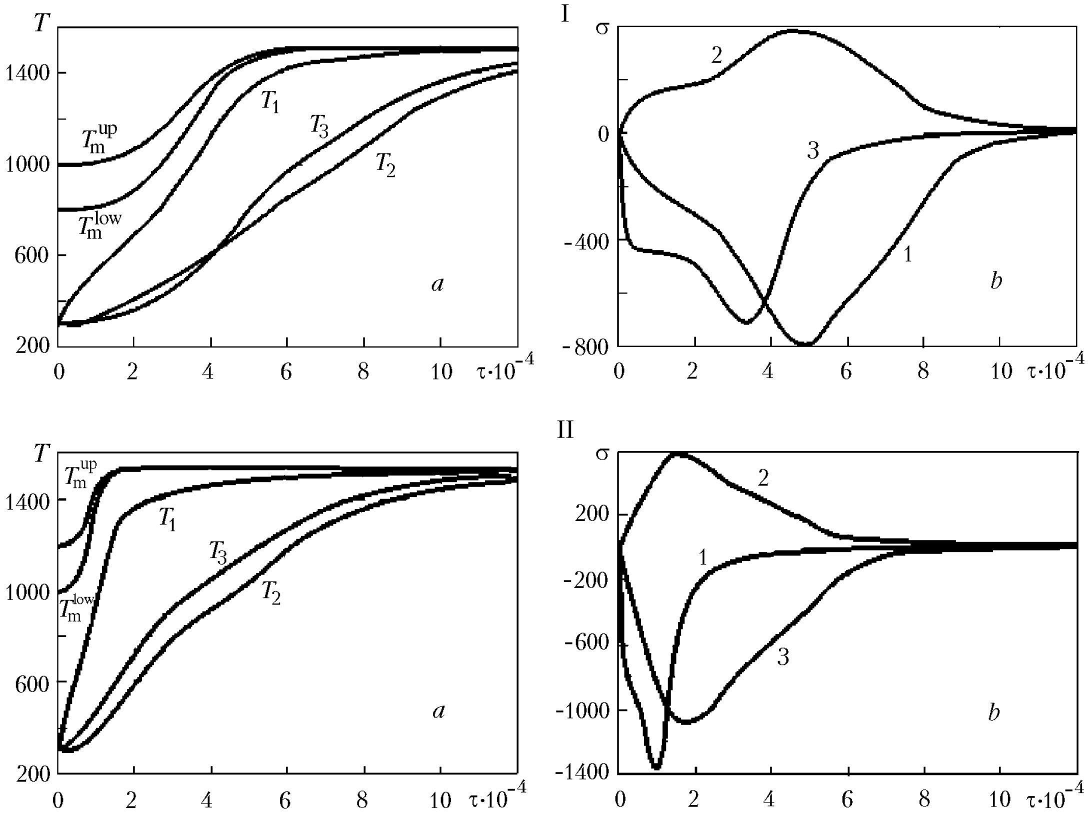

Fig. 2. Time dependences of the temperature of the heating medium of a furnace, the temperature at the cross section of an ingot (a), and the thermal stresses at the cross section of the ingot (b) for the "soft" (I) and "hard" (II) heating conditions: curves 1–3 correspond to the control points at the cross section of the ingot.

$$D=\frac{E\,(T)}{(1+\mu)\,(1-2\mu)}\begin{bmatrix}1-\mu & \mu & 0\\ \mu & 1-\mu & 0\\ 0 & 0 & \frac{1-2\mu}{2}\end{bmatrix}. \tag{5}$$

The base equations of thermoelasticity (4) are supplemented by the equilibrium equations

$$\frac{\partial \sigma_x}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}=0\,,\quad \frac{\partial \tau_x}{\partial x}+\frac{\partial \sigma_{xy}}{\partial y}=0\,,\quad \frac{\partial \sigma_z}{\partial z}=0\,. \tag{6}$$

