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The Study of the Thermal Processes in an Electrode Influenced by an Electric Arc

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Abstract. The effect of a moving arc spot on a material of a plasmatron electrode is considered in the present paper. Temperature-dependence of material thermophysical properties is taken into account. Dynamics of temperature and thermal stresses fields are calculated. The characteristic feature of temperatures distribution along radius of an electrode is large gradient of temperatures in a narrow zone near to a surface which can cause large thermostresses and microcracks.

Introduction

Heat engineering equipment elements operation is accompanied by large heat flows. High temperatures and temperature gradients develop in surface layers and the bulk in accordance with heat flow parameters (form, distribution, time of influence) and thermophysical properties of the material. Hence significant thermomechanical stresses arise. They can change essentially the general stressed state of the element and affect its serviceability.

Experimental data acquisition of space-time distribution of temperature fields and thermostressed state is rather difficult. Thus the development of the approaches and methods of mathematical modelling becomes more important. Generally, stating the problem of heating effect it is necessary to take into account the following: gas-dynamics processes, processes of melting and evaporation, processes of thermomechanical destruction and plastic deformation in view of structural condition and varied physicochemical characteristics of the materials [1]. To a first approximation, however, it is possible to research only a stressed-deformed condition for structural-stable zones.

Our research deals with the moving spot of an electric arc affecting the working surface of a plasmatron copper electrode (Fig. 1). Experimental observations of the arc spot track on the electrode surface have shown its significant non-uniformity because of the spot non-uniform structure. For example, the spots of type I as they are described in [2, 3] consist of rapidly moving, appearing and disappearing microspots, which are considerably distant from each other, and their temperature fields are not crossed. On the contrary, the spots of type II will form very dense association of microspots with overlapped temperature fields. Thus, it is possible in some cases to neglect the complex microstructure [4, 5] of arc spots and microprocesses on their surface, study their integrated thermal influence on electrodes and to use the simplified arc spot model as an equivalent surface circle form source with uniform density of the heat flux equal to average-integral value. The main parameters characterising the arc spot as the surface source are: spot diameter d_s, heat flux density q_0, constant heat flux velocity υ. Current density in the spot is j ~500 A/mm^2, density of the heat flux is q_0=10^8-5·10^9 W/m^2, frequency of arc rotation is up to 1000 Hz, t_{im}~50÷150μs. The process of heat transfer is assumed to be as following. Heat flow q_k from the plasmatron operating environment is determined by convection and radiation. The heat flow q_0 from near-electrode area of the arc in a spot is added to the heat flow q_k (Fig. 1). The external surface of electrode R_2 is cooled with high-velocity water flows q_w. The conditions of adjustable heat sink are set. They depend on the external boundary temperature. Specific heat flux q_0 is evenly distributed over the spot with diameter d_s. As the arc spot moves, the local source q_0 is impulsive for any point

or area of the surface R_1. To determine thermal fields $T(R,\varphi, z)$ one, two, three-dimensional tasks of thermal conductivity have been solved. Melting of material surface is taken into account. The thermophysical and mechanical properties of the electrode material depend on temperature $f(T)$, however their great part is obtained by the extrapolation method.

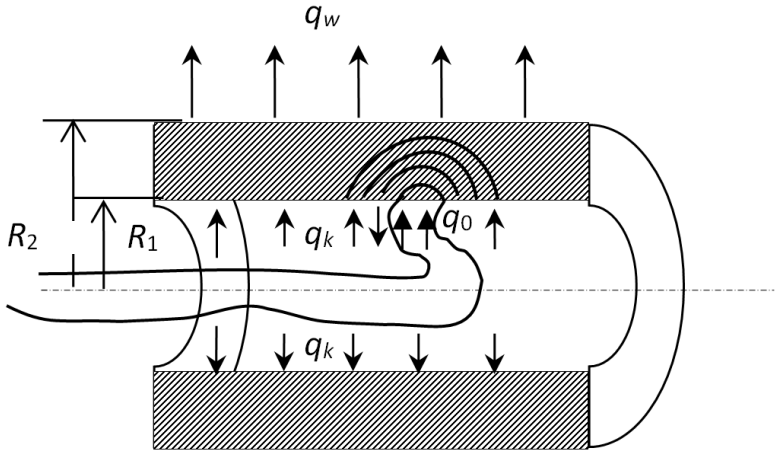

Fig. 1. Scheme of heat transfer in the output electrode of the plasmatron.

