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CONTROLLED RATIONAL HEATING OF OBJECTS FOR HEAT TREATMENT

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The article presents a method of solving the problem of controlled heating involving the reproduction of some regularity of heating the surface of an object. As an example the article presents the solution of the problem of controlled radiative heating of a steel cylinder, and the obtained calculation is compared with experimental data.

The heating of steel is a widely used operation in processes of heat treatment such as annealing, tempering, normalization, and hardening. The quality and conditions of heating largely determine the subsequent properties of parts subjected to heat treatment. The heating temperature of different marques of steel lies in a wide range from 20 to 1300°C, and heating itself is carried out at different rates. Different heat sources are therefore used: electrical, radiative, plasma, lasers, electron beams. As a rule, a certain power is established which is used during the entire heating process. The heating rate is not varied in different temperature ranges, and power expenditure on heating is not being optimized. Yet in some cases it is necessary to ensure a variable heating rate at different stages of heating. This can be done by controlling the intensity of the supplied power ensuring the required temperature regime.

In the general case the problem of external heating can be formulated in the following way: we have to heat some object in such a way that its surface is heated according to the previously specified regularity $T_s = f(\tau)$. For that we have to find such a dependence $T_{so} = T_{so}(\tau)$, that the regularity $T_s = f(\tau)$ is fulfilled.

In this case the equation of heat conduction has the form [1]

$$c_p(T)\,\rho(T)\,\frac{\partial T}{\partial \tau} = \mathrm{div}\,(\lambda(T)\,\mathrm{grad}\,T) \tag{1}$$

with the boundary condition on the surface

$$\lambda(T)\,\frac{\partial T}{\partial \bar{n}} = \varphi(T_{so}), \tag{2}$$

where $\bar{n}$ is the outer normal to the surface of the object; φ is some function whose form depends on the method of heating. It can be seen from the boundary condition (2) that if the function $\varphi(T_{so})$ has an inverse, and we know the dependence of $\partial T/\partial n$ on time, we can find the temperature of the source

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$$T_{so}(\tau) = \varphi^{-1}\left(\lambda(T)\frac{\partial T}{\partial n}\right). \qquad (3)$$

Since the change of temperature on the surface of the object predetermines the change of the temperature field within the object, we can find $\partial T(\tau)/\partial n$ by solving Eq. (1) with the boundary condition $T_s = f(\tau)$ and some initial condition $T(\bar{r}, 0) = \psi(\bar{r})$.

As an example of the application of our method we will consider the controlled heating of a cylindrical steel rod. The rod is heated uniformly from the surface by a radiative source of energy. For this heating process Eq. (1) assumes the form

$$c_p(T)\rho(T)\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial r}\left(\lambda(T)\frac{\partial T}{\partial r}\right) + \frac{\lambda(T)}{r}\frac{\partial T}{\partial r}. \qquad (4)$$

The initial and boundary conditions are:

$$T(r, 0) = T_0, \qquad (5)$$

$$\left.\frac{\partial T(r, \tau)}{\partial r}\right|_{r=0} = 0, \qquad (6)$$

$$\lambda(T)\left.\frac{\partial T(r, \tau)}{\partial r}\right|_{r=R} = \varepsilon\sigma_0\left(T_{so}^4(\tau) - T_s^4(\tau)\right). \qquad (7)$$

The problem of control consists in finding $T_{so}(\tau)$ inducing the specified temperature regime $T_s(\tau) = f(\tau)$ on the surface of the rod. In that case expression (3) for the temperature of the source assumes the form

