cross section of bed; $t = \tau/\tau_c$; T, T_0, $\overline{T}$, running temperature, initial, and final temperatures of bed, respectively; u, filtration velocity; u_1, u_2, velocities of bubble trails and descending particles; V_H, volume of batch of heated particles injected into bed from "gun"; x, longitudinal coordinate; α, coefficient of heat transfer from bed to environment; β, exchange coefficient; $\theta_i = (T_i - T_0)/(\overline{T} - T_0)$; $\xi = x/H$; $\xi_0 = h/H$; ρ_g, ρ_b, densities of gas and bed; τ, time; $\tau_c = H/u_1 + H/u_2$, circulation time; $\omega = fu_1 = (1 - f)u_2$, circulation velocity of particles over cross section of bed occupied by emulsion phase.

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INFLUENCE OF FLUCTUATIONS OF THE HEAT-TRANSFER COEFFICIENT ON THE TEMPERATURE AND THERMAL STRESSES IN A PLATE QUENCHED IN A VIBRATING FLUIDIZED BED OF A DISPERSE MATERIAL

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The influence of fluctuations of the heat-transfer coefficient on the evolution of the temperature and thermal-stress fields in a plate is analyzed.

The calculations for heat-engineering equipment with a fluidized bed are carried out, as a rule, using the time-average values of the heat-transfer coefficients between the bed and the heating or cooling surface immersed in it. On the other hand, it is well known that the heat-transfer rate between the (vibrating) fluidized bed and the surface is a time-fluctuating quantity and the amplitude of the fluctuations can be substantial (see [1], etc.). The fluctuations of the heat-transfer coefficient induce temperature fluctuations of the body subjected to heat treatment, and they, in turn, can affect the evolution of stresses and strains in the material of the product. In view of the practical difficulties of implementing the experimental investigation of the problem at the present time, we have undertaken a numerical study. We investigated the specific process of quenching a plate of chromium ball-bearing steel ShKh15 with a thickness of 10 mm in a vibrating fluidized bed of corundum particles with a diameter of 0.046 mm. A corresponding study using the time-average values of the heat-transfer coefficient obtained in [2] has been carried out previously [3]. We use the "packet" theory of heat transfer, which has already been shown [2] to be applicable to a vibrating fluidized bed. The computational procedure was similar to [4], in which the "packet" model was used to study the influence of fluctuations on the heat transfer and temperature fields in a body immersed in a fluidized bed. The process is assumed to be quasisteady, i.e., each successive fluctuation does not differ from the preceding one, and the heat transfer is determined by the continuous replacement of packets at the surface.

To calculate the instantaneous values of the heat flux on the surface of the body, we use the equation

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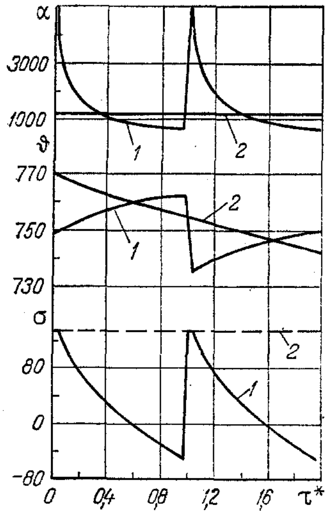

Fig. 1

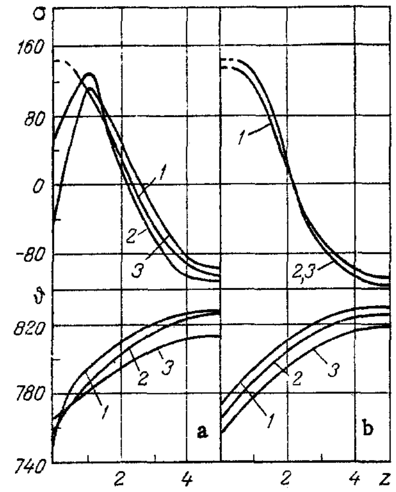

Fig. 2

Fig. 1. Heat-transfer coefficient α, W/m^2·°C, temperature ϑ, °C, and stress σ, MPa, on the surface of the plate vs. dimensionless contact time of "packets" with the surface. 1) Fluctuation values; 2) average values of α. The dashed line marks the plasticity zone.