Thermal problem

Variable temperature field $T(R, \varphi, z, t)$ in a hollow electrode is

$$c_p(T)\rho(T)\frac{\partial T}{\partial t} = \frac{1}{R}\frac{\partial}{\partial R}\left[R\lambda(T)\frac{\partial T}{\partial R}\right] + \frac{1}{R^2}\frac{\partial}{\partial \varphi}\left[\lambda(T)\frac{\partial T}{\partial \varphi}\right] + \frac{\partial}{\partial z}\left[\lambda(T)\frac{\partial T}{\partial z}\right], \tag{1}$$

$$R_1 \le R \le R_2, \quad \varphi_0 \le \varphi \le \varphi_k, \quad 0 \le z \le l_k, \quad 0 < t \le t_k.$$

Initial conditions are $T(R, \varphi, z, 0) = T_0$, $t = 0$.

Boundary conditions are

$$-\lambda(T)\frac{\partial T}{\partial R} = q_0 + q_k, \qquad \text{for } R = R_1, \ 0 \le r \le r_s; \tag{2}$$

$$-\lambda(T)\frac{\partial T}{\partial R} = q_k, \qquad \text{for } R = R_1, \ 0 \le z \le l, \ 0 \le \varphi \le \varphi_k; \tag{3}$$

$$-\lambda(T)\frac{\partial T}{\partial R} = \alpha_2'(T - T_w), \qquad \text{for } R = R_2, \ 0 \le z \le l, \ 0 \le \varphi \le \varphi_k; \tag{4}$$

$$\frac{\partial T}{\partial z} = 0, \qquad \text{for } z = 0, l. \tag{5}$$

where $c_p(T)$ is heat capacity; $\lambda(T)$ is thermal conductivity; $\rho(T)$ - density; $c_p, \lambda, \rho \ne f(R, \varphi, z)$; $t = N2\pi R_1/\upsilon$ is current time, N is the number of revolutions of the arc spot; υ - arc spot velocity; q_0 is density of the heat flow in the spot of radius r_s with the centre in a point $\Phi(\varphi_s, z_s)$; $r = \sqrt{(\varphi - \varphi_s(t))^2 + (z - z_s(t))^2}$, $\varphi_s = \upsilon \cdot t$, $z_s = z_a \cos \omega_z t$, z_a is the amplitude and frequency of scanning of the arc over axis z; l is the length of the considered electrode section.

Condition at the boundary of phase transition is

$$-\lambda_s \frac{\partial T(R_l,t)}{\partial n} = -\lambda_l \frac{\partial T(R_l,t)}{\partial n} + \rho L \frac{dR_l}{dt}, \quad (6)$$

where n is the normal in each point of the interphase of solid-liquid phases; L is specific heat of material: R_l is the position of boundary between two phases.

Results of calculations

The calculations were carried out for a copper electrode in various heat fluxes $q_0 = 10^8 - 10^9$ W/m^2 and when spot velocity υ was of 10, 20, 40 m/s.

Fig. 2 shows the temperature field of the internal surface of the electrode. The temperature changes on the internal surface at the point in the center of the moving heat flux is shown in Fig. 3 (curve 1), T_1 (t), for $q_0 = 5 \cdot 10^9$ W/m^2 (υ=40 m/s). The maximum temperature of heating T_{1h} appreciably increases. Therefore when the heat flow is $q_0 = 5 \cdot 10^9$ W/m^2 during 50μs a melted layer appears almost at once. The "liquid/solid" interphase surface exists always inside anode thickness on the circle of the radius R_l. Beyond this circle the temperature does not exceed T_l. Deep inside the anode wall temperature impulse T (t) turns into a temperature wave (Fig. 3) and quickly damps.

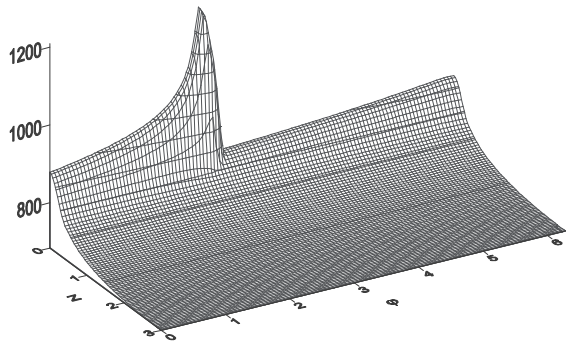

Fig. 2. Temperature field T (R_1, φ, z) of the internal surface of the electrode.