The problem on the thermoelasticity of the ingot is solved on the assumption that it is not subjected to external loads and the stress-tensor components at the boundaries of the cross section of the ingot are equal to zero. The above equations of heat conduction and thermoelasticity are solved by the finite-element method; in this case, the computational cross section of the ingot is divided into 800–1000 elements, which allows obtaining fairly accurate solutions. In the series of calculations, the results of which are presented below, we used the temperature dependence of the thermophysical parameters of the steel being investigated, constructed in accordance with the recommendations given for alloyed steels in [1], and the temperature dependence of the elastic modulus of the 60KhN steel, presented in [6].

The main calculations were carried out for the "soft" and "hard" conditions of heating of the steel ingot, under which the temperature of the furnace masonry changes in accordance with the dependences presented in Fig. 1.

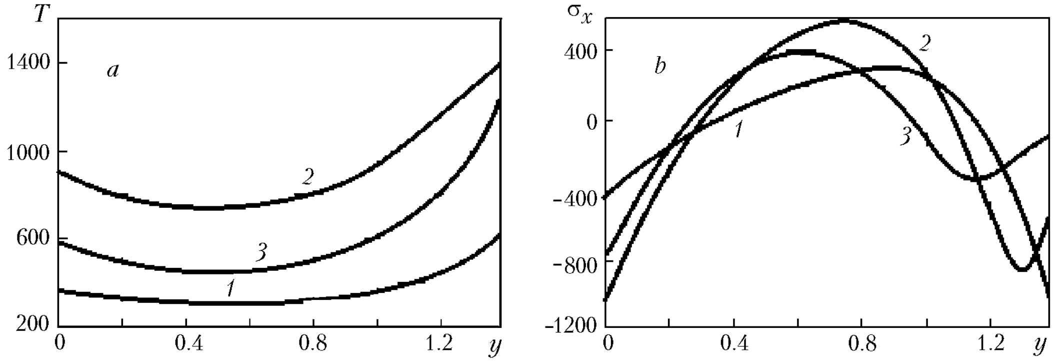

Fig. 3. Distributions of the temperature (a) and the thermal stresses (b) along the vertical plane y (see cross section 1–3 in Fig. 1a) for three subsequent instants of time in the process of heating of an ingot under the "hard" conditions: τ = 5000 (1), 15,000 (2), and 30,000 sec (3). T, K; σ_x, MPa.

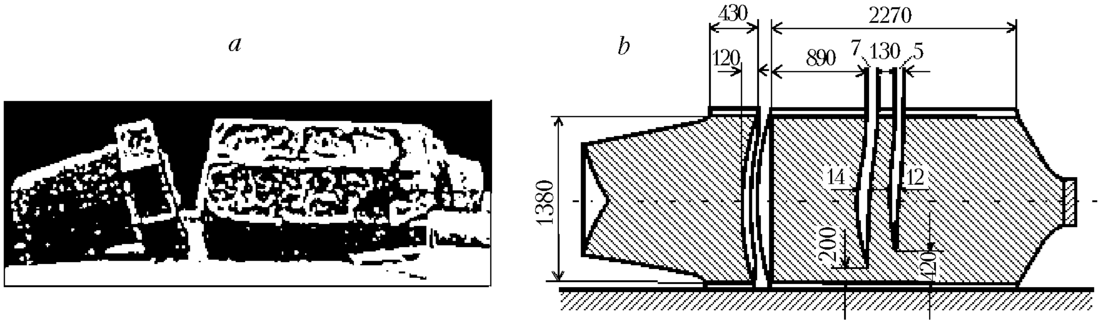

Fig. 4. Mode of failure of a 60KhN-steel ingot of weight 38 tons (a) and dimensions of the cracks at its cross section (b) according to the data of [4, 6].

