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THERMOPHYSICAL PROCESSES IN ELECTRIC CONTACTS UPON PASSAGE OF LET-THROUGH CURRENTS

Yu. M. Dolinskii

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The article presents a theoretical calculation of the thermophysical processes in the region of constriction of the streamlines of electric contacts. The problem is solved by a numerical method.

The passage of an electric current is accompanied by the heating of the region of constriction of the electric contacts. At sufficiently high temperatures attained on the contact surface, the contacts become welded together, and this welding may occur in the solid phase as well as in the case of melting of the material of the contacts. When the currents are of sufficient intensity, there may, in addition to welding, also occur deflection of the movable contact under the effect of electrodynamic forces and forces of thermal origin. Since the phenomena of welding and deflection of contacts largely determine the operational reliability of contact systems of electrical apparatuses, the study of these phenomena is a very topical task. The present article theoretically describes the processes of heating and welding of contacts, and it also determines the conditions under which their deflection occurs.

A real conducting contact surface consists of a number of contact spots which are randomly distributed over the apparent contact surface. The higher the degree of dispersion of the contact microareas is, the lower is the heating of the contact surface and the higher are the currents at which welding and deflection of the contacts occur. From this point of view, the most unfavorable is single-point contact which was made the basis of the present examination. Following [1], we assume that the streamline passes from one contact to the

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other through a circular contact spot with radius f. In consequence of axial symmetry the process of heat propagation for thermally symmetric contacts is described by the equation

$$C_V(\vartheta)\frac{\partial\vartheta}{\partial t}=\frac{\partial}{\partial r}\left[\lambda(\vartheta)\frac{\partial\vartheta}{\partial r}\right]+\frac{1}{r}\lambda(\vartheta)\frac{\partial\vartheta}{\partial r}+\frac{\partial}{\partial z}\left[\lambda(\vartheta)\frac{\partial\vartheta}{\partial z}\right]+\delta^2(r,\ z,\ t)\,\rho(\vartheta)\ \ (0<r,\ z<A_\text{т}(t)). \quad (1)$$

The current density distribution in the region of constriction of the electric contacts, according to [2], is determined by the expression

$$\delta^2(r,\ z,\ t)=\frac{i^2(t)}{16\pi^2f^2r^2}\left[\sqrt{\frac{z^2+(r+f)^2}{z^2+(r-f)^2}}+\sqrt{\frac{z^2+(r-f)^2}{z^2+(r+f)^2}}-2\right]. \quad (2)$$

Since we are interested in the temperature distribution on the contact surface, it is necessary, for the sake of reducing computer time, to limit the region of integration of Eq. (1) by the dimensions whose increase has practically no effect on the accuracy of calculating the temperature within the limits of the contact surface. From this point of view, it is expedient to introduce a variable region of integration whose boundaries move according to the regularity

$$A_\text{т}(t)=f(t)+2a_\text{т}\sqrt{t}. \quad (3)$$

Let us formulate the initial and boundary conditions of Eq. (1). Usually the passage of heavy let-through currents is preceded by normal operation of the contacts where, after lengthy passage of current through the contacts, the temperature of the contact surface differs but slightly from the temperature of the bulk of the contact, and we may, therefore, adopt as initial condition that

$$\vartheta(r,\ z,\ 0)=\vartheta_0. \quad (4)$$

In consequence of axial symmetry of the problem,

$$\frac{\partial\vartheta(0,\ z,\ t)}{\partial r}=0. \quad (5)$$

Preliminary theoretical evaluations and experience with computer calculations showed that when condition (3) is fulfilled, the temperature on the end surfaces has no noticeable effect on the heating of the contact surface; therefore, to simplify the problem, we adopt the following temperature values on the boundaries of the examined region:

