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SIMULATION OF THE TEMPERATURE FIELD IN THE SURFACE LAYER UNDER PULSED ELECTRON-BEAM HEATING

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This paper presents the results of the numerical simulation of the temperature field in single- and double-layer materials under electron-beam heating in stationary and pulsed modes and analyzes the conditions under which control of the heat-treated-layer parameters by varying the duration, the off-duty ratio, and the number of heating pulses is provided.

One method of strengthening the surfaces of structural elements in machine-building is adequate thermal treatment [1]. To realize this method, laser, electron- and ion-beam technologies are promising [2, 3]. In so doing, it is often necessary to heat surface areas considerably exceeding the cross section of high-energy beams, which requires their surface scanning. The use of plasma electron sources (PELSs) with beams having a large cross section makes it possible to increase the homogeneity of the thermal electron-beam action [4]. Moreover, PELSs, as compared to the traditional thermocathode electron guns, are less sensitive to the gas emission accompanying the thermal treatment [5, 6] and are also able to provide a wider control range of the energy flux incident on the surface, e.g., due to the realization of pulsed heating of the surface by an electron beam. The influence of the value of the pulse energy input on the temperature field formation in the surface layer under laser radiation was considered, in particular, in [7]. However, in the above works primary consideration was given to the results of the thermophysical modification of the surface properties, and the possible variation of the pulse energy input parameters on the modified surface layer parameters was practically not analyzed. At the same time, it may be suggested that variation of the width of energy input pulses, the duration of the pauses between pulses, and the number of pulses will widen the possibilities of controlling the thickness of the modified surface layer and the temperature gradient in the layer, as well as make it possible to weaken the thermal action on the regions of the material adjoining the layer.

This paper presents the results of numerical simulation of the temperature field in the surface layers of the material under continuous operation and in different pulsed regimes of energy input provided by actually existing PELSs [4, 5].

Thermophysical Model. Let us consider the electron beam as a surface heat source, which is appropriate at accelerating voltages of ~30 kV and is characteristic of plasma electron sources [4, 5]. Such an assumption is possible for the reason that at energies of ~30 keV the free path of an electron in a substance is $\sim 10^{-9}$ m (for steel) [8, p. 12], whereas the thickness of the thermally modified layer is $\sim 10^{-3}$ m.

Under the conditions of radial symmetry of the electron beam, the formulation of the heat-conduction problem with account for the temperature dependence of thermophysical coefficients is of the form

$$C(T)\frac{\partial T(r,z,t)}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[\lambda(T)\,r\frac{\partial T}{\partial r}\right]+\frac{\partial}{\partial z}\left[\lambda(T)\frac{\partial T}{\partial z}\right]. \tag{1}$$

The boundary conditions for single-layer materials are

$$-\lambda(T)\frac{\partial T(r,0,t)}{\partial z}=q(r)\,, \tag{2}$$

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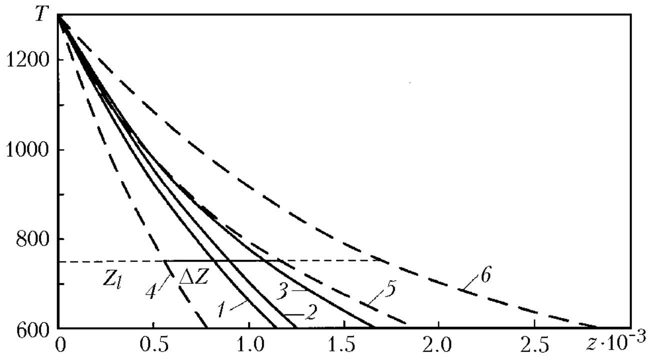

Fig. 1. Temperature distribution in the single-layer material thickness for various parameters of the pulse: 1, 2, and 3) $Q = 2 \cdot 10^7$ W/m^2; 4, 5, and 6) $3 \cdot 10^7$ W/m^2; 1 and 4) continuous mode of action; 1) $\tau_h = 0.279$ sec; 4) 0.111 sec; 2, 3, 5, and 6) pulsed mode of action; 2) $\tau_h = 0.01$ and $\tau_c = 0.01$; 3) 0.05 and 0.05; 5) 0.01 and 0.02; 6) 0.01 sec and 0.03 sec. T, $^{\circ}$C; z, m.