It should be noted that each of the heating regimes is characterized by the following set of parameters: $T_{\mathrm{m}}^{\mathrm{up0}}$, $T_{\mathrm{m}}^{\mathrm{low0}}$, T_{fin}, and τ_{fin}, where T_{fin} is assumed to be equal to 1520 K. For the "soft" and "hard" conditions of heating of ingots, the indicated parameters were taken to be equal to

$$T_{\mathrm{m}}^{\mathrm{up0}} = 1000\ \mathrm{K}\,,\quad T_{\mathrm{m}}^{\mathrm{low0}} = 800\ \mathrm{K}\,,\quad \tau_{\mathrm{fin}} = 6\cdot 10^{4}\ \mathrm{sec}\,;\quad T_{\mathrm{m}}^{\mathrm{up0}} = 1200\ \mathrm{K}\,,\quad T_{\mathrm{m}}^{\mathrm{low0}} = 1000\ \mathrm{K}\,,\quad \tau_{\mathrm{fin}} = 1.8\cdot 10^{4}\ \mathrm{sec}\,.$$

The calculation data on the temperatures and thermal stresses of an ingot of diameter 1.38 m heated under the "soft" and "hard" conditions are presented in Fig. 2.

Analysis of the results obtained shows that, when a steel ingot is heated, on its surface there arise compression stresses and tensile stresses arise in the axial zone. It is seen that these stresses reach their maximum values at the instant τ_{fin} the temperature of the masonry reaches a definite maximum value (1520 K). In this case, the maximum tensile stresses at the axis of the ingot are respectively equal to 480 MPa ("hard" conditions) and 280 MPa ("soft" conditions).

The above-described physical-mathematical model allows one to estimate the asymmetry of heating of an ingot in a chamber furnace, caused by the large difference between the heat flows received by the upper and lower surfaces of the ingot because of the difference between the values of χ_{up}, $T_{\mathrm{m}}^{\mathrm{up}}$ and χ_{low}, $T_{\mathrm{m}}^{\mathrm{low}}$. Figure 3 presents the distribution of temperatures and thermal stresses along the y axis for three instants of time. The results obtained point to the fact that the asymmetry of heating of an ingot insignificantly influences the distribution of the thermal stresses along the indicated coordinate; it is seen that the maximum stresses at the symmetry axis of the ingot (at y = 0.69 m) differ from those at the point of attainment of an extremum (y = 0.75 m) by no more than 5–7%. This result warrants the wide use of the solutions of axisymmetric thermoelasticity-theory problems [1, 7] for calculating the thermal stresses in ingots and blanks in the process of their heating in combustion furnaces.