Fig. 2. Distribution of temperatures and stresses along the thickness z, mm, of the plate in the initial cooling period. a) Fluctuation values; b) average values of α; 1) time from the instant of contact of the packet with the plate τ = 0.008 sec; 2) 0.1; 3) 0.33. The dashed line marks the plasticity zone.

$$\mathrm{Nu}(0,\ \mathrm{Fo}) = \frac{k}{\sqrt{\mathrm{Fo}_r}} \exp\left(-\frac{\mathrm{Fo}}{2\mathrm{Fo}_r}\right) I_0\left(\frac{\mathrm{Fo}}{2\mathrm{Fo}_r}\right), \tag{1}$$

which for k = 1 coincides with the relation derived in [5] for Dirichlet boundary conditions. The validity of this relation under mixed boundary conditions ("of the fourth kind") for bodies having a high heat capacity, for example, as in the case treated here, where the relative heat capacity of the body μ ≈ 200, has been demonstrated in [4, 6]. The coefficient k is introduced to account for the dependence of Nu on the surface temperature of the body and is evaluated on the basis of the experimental data for the time-average values of α given in [2]. The variations of k during the cooling process of the plate do not exceed ±20%. The cycle-average values of α calculated according to Eq. (1) coincide with the experimental values in [2]. We approximate the latter values for the investigated situation, in turn, by the expression

$$\bar{\alpha} = 0.427\vartheta_p + 860 \left[\frac{\mathrm{W}}{\mathrm{m}^2\cdot{}^\circ\mathrm{C}}\right]. \tag{2}$$

It is assumed in the calculations that [5]: Fo_r = 0.25 and the duration of the fluctuation cycle (time of contact of the packet of particles with the surface) [2] is 0.33 sec. The initial temperature of the body is taken to be 840°C, and the temperature of the bed 25°C. The temperatures and stresses are calculated on an ES (Unified Series) computer according to the algorithm and numerical scheme described in [7]. Allowance is made for the temperature dependence of all the parameters, as well as kinetic plasticity and the heat release in phase transitions. In view of the lack of published quantitative data on the conversions of steel ShKh15 in connection with a rapid temperature increase, we adopt the "frozen" structure approximation when the temperature is not lowered at a given time at a given point of the cooled body. To determine the role of fluctuations we also carry out calculations when the time-invariant average value $\bar{\alpha}$ depending only on the temperature is specified according to expression (2).

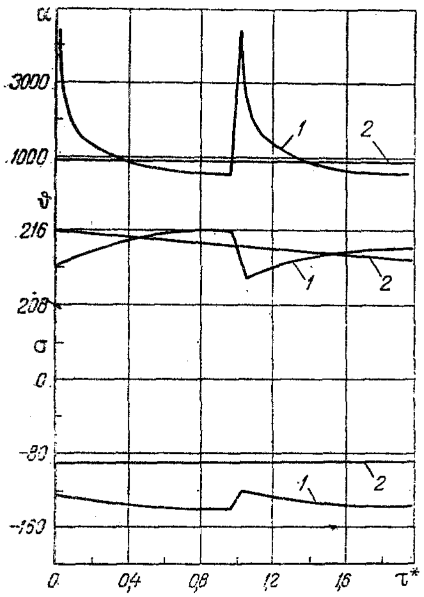

Fig. 3

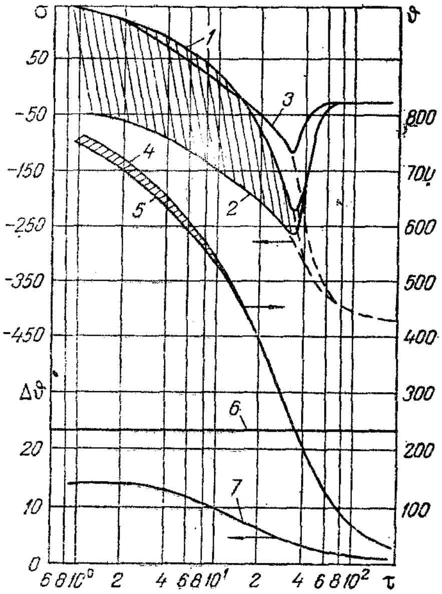

Fig. 4

Fig. 3. Heat-transfer coefficient, temperature, and stress on the surface of the plate vs dimensionless contact time of "packets" with the surface. 1) Fluctuation values; 2) average values of α.