$$-\lambda(T)\frac{\partial T(r, H, t)}{\partial z} = 0\,, \tag{3}$$

$$-\lambda(T)\frac{\partial T(R, z, t)}{\partial r} = 0\,. \tag{4}$$

For the cross-section-homogeneous electron beam of radius r_f the distribution q is given by the function

$$q(r) = \begin{cases} Q\,, & r < r_f\,; \\ 0\,, & r \geq r_f\,. \end{cases} \tag{5}$$

Conditions (3) and (4) take into account the absence of heat removal from the reverse and end sides of a product, since the electron-beam action is realized in vacuum.

Of particular technological interest seems to be the analysis of the results of the pulsed action on double-layer materials with different thermophysical properties. For such materials, it is necessary to add to conditions (2)–(4) the condition of ideality (or nonideality) of the thermal contact of materials. In the cases of an ideal thermal contact, the boundary conditions take on the form

$$\begin{gathered} -\lambda_1(T)\frac{\partial T(r, 0, t)}{\partial z} = q(r)\,, \quad -\lambda_2(T)\frac{\partial T(r, H, t)}{\partial z} = 0\,, \\ \lambda_1(T)\frac{\partial T(r, H_1, t)}{\partial z} = \lambda_2(T)\frac{\partial T(r, H_1, t)}{\partial z}\,, \quad H = H_1 + H_2\,. \end{gathered} \tag{6}$$

The initial condition for the ith cycle of heat treatment can be given in the form of the function

$$T_i(r, z, 0) = \begin{cases} T_0\,, & i = 1\,; \\ T_{i-1}(r, z, \tau_h + \tau_c)\,, & i > 1\,. \end{cases} \tag{7}$$

Equation (1) jointly with the boundary conditions (2)–(4) or (6) and the initial condition (7) was solved numerically.

Simulation Results. In the calculations, we used the experimental temperature dependences of the thermophysical coefficients $\lambda(T)$ and $C(T)$ for steel 45 [9], as well as the parameters of the electron beam of the experimental plasma source of electrons [4, 5] providing in the stationary mode a beam power of up to $5 \cdot 10^7$ W/m^2, and in the

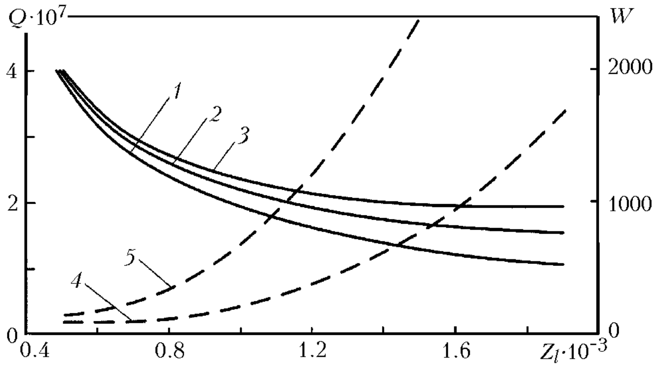

Fig. 2. Power density (1, 2, 3) and total energy input (4, 5) versus the heat-treated layer thickness; 1 and 4) stationary mode of action; 2, 3, and 5) pulsed mode of action; 2) τ_h = 0.05 sec, τ_c = 0.03 sec; 3) and 5) 0.05 and 0.1 sec. Q, W/m^2; Z_l, m.

pulsed mode up to $5\cdot10^8$ W/m^2. To illustrate the features of the pulsed action compared to the stationary one, we calculated the cycle of heat treatment in a chosen temperature range for some material (steel 45). To this end, the calculation of the temperature field was stopped as soon as on the surface the given temperature (1300°C) was attained, and by the temperature distribution we determined the layer thickness, on which the given temperature (750 or 900°C) was attained, by varying the power density, the number of pulses, and their off-duty ratio. Figures 1 and 2 present the results of the calculations obtained from the point of view of the proposed model — a fragment of the temperature distribution in the material and the dependence of the heat-treated-layer thickness on the electron-beam power density and the total energy input to the product for the stationary and pulsed modes of action.