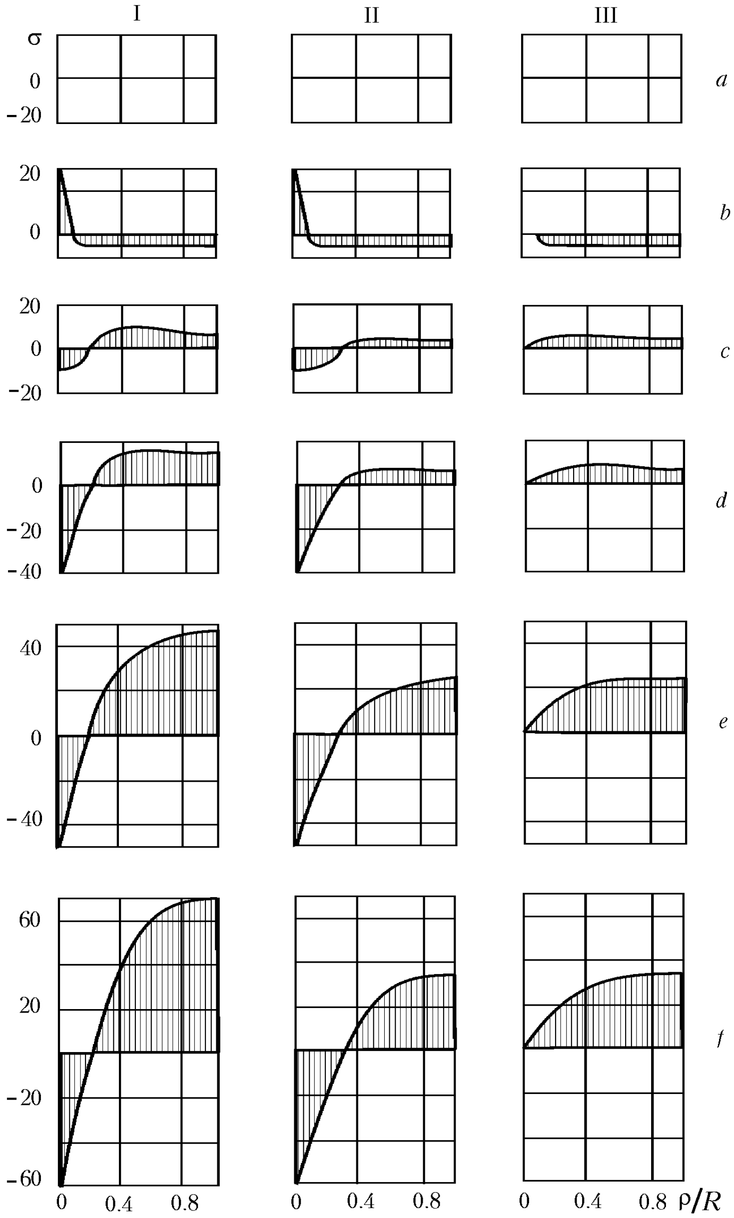

Fig. 5. Distribution of the residual thermal stresses over the cross section of an ingot of weight 38 tons and diameter 1380 mm in the process of its cooling in a mould and, then, in a wagon-thermos and in the air by the data of [6]: I) axial stresses; II) tangential stresses; III) radial stresses; cooling of the ingot in the wagon-thermos at the initial stage (a), after 5 h (b), after 13 h (c), after 21 h (d), after 43 h (e) (at the final stage of the cooling in the thermos), after 190 h (f) (cooling in the air). σ, kg/mm^2.

The calculation of the thermal stresses arising in the process of heating of a cast-steel ingot allows one to estimate the influence of the main heating parameters on the appearance of a discontinuity of the cast steel. An extremely important result was obtained in [4–6] where the interrelation between the regime of cooling of an ingot and its failure under the action of the residual thermal stresses was determined. Figure 4 presents a photography of a failured ingot as well as the configuration and dimensions of the cracks, the disposition of which points to the fact that the longitudinal component of the stress tensor plays a major part in the failure of the ingot.

The temperature dependences of the mechanical characteristics of the 60KhN steel were taken from [5]. Figure 5 presents the results of calculating the residual stresses in a 60KhN-steel ingot cooled with the use of the Abramov method [6, 8].

Comparison of the residual stresses in the ingot (components σ_z), presented in [4], with the time dependence of the ingot-surface temperature points to the fact that, when the temperature of the ingot surface becomes lower than 800 K, the longitudinal residual stresses increase to 600–700 MPa and there arises a real risk of discontinuity of the cast steel because the ultimate strength of the 60KhN steel comprises 600 MPa at a temperature $T = 773$ K.

In [6], the massive ingots, the surface temperature of which reached 800 K in the process of cooling, were considered as partially cooled ingots. Such ingots were held for a long time at a low temperature in the initial period of their heating in a furnace. For example, when an ingot of wight 38 tons was charged into a furnace, "the furnace temperature" was held at a level of 1150 K for 3.5–4 h [6, p. 116]. The authors of [6] considered the ingots cooled to 450°C and to lower temperatures as significantly cooled ingots. These ingots were heated under the conditions of heating of "cold" ingots, characterized by very small rates of heating and long holdings. A statistical analysis of the results obtained and examinations of the ingots treated have shown that the majority of the massive ingots, the temperature of whose surface was 300–400°C and lower before the heating, were broken down as a result of the heating in the furnace with an "explosion." The empirical data presented point to the fact that the thermal stresses in ingots must not exceed the values corresponding to the ultimate strength of the steel at a corresponding temperature: $(\sigma_z)_{\max} \le \sigma_{\mathrm{str}}$.