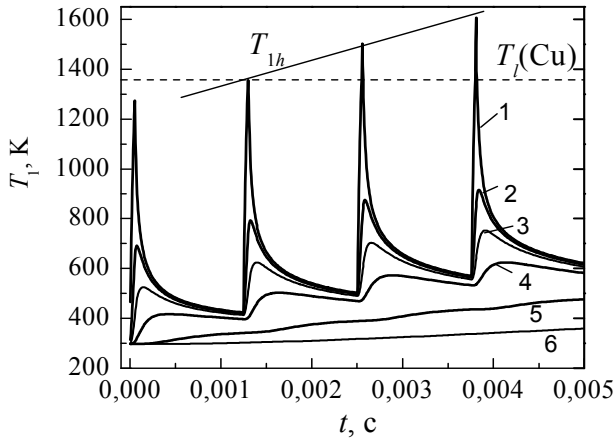

Fig. 3. Development of pulsing process with parameters v_φ=40 m/s, $q_0 = 5 \cdot 10^9$ W/m^2. Distribution of a thermal wave deep into of a material: 1-R_1; 2-6- R-R_1= 0.07; 0.14; 0.3; 0.7; 1.4 mm.

Fig. 4 demonstrates the process of heating and cooling of the anode internal surface under various conditions (velocity of the moving spot of 20 m/s and various heat flux $q_0 = 10^8, 5 \cdot 10^8, 10^9$ W/m^2 (accordingly curves 1-3)).

As it is seen from the calculation results the following regimes are possible with respect to the heat flow value and the velocity of the moving arc spot:

1. Existence of a melted layer in a spot trace (curves 3 in Fig. 4);
2. Submelting and subsequent solidification of the material (curves 2 in Fig. 4);
3. Heating up to temperatures which are lower than the melting temperature (curves 1).

Also we can note that the large temperature gradient of dT/dR~10000K/mm in a narrow zone near-surface which can cause large thermostresses is a characteristic feature of temperatures distribution along the electrode radius.

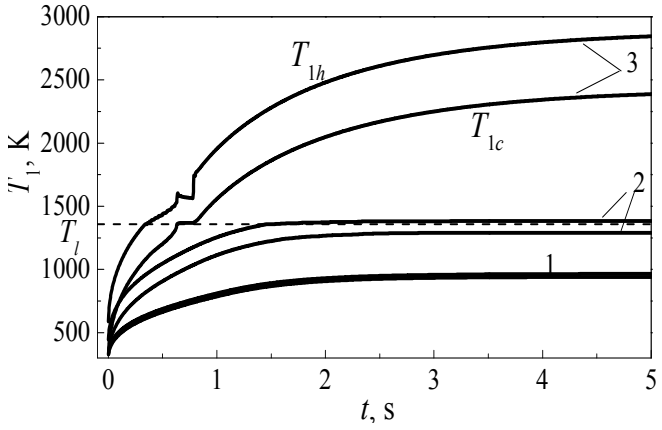

Fig. 4. Temperatures of maximum heating (T_{1h}) and interpulsing cooling (T_{1c}) of the electrode internal surface at arc spot velocity of 20 m/s; 1 - 3 - q0=0.1; 0.5; 1 kW/mm2

Thermal stresses in plasmatron electrode

Because of local character of heating, when the arc spot starts influencing the electrode surface intensive volumetric expansion of metal takes place in the zone of arc effect. The intensity and size of expansion are determined by heating velocity and temperature. The cold layers surrounding the area of heating hinder volume increasing. Therefore compressing stresses appear in the zone of temperature influence. Hence increasing metal heating temperature leads to growing the value of the stresses. The compressing stress growth takes place until the heated metal is not plastic, and temporarily arising stresses are not relieved partially or completely. The temporal thermostresses caused by pulsing source action were determined in [6].

However, yield stress of pure copper σ_y is very low at high temperature, and the elastic-plastic electrode state also has been studied with respect to the deformation theory of thermoplasticity. The problem was solved by the method of "elastic" decisions with the assumption of small deformations with the von Mises yield condition and with application of operators of additional stresses. To analyse the basic peculiarities of a stress field, the solutions of thermal problem $T(t)$ and $T(R)$ were used.

Quasi-static thermal-elastic problem is as following:

$$(\lambda' + \mu)\left(\frac{\partial^2 u}{\partial R^2} + \frac{1}{R}\frac{\partial u}{\partial R} - \frac{u}{R^2}\right) = \alpha(3\lambda' + 2\mu)\frac{\partial T}{\partial R}, \tag{7}$$

$$\sigma_{RR} = (\lambda' + \mu)\frac{\partial u}{\partial R} + \lambda'\frac{u}{R}(3\lambda' + 2\mu)\alpha T, \tag{8}$$

$$\sigma_{\varphi\varphi} = (\lambda' + \mu)\frac{u}{R} + \lambda'\frac{\partial u}{\partial R} - (3\lambda' + 2\mu)\alpha T, \tag{9}$$

$$\sigma_{zz} = \sigma_{\varphi\varphi} + \sigma_{RR}. \tag{10}$$

Initial conditions are $u(R, 0)$, $\frac{\partial u}{\partial R}(R, 0) = 0$.