$$\vartheta(A_\text{т}(t),\ z,\ t)=\vartheta_0, \quad (6)$$

$$\vartheta(r,\ A_\text{т}(t),\ t)=\vartheta_0. \quad (7)$$

According to [1], oxide films with tunneling conductivity may form on the contact surface. The electrons that penetrate through the film give up their excess kinetic energy to the anode, and part of this energy is transmitted to the cathode in consequence of the finite thermal conductivity of the film. In the general case there may be temperature asymmetry between the anode and the cathode, but when the contact surface is sufficiently large, which is a characteristic feature of high current contacts, then this temperature asymmetry is slight and may be disregarded [3]. An additional resistance of the oxide film is taken into account by introducing a surface source of heat that is uniformly distributed over the entire contact surface. Therefore, with $z=0$, we formulate the boundary condition in the form

$$-\lambda[\vartheta(r,\ 0,\ t)]\frac{\partial\vartheta(r,\ 0,\ t)}{\partial z}=\frac{\sigma(r,\ t)\,i^2(t)}{2\pi^2f^4(t)}\quad(0\leqslant r\leqslant f(t)), \quad (8)$$

$$\frac{\partial\vartheta(r,\ 0,\ t)}{\partial z}=0\quad(r>f(t)). \quad (9)$$

At high temperatures, plastic deformation of the contact surface predominates. Microscopic shift of the movable contact in the process of deformation is characterized by the combination of two opposing processes. On the one hand, the contact elements come closer to each other upon deformation; on the other hand, they are removed from each other in consequence of the expansion of the material of the contacts when it is heated. Special measurements with strain gauges showed that as a rule the second process predominates, i.e., the movable contact is somewhat removed from the fixed one, but because the resulting shift is small, inertia effects may be neglected. Therefore, we write the equation of plastic deformation without the inertial term in the form

$$2\pi \int_0^{f(t)} H[\vartheta(r,\ 0,\ t)]\, r dr = F_p. \tag{10}$$

The resulting force acting on the movable contact is:

$$F_p = F_к - \frac{\mu_0}{4\pi} i^2(t) \left(\ln \frac{R}{f(t)} \mp K \right) - F_п - F_т. \tag{11}$$

In expression (11) the external electrodynamic forces acting on the movable contact are taken into account by introducing the coefficient K which depends on the geometry of the conductors interacting with the currents. The minus sign corresponds to the case when external electrodynamic forces are an obstacle to the deflection of the contacts.

Equation (10) has to be complemented by the ratio

$$\frac{df(t)}{dt} \geqslant 0, \tag{12}$$

which indicates that the change of the contact surface in the process of plastic deformation is irreversible. The tunneling resistivity of the oxide film $\sigma(r,\ t)$ is determined on the basis of the following notions. With relatively cold contacts

$$\sigma(r,\ t) = \sigma_0. \tag{13}$$

As the contacts become hotter and the process of thermal diffusion of the atoms becomes more intense, diffusion resorption of the oxide films occurs. To simplify the problem we will assume that the tunneling resistance drops jumplike to zero when the relative concentration of the metal atoms on the interface of the contacts attains some value c_M or when the temperature at the examined point of the contact surface attains the melting point. Thus, for the contact surface $(r \leq f(t))$ we write the relationships:

$$\sigma(r,\ t) = \begin{cases} \sigma_0 \text{ for } & \vartheta(r,\ 0,\ t) \leqslant \vartheta_п \text{and} \, c(r,\ t) < c_м, \\ 0 \text{ for } & \vartheta_{\max}(r,\ 0,\ t) > \vartheta_п \text{ or } c(r,\ t) \geqslant c_м. \end{cases} \tag{14}$$

In accordance with the diffusion model of [4], the relative concentration of metal atoms on the interface of the contacts is determined by the expression

$$c(r,\ t) = 1 - \frac{2}{\pi} \int_0^\infty \frac{\sin y}{y} \exp\left(-\frac{y^2}{\Delta_п^2} \int_{t_r}^{t} D[\vartheta(r,\ 0,\ t)]\, dt \right) dy. \tag{15}$$

The instant $t_r = 0$ for $r \leq f_0$. When $f_0 < r < f(t)$, then t_r is determined from the equation $f(t_r) = r$.