For an unannealed steel ingots, in which residual stresses are practically absent, the above-indicated condition of continuity conservation takes the form

$$2K\,(\sigma_x)_{\max} \le \sigma_{\mathrm{str}}\,(T)\,, \tag{7}$$

since $\sigma_z \cong 2\sigma_x$ at the symmetry axis of a cylindrical ingot heated under the temperature-field-symmetry conditions.

For an unannealed steel ingot, heated in a forging chamber furnaces, the residual tensile stresses at the axis of the ingot should be taken into account in accordance with the condition of metal-continuity conservation

$$2K\,[(\sigma_x)_{\max} + (\sigma_x)_{\mathrm{res}}] \le \sigma_{\mathrm{str}}\,(T)\,. \tag{8}$$

Let us estimate the rate of heating of a 60KhN-steel ingot by (7) and (8) with the use of the above-presented calculation data on the stresses arising in such an ingot in the process of its heating. As was shown above, even under the "soft" heating conditions the maximum thermal stresses σ_x in the ingots being considered can reach 280 MPa (see Fig. 2). According to the data of [5], the ultimate strength of the 60KhN steel at a temperature of 700 K does not exceed 500–510 MPa. In accordance with condition (7), the admissible maximum stress at the axis of an annealed ingot should not exceed $\sigma_{\mathrm{ad}} = 1.1 \cdot 2 \cdot 280 = 616$ MPa, so that the condition $\sigma_{\mathrm{ad}} > \sigma_{\mathrm{str}}$ and the continuity-conservation condition are not fulfilled in this case (in the calculations by formula (7), the safety factor was taken to be equal to $K = 1.1$). The residual tensible stresses in the bulk of a cast-steel ingot can further increase the risk of discontinuity of the cast steel; because of this, it is necessary to provide such heating conditions (determined by the quantities $T_{\mathrm{m}}^{\mathrm{up0}}$, $T_{\mathrm{m}}^{\mathrm{low0}}$, and τ), under which the more common conditions of continuity conservation (8) are fulfilled. The conditions of heating of massive forging ingots in combustion furnaces, recommended in [9–11], allow the conclusion that unannealed steel ingots should be heated with great care in combination furnaces prior to their treatment by pressure; at the initial stage of heating, they should be held at a temperature of 50–600 K for many hours before "the furnace temperature" is gradually increased to a definite final temperature determined by the conditions of treatment of the ingots by pressure (forging or compression).

The above-described method of calculating the temporary thermal stresses arising in a steel ingot in the process of its heating in a combustion furnace can be used for determining concrete admissible parameters of heating of steel ingots.

NOTATION

c_p, specific heat capacity, kJ/(kg·m^3); D, tensor of elastic constants of the material of an ingot; $E(T)$, modulus of elasticity, MPa; K, safety factor of the steel; n, normal; R, radius, m; T, temperature, K; x, y, current coordinates, m; α, coefficient of thermal expansion of the steel, 1/K; ε_x, ε_y, γ_{xy}, components of the deformation tensor; λ, heat conductivity of the steel, W/(m·K); μ, Poisson number; ρ, density of the steel, kg/m^3; χ, coefficient of radiative heat exchange on the surface of the ingot, W/(m^2·K^4); σ_{str}, ultimate strength of the steel, MPa; σ_x, σ_y, τ_{xy}, components of the stress tensor; τ, time, sec. Subscripts: up, upper; ad, admissible; fin, final; m, masonry of a furnace; max, maximum; low, lower; res, residual; str, strength; sur, surface; 0, initial; 1, 2, 3, control points of the cross section of the ingot.

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