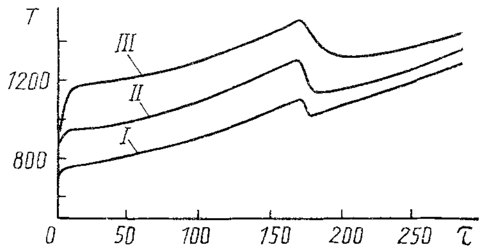
$$T_{so}(\tau) = \sqrt[4]{f^4(\tau) - \frac{\lambda(T)}{\varepsilon\sigma_0}\left.\frac{\partial T(r, \tau)}{\partial r}\right|_{r=R}}, \qquad (8)$$

and the problem reduces to determining $\left.\frac{\partial T(r, \tau)}{\partial r}\right|_{r=R}$. To find $\left.\frac{\partial T(r, \tau)}{\partial r}\right|_{r=R}$, we have to know the temperature field at each instant, i.e., we have to solve the direct problem of heat conduction with a boundary condition of the first kind:

$$T(R, \tau) = f(\tau). \qquad (9)$$

The system of equations (4), (5), (6), (9) was solved numerically by the Crank–Nicholson procedure. Actual calculations were carried out for a cylinder of steel R6M5 with radius $r = 0.005$ m. The thermophysical properties of the steel (λ, c_p, ρ) were taken according to the data of [2]. The regularity of heating the surface was specified in the following form:

$f(\tau) = 5\tau + 20$ in the temperature range 20—900 °C,
$f(\tau) = 3\tau + 900$ in the temperature range 900—1230 °C.



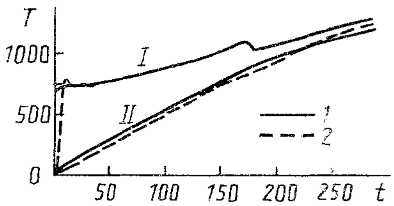


Fig. 1

Fig. 2

Fig. 1. Calculated dependence of the temperature of the source (degrees) on time (seconds) ensuring the specified temperature $f(\tau)$ on the surface of the cylindrical specimen: I) R = 0.005 m; II) 0.01; III) 0.02.

Fig. 2. Comparison of the experimental (1) and the calculated (2) temperatures of the source (I) and of the surface of the specimen (II) in radiative heating. T, °C; t, seconds.

The specified function $f(\tau)$ is characteristic of salt baths in which tools are heated for heat treatment. Figure 1 presents the calculated dependences of the temperature of the source ensuring the regularity of heating the surface $T_s = f(\tau)$ for specimens with radius 0.005, 0.01, and 0.02 m.

Figure 2 shows the calculated and the experimental dependences of the temperature of the source and of the surface for specimens with radius 0.005 m.

The experimental installation for radiative heating of objects and the experimental method were presented by us in [3]. It can be seen from Fig. 2 that the experiment is in good agreement with the calculation.

The obtained result is of great practical importance because controlled radiative heating can be instrumental in attaining specified regimes of heat treatment so that ecologically harmful heat sources can be replaced in production.

NOTATION

$T = T(\bar{r}, \tau)$ is temperature at the point with the radius vector $\bar{r}$ at the instant τ; T_{so} and T_s) temperature of the source and of the surface, respectively; c_p) specific heat; ρ) density; λ) thermal conductivity; ε) reduced degree of blackness; σ_0) Stefan–Boltzmann constant.

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NONSTEADY THERMOELASTIC DEFORMATION OF COOLED LASER MIRRORS

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The article investigates the temperature fields and distortions of the optical surface of laser mirrors of different materials subjected to different kinds of thermal loading.

The designing, production, and testing of high-energy laser mirrors is very laborious and expensive. That is why various engineering–physical models are worked out for them, making it possible to determine theoretically distortions of the shape of the optical surface of reflectors in dependence on their geometric dimensions, properties of the materials, the structure of the cooling system, the flow rate of the heat carrier, the profile of the luminous load, etc. [1-3]. Most fully developed are methods of calculating round mirrors subjected to axisymmetric beam load, based on the examination of steady temperature fields. It was shown in [3] that for solid disk mirrors cooled from the rear surface there exists an exact solution of the spatial axisymmetric problem of thermoelasticity. Nonsteady deformation of uniformly illuminated reflectors was dealt with in [4] in the approximation of the theory of thermoelasticity of thin plates.

In the present work we explain the method of calculating three-dimensional nonsteady distributions of temperature and of thermoelastic displacements in cooled mirrors that have the shape of parallelepipeds (Fig. 1). The method takes into account the special traits of spatial distribution of the thermal load, the anisotropy of the thermal conductivities,

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