As follows from Figs. 1 and 2, in the stationary mode of action, with decreasing power density of the electron beam the slope of the temperature-distribution curve decreases (Fig. 1, curves 1 and 4), and the thickness of the heat-treated layer and the total energy input increase (Fig. 2, curves 1 and 4). This means that theoretically even in the stationary mode of action it is possible to obtain a thermally treated layer with a large thickness. However, it is clear that in so doing the remaining part of the product is subjected to substantial heating, which in many cases is inadmissible [1].

In pulsed heating, the tendencies of the stationary mode remain; however, all other conditions being unaltered, the heat-treated-layer depth is largely determined by the time interval between pulses (cooling time τ_c).

As the calculations have shown, if the cooling time is much shorter than the heating time in the heat-treatment cycle, then the temperature distributions in the material in the stationary and pulsed modes of heating differ only slightly (Fig. 1, curves 1 and 2). A marked increase in the heat-treated-layer thickness is attained in the case where the energy received by the material upon heating (τ_h) has time to be redistributed, i.e., where the cooling time τ_c is comparable to or larger than the heating time τ_h in the cycle (pulse) (Fig. 1). However, as in the stationary mode of heating with a low power density (Fig. 2, curve 1), an increase in the cooling time τ_c leads to a superheating of the entire specimen due to the increase in the total energy input.

It should be noted that with increasing cooling time τ_c and decreasing power density of the electron beam Q there is also a decrease in the cooling rate. Therefore, at some combination of these parameters the cooling rate may turn out to be below the critical value at which strengthening of the given material can be realized. Consequently, such conditions of heat treatment (at small Q and $\tau_c >> \tau_h$) are of no technological interest.

Thus, there exists some optimal range of τ_h and τ_c ratios for each value of the power density in which a marked increase in the heat-treated-layer thickness can be attained without a substantial superheating of the entire product and at a reasonable increase in the total energy input (Fig. 2, curves 3, 5).

Figure 3 shows the dependences of the temperature gradient and the thickness of the heat-treated layer on the dimensionless parameter corresponding to the specific heating time ($\tau_h/(\tau_h + \tau_c)$). As is seen from Fig. 3, the choice of adequate parameters of the pulsed mode of heating permits decreasing the temperature gradient in the layer with a

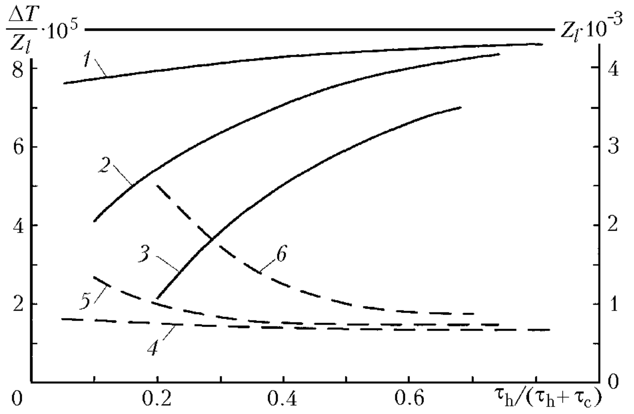

Fig. 3. Temperature gradient in the heat-treated layer and layer thickness versus the specific heating time (Q = $3\cdot10^7$ W/m^2): 1, 2, and 3) temperature gradient in the layer; 4, 5, and 6) layer thickness; 1 and 4) τ_h = 0.05; 2 and 5) 0.03; 3 and 6) 0.01 sec.

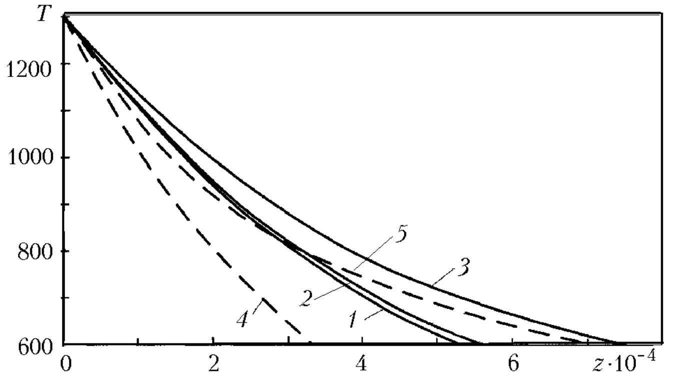

Fig. 4. Temperature distribution in the layer thickness of the boron-containing material on a steel substrate: 1 and 4) stationary mode of action; 2, 3, and 5) pulsed mode of action; 1, 2, and 3) Q = $2\cdot10^7$ W/m^2; 4 and 5) $3\cdot10^7$ W/m^2; 2) τ_h = 0.05; τ_c = 0.01; 3) 0.05 and 0.05; 5) 0.01 sec and 0.02 sec. T, °C; z, m.