Let us briefly dwell on the problem of calculating the forces F_π and F_T contained on the right-hand side of expression (11). If at the instant under examination the maximum temperature of the contact surface $\vartheta_m(r,\ 0,\ t) \leq \vartheta_\pi$, then $F_\pi = 0$. Otherwise there exists a zone of liquid metal on the contact surface, the zone being bounded by the melting isotherms with radii $r_{\pi 1}$ and $r_{\pi 2}$ $(r_{\pi 1} < r_{\pi 2})$. We determine the positions of the melting isotherms by solving the equation

$$\vartheta(r_{пi},\ 0,\ t) = \vartheta_п \quad (i = 1,\ 2). \tag{16}$$

Using Biot's formula for electromagnetic force density and integrating along the radius r of the contact surface within the limits of the molten zone, we obtain the expressions for the electromagnetic pressure in the melt and the values of the force due to the pinch effect:

$$P_{em}(r) = \frac{\mu_0 i^2(t)}{4\pi^2 f^2} \ln\left(\frac{f + \sqrt{f^2 - r^2}}{f + \sqrt{f^2 - r_{п2}^2}} \right), \tag{17}$$

$$F_п = \frac{\mu_0}{4\pi} i^2(t) \left[\sqrt{1 - \frac{r_{п1}^2}{f^2}} - \sqrt{1 - \frac{r_{п2}^2}{f^2}} - \frac{0.5}{f^2}(r_{п2}^2 - r_{п1}^2) - \frac{r_{п1}^2}{f^2} \ln\left(\frac{f + \sqrt{f^2 - r_{п1}^2}}{f + \sqrt{f^2 - r_{п2}^2}} \right) \right]. \tag{18}$$

The thermal force F_T can be determined on the basis of the following physical notions. With increasing temperature, conditions are created in the melt for the liquid metal to boil up. The process of boiling is characterized by the formation of bubbles with saturated vapor. In the case under consideration, which is characterized by greatly monuniform heating of the melt, the most probable place of bubble formation is the point with maximum temperature. A bubble forms on condition that the saturated vapor pressure exceeds the external pressure which in our case is composed of the sum of the electromagnetic and atmospheric pressures. The excess pressure of the saturated vapor is spread over the entire molten zone, and it creates an additional force tending to open the contacts.

What was explained above can be formulated mathematically in the form

$$F_{\text{т}} = 0 \quad \text{for} \quad P_{\text{н}}(\vartheta_{\text{м}}) \leqslant P_{\text{em}}(r_{\text{м}}) + P_{\text{at}}, \tag{19}$$

$$F_{\text{т}} = \pi (r_{\text{п}2}^2 - r_{\text{п}1}^2)[P_{\text{н}}(\vartheta_{\text{м}}) - P_{\text{em}}(r_{\text{м}}) - P_{\text{at}}] \tag{20}$$

for $P_H(\vartheta_m) > P_{em}(r_m) + P_{at}$, where

$$P_{\text{н}}(\vartheta_{\text{м}}) = \frac{P_{\text{н}0}}{\sqrt{\vartheta_{\text{м}} + 273}} \exp\left(-\frac{T_{\text{м}}}{\vartheta_{\text{м}} + 273}\right),$$

$$P_{\text{н}0} = 5{,}75\, \frac{(m v_0^{*2})^{3/2}}{\sqrt{k_{\text{B}}}}.$$

In calculating the temperature dependences of the thermophysical parameters of the material of the contacts we used the piecewise linear approximation of the temperature dependence of the electrical resistivity $\rho(\vartheta)$. Thermal conductivity was calculated by the Wiedemann–Franz–Lorenz law [1]

$$\lambda(\vartheta) = \frac{L(\vartheta + 273)}{\rho(\vartheta)}. \tag{21}$$

For multicomponent (powder metal) material the temperature dependence of the specific volumetric heat capacity was calculated by the formula

$$C_V(\vartheta) = \sum_{n=1}^{m} p_n C_{Vn}(\vartheta). \tag{22}$$

The specific heat capacities of separate components were calculated with a view to the additional heat capacity taking into account the latent heat of fusion of the components [5]:

$$C_{Vn}(\vartheta) = C_{V0n} + \beta_n \vartheta + \frac{(Q\gamma)_n}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(\vartheta - \vartheta_{\text{п}n})^2}{2\sigma^2}\right]. \tag{23}$$

