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]

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

with the boundary condition on the surface

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

where $n$ is the outer normal to the surface of the object; $\varphi$ 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.

The initial and boundary conditions are:

\[ T(r, 0) = T_0, \]

\[ \frac{\partial T(r, \tau)}{\partial r} \bigg|_{r=R} = 0, \]

\[ \lambda(T) \frac{\partial T(r, \tau)}{\partial r} \bigg|_{r=R} = \sigma \sigma_0 (T_{so}^i - T_s^i(\tau)). \]  

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

\[ T_{so}(\tau) = \frac{1}{f^i(\tau)} \int_{R}^{r} \lambda(T) \frac{\partial T(r, \tau)}{\partial r} \bigg|_{r=R} \, dr. \]

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 \( r = 0.005 \text{ m} \). The thermophysical properties of the steel (\( \lambda, c_p, \rho \)) were taken according to the data of [2]. The regularity of heating the surface was specified in the following form:

\[ f(\tau) = 5\tau + 20 \text{ in the temperature range } 20-900 \degree \text{C}, \]

\[ f(\tau) = 3\tau + 900 \text{ in the temperature range } 900-1230 \degree \text{C}. \]

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) \( R = 0.005 \text{ m} \); 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. \( T, \degree \text{C} \); \( t, \text{ seconds} \).