Fig. 4. Stresses and temperatures on the surface of the plate vs. cooling time τ, sec. 1, 2) Upper and lower limits of variation of σ for fluctuating coefficients α; 3) σ calculated according to average α; 4, 5) upper and lower limits of temperature variation; 6) temperature of start of the martensitic transformation; 7) peak-to-peak amplitude of surface temperature fluctuations (Δϑ, °C) for fluctuating α. The dashed lines represent σ calculated without kinetic plasticity.

The calculations show (see Figs. 1 and 2) that the influence of fluctuations on the stresses generated in the body, as might be expected, is localized in the surface zone of the body, where the temperature fluctuations are a maximum. At the start of cooling, for large differential temperatures between the surface of the body and the bed and for elevated values of α the temperature fluctuations on the surface are large. Inasmuch as the yield point is low at the start of cooling (according to the data of [8], we use the approximate relation $\sigma_T = 429.8 - 0.393\vartheta$ MPa and $\sigma_T = 100$ MPa at $\vartheta = 840\,°C$), at certain times the stresses can exceed the yield point. It is shown in Fig. 1 how the values of α, ϑ and σ vary on the surface of the body in two successive fluctuation cycles corresponding to a variation of the surface temperature in the interval 770-740°C. Also shown in the same figure for comparison are the corresponding values calculated without regard for the fluctuation behavior of the heat transfer. It is evident from the figure that immediately after contact with a packet a narrow zone close to the surface acquires plastic regions with transient stresses that attain the yield point. Then the stresses drop to zero and are converted into compressive stresses. The stresses near the surface also attain the yield point in the initial cooling period in the calculations using the average values. In the temperature interval 200-220°C the influence of fluctuations of α on the temperatures and stresses is inconsequential (Fig. 3). The results of the calculations are generalized in Fig. 4, from which it is evident that the amplitudes of the temperature and stress fluctuations on the surface of the body decrease in the course of cooling. In the vicinity of the martensitic transformation these amplitudes are already scarcely perceptible, and with further cooling the temperatures and stresses calculated according to the fluctuation and time-average values of the heat-transfer coefficients gradually merge. This is explained by the decrease in the amplitude of the heat-flux fluctuations with decreasing surface temperature, the increase in the yield point, the reduction in the temperature gradient within the cross section of the body, and the influence of the kinetic plasticity of the material in the martensitic transformation. To illustrate the significant influence of the kinetic plasticity we have carried out supplementary calculations, from which it is evident (Fig. 4) that neglecting this effect results in a large variation of the stresses.

On the whole, the results do not exhibit any appreciable influence of the fluctuating behavior of the heat transfer on the magnitude of the post-quenching stresses. On the other hand, the study has shown that additional investigations are needed before any more definite assessment of the given problem can be made. In particular, it would be desirable to study the phase-transition kinetics in the fluctuating cooling regime. It is also conceivable that the existence of thermoplastic stresses in the initial cooling period could affect the fatigue characteristics of the product.

It must be noted in conclusion that the formulation of the given problem and the results should be useful for investigating thermal stresses not only in connection with quenching in a vibrating fluidized bed, but in many other situations where the heat-transfer rate is a time-fluctuating quantity.

NOTATION

ϑ, temperature; λ, effective thermal conductivity of "packet"; $c_0\rho_0$, volume specific heat of plate; $c\rho(1-\varepsilon)$, volume specific heat of disperse bed; d, particle diameter; ε, porosity (relative void space); τ, time; τ_r, relaxation time in the hyperbolic heat-conduction equation for disperse systems; τ_p, contact time between "packet" and plate; α, heat-transfer coefficient between bed and plate; $Nu = \alpha d/\lambda$, Nusselt number; $Fo = \lambda\tau/c\rho \times (1-\varepsilon)d^2$, Fourier number; $Fo_r = \lambda\tau_r/c\rho(1-\varepsilon)d^2$, dimensionless relaxation time; $\tau^* = \tau/\tau_p$, dimensionless time; δ, plate thickness; $\mu = (c_0\rho_0\delta)/(2c\rho(1-\varepsilon)d$, dimensionless parameter; σ, stress; $I_0(x)$, zeroth-order modified Bessel function of the first kind.

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