REGULARITIES OF CYLINDRICAL BODY HEATING BY A HIGH-TEMPERATURE HETEROGENEOUS JET

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A mathematical model is proposed and a numerical computation is executed for heating the base and the coating during gas-thermal deposition on a cylindrical body. The influence of the frequency of body rotation on its heating rate is established.

One of the most promising hardening technologies for articles by using coating deposition is gas-thermal sputtering during which the article is heated by both a gas jet and the powder particles it contains. The velocity and the temperature variation band in the solid during formation of the gas-thermal coating directly affect the nature and magnitude of the residual stresses and the adhesion strength of the coating layer to the base [1, 2]. Consequently, determination of the temperature fields in the coating and the base during sputtering is an urgent problem.

Heating of a cylindrical body rotating at a constant frequency is investigated in this paper during the action of a high-temperature heterogeneous jet on it without a change in its location relative to the surface being sprayed.

Let us consider the physical model of coating deposition on an elementary section of a cylindrical base surface rotating at a constant frequency. A high-temperature gas jet with particles to be sprayed within its stream is directed along the radius to the cylindrical surface. As it moves through the jet the section is subjected to the action of a heat flux from the gas jet whose density $q_g = f(n, \tau)$ grows smoothly from zero to the maximal value and then decreases to zero as the elementary section approaches the edge of the gas jet. As the section enters the stream of particles being sprayed it is simultaneously subjected to the action of a discrete stream of individual particles whose average density $q_p = f(n, \tau, G_p)$ also varies between zero and the maximum and then again to zero.

After emergence beyond the limits of the gas jet the surface of the elementary section is cooled in the environment because of convection caused by body rotation. The cooling mode continues until the beginning of the next cycle of elementary section interaction with the gas jet and the flux of particles being sprayed. Moreover, during the surface heating and cooling periods, the heat transfer process by heat conduction proceeds in the bulk of the coating and the article as does also the process of radiation into the environment.

Therefore, under real conditions the surface section is subjected to alternating cyclic action of thermal and mass flows while the coating layer thickness constantly grows.

It is assumed in the development of the mathematical model that the cylindrical article being sprayed rotates at a constant frequency, the heterogeneous jet axis is perpendicular to the surface being sprayed, and is not shifted relative to the article. The spraying spot diameter and the transverse gas jet section are less than the article diameter.

The following assumptions are also made: The thickness of the superposable coating layer is very much less than the article radius, the article is considered as a semi-bounded body, the densities of the thermal fluxes from the gas jet and from the particles during interaction with the elementary section are constant and correspond to experimentally determined average density, the heat sink from the heated body in the environment is determined by radiation, the relationship between the time of elementary section interaction with the gas jet and the particle flux per cycle is determined by the relationship between the diameters of the transverse gas jet section, the spraying spot, and the article diameter.

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The temperature field distribution in the coating-article system is described by a nonstationary heat conduction equation of the form [3]

$$c_i(T)\rho\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\left(\lambda_i(T)\frac{\partial T}{\partial x}\right),\quad i=1,\ 2. \tag{1}$$

The rate of coating growth is determined by the given mass flow rate of the powder material and the diameter of the spraying spot. The coordinate x is measured from the body axis and $x = \ell(\tau)$ increases as the coating layer is deposited during the spraying cycle. During the spraying the article temperature on the axis remains constant

$$T|_{x=0}=T_0^0=\mathrm{const}. \tag{2}$$

For $x = \ell(\tau)$ on the outer cylindrical body boundary

$$-\lambda_i(T)\frac{\partial T}{\partial x}\bigg|_{x=l(\tau)}=q_p+q_g-q_\varepsilon. \tag{3}$$

When the elementary section is in the flow zone of the particles being sprayed, thermal fluxes from the heated particles and the gas jet with the densities q_p and q_g act on it. The heat losses to the outer medium are determined by radiation with density $q_\varepsilon = \varepsilon\delta T^4$. In the zone of pure gas jet action q_p is eliminated from the right side of (3) while also q_g is eliminated in the action zone of the environment.

The system (1)-(3) is closed by the initial condition

$$T|_{\tau=0}=T_0^0 \tag{4}$$

and the adjoint condition on the line $x = \ell(\tau_0)$ of the form

$$[T]=0;\quad \left[\lambda\frac{\partial T}{\partial x}\right]=0. \tag{5}$$

Equation (1) was approximated by a homogeneous conservative difference scheme with lead. The conservativity principle is one of the governing ones in constructing algorithms for solutions of problems with discontinuous coefficients. The difference scheme was constructed by an integrointerpolation method in meshes not orthogonal over time [4, 5]. Utilization of nonorthogonal meshes was associated with taking account of the coating growth during action of the heterogeneous jet on the elementary section. Taking account of the coating growth resulted also in the need to approximate the boundary condition (3) along the curve $x = \ell(\tau)$. The steps of the spatial mesh in the segment $[\ell(0), \ell(\tau)]$ were selected as a function of the spraying velocity v_s.

Values of the heat conduction and specific heat for materials of the base and the coating were determined as a function of the body temperature at the computation point while the initial data [6-8] were approximated by the expressions

$$\begin{aligned}&c_1=398+0{,}2T,\ \mathrm{J/(kg\cdot K)},\quad c_2=450+0{,}15T,\ \mathrm{J/(kg\cdot K)},\\&\lambda_1=110-0{,}11T,\ \mathrm{W/(m\cdot K)},\quad \lambda_2=3+0{,}028T,\ \mathrm{W/(m\cdot K)}.\end{aligned} \tag{6}$$

These expressions are valid in the coating temperature range 290-1200 K and in the base temperature range 290-900 K.