For the numerical solution of Eq. (1) we use the finite difference scheme of variable directions [5]. According to this scheme, the transition from the j-th to the j+1st time layer is effected in two stages in steps of 0.5τ. At the first stage we use the scheme that is explicit with respect to z and implicit with respect to r. If we replace the differential operators by finite-difference analogs, we obtain a system of three-point equations for calculating the temperature on the half-layer

$$A_{ikj}\vartheta_{i-1,k,j+1/2} - D_{ikj}\vartheta_{ik,j+1/2} + B_{ikj}\vartheta_{i+1,k,j+1/2} = -F_{ikj}$$
$$(i = 2, 3, \ldots, N_j; \quad k = 2, 3, \ldots, N_j). \tag{24}$$

The coefficients in Eq. (24) are:

$$A_{ikj} = \frac{1}{h^2}\left[a_{ikj} - \frac{\lambda_{ikj}}{2(i-1)}\right], \quad D_{ikj} = \frac{2C_{ikj}}{\tau} + \frac{1}{h^2}(a_{ikj} + a_{i+1,kj}),$$

$$B_{ikj} = \frac{1}{h^2}\left[a_{i+1,kj} + \frac{\lambda_{ikj}}{2(i-1)}\right],$$

$$F_{ikj} = \frac{2C_{ikj}\vartheta_{ikj}}{\tau} + \frac{1}{h^2}[b_{i,k+1,j}(\vartheta_{i,k+1,j} - \vartheta_{ikj})$$
$$- b_{ikj}(\vartheta_{ikj} - \vartheta_{i,k-1,j})] + \delta_{ikj}^2 \rho_{ikj},$$

$$a_{ikj} = \lambda\left(\frac{\vartheta_{ikj} + \vartheta_{i-1,kj}}{2}\right), \quad b_{ikj} = \lambda\left(\frac{\vartheta_{ikj} + \vartheta_{i,k-1,j}}{2}\right),$$

$$\lambda_{ikj} = \lambda(\vartheta_{ikj}), \quad C_{ikj} = C_V(\vartheta_{ikj}), \quad \rho_{ikj} = \rho(\vartheta_{ikj}), \quad N_j = \left[\frac{A_{\text{т}j}}{h}\right].$$

We write the boundary conditions (5), (6) in finite-difference form:

$$\vartheta_{1k,j+1/2} = \vartheta_{2k,j+1/2}, \tag{25}$$

$$\vartheta_{N_j+1,k,j+1/2} = \vartheta_0 \quad (k = 2,\ 3,\ \ldots,\ N_j). \tag{26}$$

The system of equations (24) with the boundary conditions (25) and (26) is solved by the method of matching [5]. Here is a summary of the formulas for the calculation:

$$\alpha_{2k,j+1/2} = 1; \quad \beta_{2k,j+1/2} = 0, \tag{27}$$

$$\alpha_{i+1,k,j+1/2} = \frac{B_{ikj}}{D_{ikj} - \alpha_{ik,j+1/2}A_{ikj}}, \tag{28}$$

$$\beta_{i+1,k,j+1/2} = \frac{A_{ikj}\beta_{ik,j+1/2} + F_{ikj}}{D_{ikj} - \alpha_{ik,j+1/2}A_{ikj}} \tag{29}$$

$$(i = 2,\ 3,\ \ldots,\ N_j; \quad k = 1,\ 2,\ \ldots,\ N_j),$$

$$\vartheta_{ik,j+1/2} = \alpha_{i+1,k,j+1/2}\vartheta_{i+1,k,j+1/2} + \beta_{i+1,k,j+1/2} \tag{30}$$