marked increase in the heat-treated-layer thickness by ΔZ (Fig. 1). Apparently, also in this case the total energy input will increase with increasing number of pulses.

From the analysis of Fig. 3 it follows that there exists a range of parameters $\tau_h/(\tau_h + \tau_c)$ for which satisfactory fulfillment of all requirements is possible.

From the technological point of view, it is interesting to analyze the results of the thermal action on double-layer materials, especially if the heat conductivities of these materials differ considerably. Figure 4 shows fragments of the temperature distribution in a layer with a boron-containing material on a steel substrate (the thickness of the boron-containing layer is 0.5 mm, that of the steel substrate is 9.5 mm, the specimen radius is 10 mm, the electron beam radius is 3 mm). Because of the low heat conduction of the boron-containing coating, it is difficult to obtain a heat-treated layer with a large thickness. However, in this case as well the use of the pulsed mode of action makes it possible to increase the layer thickness (Fig. 4, curves 4 and 5) or decrease the temperature gradient in the layer (increase the thickness homogeneity of the properties).

In general and in the case of double-layer materials with different thermophysical parameters, the above-mentioned mechanisms manifest themselves. Therefore, for such materials it is possible to determine the range of parameters of the electron-beam action in which control of the heat-treated layer characteristics is attained.

It should be noted that the dependences obtained can in no way be considered as the technological conditions of thermal treatment of a given material but should be regarded as dependences illustrating the possibility of controlling the complex of properties of the heat-treated layer (temperature gradient, thickness, cooling rate) by using the pulsed action with different parameters.

CONCLUSIONS

1. The pulsed mode makes it possible to attain a larger thickness of the modified layer than in the stationary mode with a high homogeneity of properties, i.e., upgrade, under certain conditions, the efficiency of the energy input in treating both single-layer materials and materials with coatings.
2. It is possible to find optimal conditions of thermal treatment for each material with account for the corresponding temperature dependences of the thermophysical coefficients, the presence of the substrate, the geometric parameters of the product, etc., which can be realized from the viewpoint of the proposed model on the basis of the developed software.
3. The results of the simulation illustrate the widening of the potentialities of strengthening technologies with the use of pulsed thermal electron-beam heating.

NOTATION

$C(T)$, specific heat capacity of the treated material, J/(kg·K); H, thickness of the treated material, m; H_1, H_2, layer thicknesses, m; Q, electron-beam power density, W/m^2; $q(r)$, power density, W/m^2; R, radius of the treated material, m; r, radial coordinate, m; r_{f}, radius of the spot of action, m; T, temperature of the material, $^{\text{o}}$C; T_0, initial value of the material temperature, $^{\text{o}}$C; T_i $(r, z, 0)$, initial temperature distribution in the material for the ith cycle of heat treatment; T_{i-1} $(r, z, \tau_{\text{h}} + \tau_{\text{c}})$, temperature distribution in the material after the $i-1$th cycle of heat treatment; t, time of action, sec; W, total energy input, J; z, coordinate varying with material thickness, m; ΔZ, increase in the heat-treated-layer thickness under the pulsed action compared to the continuous action at the same power density, m; Z_l, thickness of the heat-treated layer, m; $\lambda(T)$, heat-conductivity coefficient, W/(m·K); $\lambda_1(T)$, heat-conductivity coefficient of the first layer; $\lambda_2(T)$, heat-conductivity coefficient of the second layer; τ_{c}, pulse separation, sec; τ_{h}, heating time of the material during one pulse of action, sec. Subscripts: 0, initial value; 1, 2, number of the heat-treated material layer; c, cooling; f, spot of action; h, heating; i, ordinal number of the heat-treatment cycle.

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