The heat flux density profiles measured experimentally for the particles and gas jet of a gas-flame burner [9] were approximated by step profiles convenient for performing numerical computations.

The computation program developed on the basis of the mathematical model was realized on a BÉSM-6 electronic computer. The step in the depth of the base and the coating, the spraying velocity, the values of the heat flux densities from the particles and from the gas jet, the properties of the base and coating materials, the article frequency of rotation, and the initial temperature of the base were given in the computation.

The computation of the temperature distribution in the body were executed for the process of gas-flame spraying of a coating of self-fixing powder on a nickel base PT-19N-01 on a steel cylindrical 120-mm diameter article rotating at the frequency 20 and 200 rpm.

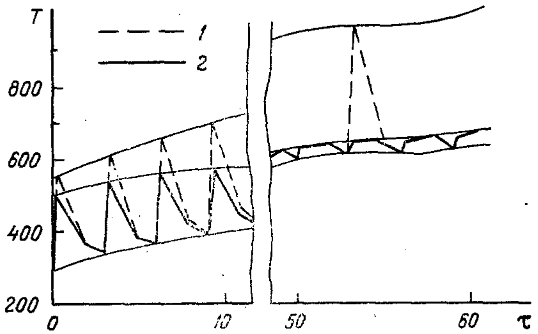

Fig. 1. Cyclic temperature change of the surface being sprayed and of the base surface ($q_p = 7.4 \cdot 10^6$ W/m²; $q_g = 4 \cdot 10^5$ W/m²; $G_p = 7.4$ kg/h; D = 0.12 m; n = 20 rpm): 1) temperature of surface being sprayed; 2) temperature of the base surface, T, K; τ, sec.

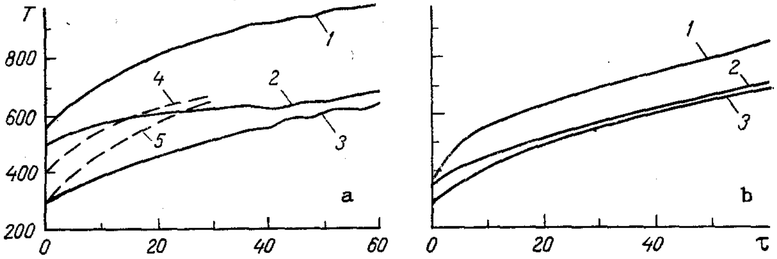

Fig. 2. Change in the maximal (1) temperature of the surface being sprayed and in the maximal (2, 4) and minimal (3, 5) temperatures of the base surface during coating deposition on a cylindrical article with frequency of rotation 20 (a) and 200 rpm (b) ($q_p = 7.4 \cdot 10^6$ W/m², $q_g = 4 \cdot 10^5$ W/m², $G_p = 7.4$ kg/h, D = 0.12 m): 1, 2, 3) computation; 4, 5) experiment, n = 35 rpm.

Experimental measurement of the article surface temperature during spraying of the coating was realized by using a Chromel–Alumel thermocouple mounted on the surface of a 4-mm-thick steel plate that was fastened to the flat face of a continuous steel mandrel at a 56-mm radius. The thermocouple was connected to a KSP-4 device through a mercury current pick-up that permitted measurement of the temperature of the plate being sprayed during mandrel rotation.

The nature of the change in the computed temperatures of the base and coating surfaces during cyclic action of a heterogeneous jet on the surface being sprayed is presented in Fig. 1. It follows from the results of the computation that the amplitude of base surface oscillation exceeds 200 K at the beginning and then is lowered to 50 K as the spraying time increases. At the same time the amplitude of the coating surface temperature fluctuations grows from 200 to 300 K and more. However, both the minimal and maximal values of the base and coating temperatures grow as the spraying time increases and the coating layer thickness grows correspondingly (Fig. 2). The high amplitude of the temperature fluctuations in the deposited coating layer because of the cyclic nature of the spraying process can result in the origination of significant stresses in the coating and scaling of the coating during the spraying process, as is observed in experiment. An increase in the frequency of rotation of the surface being sprayed results in a reduction of the base and coating temperature fluctuation amplitude (Fig. 2b). The amplitude of the temperature fluctuation of the base surface diminishes as the coating thickness grows and its shielding effect on the heat flux to the base increases.

Experimental data (Fig. 2a) verified the fundamental regularities of the change in temperature of a cylindrical body surface as obtained by computational means. The high rate of surface heating in the experiment as compared with the computation can be explained by the thermal resistance in the plate-mandrel contact. The amplitude of the temperature change diminishes as compared with the computed value (Fig. 2a) because of the increase in the frequency of the spraying cycles from 20 to 35 rpm. It is also established that the nature of the base surface temperature change in an individual heating and cooling cycle agrees completely with the computation.

The nonlinear nature of heat propagation in the coating and base results in spoiling the periodicity of the body temperature change for high values of the spraying time in contrast to small values of the spraying time (see Fig. 1). The imposition of thermal waves after each other results in a temperature change that does not agree with the direction and intensity of the external thermal fluxes in the spraying cycles. As the cycle frequency increases this feature becomes less noticeable.

NOTATION

c, specific heat; G_p, mass flow rate of the superposable material; q_g, q_p and q_ε, heat flux densities from the gas, the material particles and radiation from the body; n, frequency of article rotation; ℓ, coating thickness; T, temperature; x, running coordinate; δ, Stefan–Boltzmann constant; λ, heat conduction; ρ, density; ε, coating emissivity; τ, time; is the subscript for the coating (1) and the base (2).

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