$$(i = N_j,\ N_j - 1,\ \ldots,\ 1; \quad k = 1,\ 2,\ \ldots,\ N_j).$$

At the second stage we use a scheme that is explicit with respect to r and implicit with respect to z. For calculating the temperature at the j +1st layer we have the system of equations

$$A_{ik,j+1/2}\vartheta_{i,k-1,j+1} - D_{ik,j+1/2}\vartheta_{ik,j+1} + B_{ik,j+1/2}\vartheta_{i,k+1,j+1} = -F_{ik,j+1/2} (i = 1,\ 2,\ 3,\ \ldots,\ N_j;\ k = 2,\ 3,\ \ldots, N_j). \tag{31}$$

The coefficients in Eq. (31) are determined by the expressions:

$$A_{ik,j+1/2} = \frac{b_{ikj}}{h^2}, \quad D_{ik,j+1/2} = \frac{2C_{ikj}}{\tau} + \frac{b_{i,k+1,j} + b_{ikj}}{h^2},$$

$$B_{ik,j+1/2} = \frac{b_{i,k+1,j}}{h^2},$$

$$F_{ik,j+1/2} = 2\frac{C_{ikj}\vartheta_{ik,j+1/2}}{\tau} + \frac{1}{h^2}\left[a_{i+1,kj}\left(\vartheta_{i+1,k,j+1/2} - \vartheta_{ik,j+1/2}\right) - a_{ikj}\vartheta_{ik,j+1/2}\right] + \delta^2_{ikj}\rho_{ikj} + \Delta F_{ik,j+1/2},$$

$$\Delta F_{1k,j+1/2} = \frac{2a_{1kj}}{h^2}\vartheta_{1k,j+1/2}, \quad \Delta F_{ik,j+1/2} = \frac{a_{ikj}}{h^2}\vartheta_{i-1,k,j+1/2} +$$

$$+ \frac{\lambda_{ikj}}{2(i-1)h^2}\left(\vartheta_{i+1,k,j+1/2} - \vartheta_{i-1,k,j+1/2}\right) \quad (i = 2,\ 3,\ \ldots,\ N_j).$$

We write the boundary conditions (7)-(9) in finite-difference form:

$$\vartheta_{i,Nj+1,j+1} = \vartheta_0, \tag{32}$$

$$\vartheta_{i1,j+1} = \vartheta_{i2,j+1} + \frac{h\sigma_{i,j+1}i^2(t_{j+1})}{2\pi^2 f_j^4 \lambda_{i1j}}\varphi(r_i) \quad (i = 1,\ 2,\ \ldots,\ N_j), \tag{33}$$

where

$$\varphi(r_i) = \begin{cases} 1 & \text{for } r_i \leqslant f_j, \\ 0 & \text{for } r_i > f_j, \end{cases} \quad r_i = (i-1)h; \ t_{j+1} = t_j + \tau.$$

The system of three-point equations (31) with the boundary conditions (32), (33) is solved by the method of matching. The calculations are carried out in the following sequence:

$$\alpha_{i2,j+1} = 1; \ \beta_{i2,j+1} = \frac{h\sigma_{ij}i^2(t_{j+1})}{2\pi^2 f_j^4 \lambda_{i1j}}\varphi(r_i), \tag{34}$$

$$\alpha_{i,k+1,j+1} = \frac{B_{ik,j+1/2}}{D_{ik,j+1/2} - \alpha_{ik,j+1}A_{ik,j+1/2}}, \tag{35}$$

$$\beta_{i,k+1,j+1} = \frac{A_{ik,j+1/2}\beta_{ik,j+1} + F_{ik,j+1/2}}{D_{ik,j+1/2} - \alpha_{ik,j+1}A_{ik,j+1/2}} \tag{36}$$