Boundary conditions are

$$\sigma_{RR} = 0 \text{ for } R = R_1,\ R = R_2,\ \int_{R_1}^{R_2} \sigma_{zz}(R) R dR = 0\,, \tag{11}$$

where u is displacement; α is the coefficient of material thermal expansion; $\lambda' = \dfrac{\nu E}{(1+\nu)(1-2\nu)}$, $\mu = \dfrac{E}{2(1+\nu)}$; E is module of elasticity, ν is Poisson's ratio; $T = f(R, t)$ is temperature rise.

Plastic problem. Elasticity condition of material is

$$(\sigma_{\varphi\varphi} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{RR})^2 + (\sigma_{RR} - \sigma_{\varphi\varphi})^2 = {\sigma_i}^2 = 2\sigma_y^2\,, \tag{12}$$

where σ_i is stress intensity; σ_y - yield strength

The expression for calculation of valid elastic-plastic stresses is

$$\sigma_{jk} = 2G\left(\varepsilon_{jk} + \delta_{jk}\frac{\nu\theta}{1-2\nu} - \delta_{jk}\frac{1+\nu}{1-2\nu}\alpha t\right) - {\sigma_{jk}}^*,\ (\delta_{jk}) = \begin{cases} 1 \text{ at } j = k \\ 0 \text{ at } j \neq k \end{cases}, \tag{13}$$

where σ^*_{jk} is the operator of additional stresses.

Summaries

The character of stresses behaviour changes together with electrode heating. The calculations have shown that the impulse impact of the electrical arc spot results in a sign-alternating distribution of the thermal stresses just inside the cylinder. Radial stresses (σ_{RR}) are always compressing but rather small. The tangential ($\sigma_{\varphi\varphi}$), axial (σ_{zz}) stresses play the main role in the anode thermostressed condition. The results have demonstrated that in a copper electrode the tensile stresses $\sigma_{\varphi,\,z}$ can exceed the ultimate tensile σ_s somewhere in the middle of thickness, whereas compressing stresses σB are near the hot internal surface of the cylindrical electrode (Fig. 5).

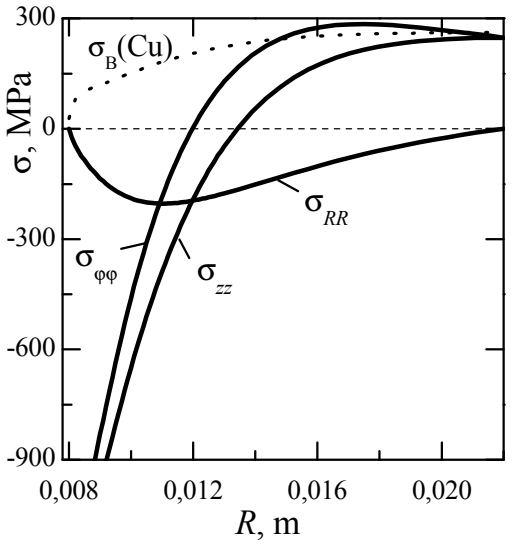

Fig. 5. Distribution of elastic thermostresses in the electrode (σ_B – is ultimate stress)

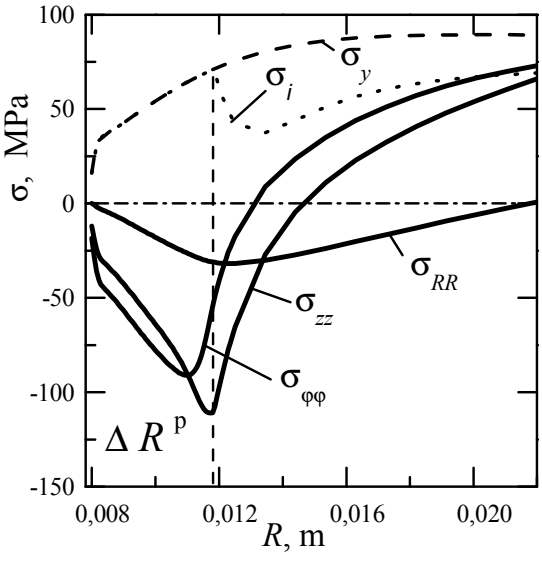

Fig. 6. Distribution of elastic-plastic thermo-stresses in the electrode.

The values of stresses can exceed the copper yield stress (σ_T), too. Thus plastic zone ΔR^p is formed. It can grow during further repeatedly-variable influence of the arc spot and cause irreversible changes in material structure (Fig. 6). But variable compressive stresses can result in surface hardening. On peripheral sections of the zone of spot thermal influence (Fig. 5), the tensile stresses, causing formation of microcracks, prevail. The appearance of set cracks can cause changes in $T(R)$ such as increasing temperature of the surface, evaporation of the surface, and mechanical effects of increase of erosion [7].

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