$$(i = 1,\ 2,\ \ldots,\ N_j; \quad k = 2,\ 3,\ \ldots,\ N_j),$$

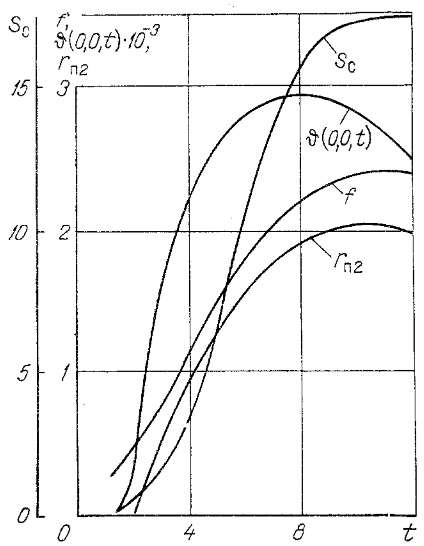

Fig. 1. Results of the theoretical calculation of the process of heating and welding contacts (f, mm; $r_{\Pi 2}$, mm; $\vartheta(0, 0, t)$, °C; S_c, mm^2; t, msec).

$$\vartheta_{ik,j+1} = \alpha_{i,k+1,j+1}\vartheta_{i,k+1,j+1} + \beta_{i,k+1,j+1} \tag{37}$$
$$(i = 1,\ 2,\ \ldots,\ N_j; \quad k = N_j,\ N_j - 1,\ \ldots,\ 1).$$

According to the calculated temperature field on the j + 1st time layer we determine the radius of the f_{j+1}-th contact microarea by numerically solving Eq. (10) taking into account relationships (11), (12), (16)-(20). Then we determine the value of $\sigma_{i,j+1}$ by numerically integrating Eq. (15).

The area on which the contacts are welded together is calculated approximately from the relationships:

$$S_c = \sum_i \Delta S_{ci}, \quad r_i \leqslant f_{j+1}, \tag{38}$$

$$\Delta S_{ci} = \begin{cases} \frac{\pi}{4} h^2 \eta_i & \text{for} \quad i = 1, \\ 2\pi r_i h \eta_i & \text{for} \quad i \neq 1. \end{cases} \tag{39}$$

The weight coefficients η_i are determined from the expressions:

$$\eta_i = \begin{cases} 1 & \text{for} \quad \sigma_{i,j+1} = 0, \\ 2c^2(r_i,\ t_{j+1}) & \text{for} \quad \sigma_{i,j+1} = \sigma_0. \end{cases} \tag{40}$$

In these last relationships it was accepted that diffusion resorption of the oxide film leads to welding at the corresponding points of the contact surface. For $c(r, t) < c_M$ it was accepted that the welded area is proportional to the number of singular metal bonds formed between the metal atoms that diffused to the interface of the contacts, and the number of such bonds is proportional to the square of the concentration of atoms. The described mathematical model makes it possible to describe the process of fusion welding as well as of welding in the solid phase.

We present the results of calculations of the process of heating and welding of powder metal silver—nickel contacts KMK-A30. The calculations were carried out on a computer for the following regularity of change of current:

$$i(t) = I_M[\sin(314.16t - 1) + 0.841\, e^{-200t}].$$

With $F_K = 200$ N, K = 0, $I_M = 6400$ A, the highest temperature attained on the contact surface, according to the calculations, is 762°C ($\vartheta_0 = 20$°C), and the size of the weld area is $S_c = 0.865\ mm^2$, which, with the welding strength of the contact material of 55 N/mm^2 [6], yields a welding force of 47.6 N. In an experiment with the same conditions, the force for separating the welded contacts was 40-50 N. With a current $I_M = 22{,}200$ A, deflection of the contacts was experimentally ascertained. According to the calculations, deflection of the contacts occurs at $I_M = 25{,}000$ A (the force F_p becomes negative). The results of the numerical calculation of the welding process of the contacts ($F_K = 125$ N, K = 3, $I_M = 43{,}200$ A) are presented in Fig. 1.

Thus, the suggested mathematical model describes with satisfactory accuracy of thermophysical processes in electric contacts upon passage of let-through currents.

NOTATION

ϑ, temperature; ϑ_0, initial temperature; $C_V(\vartheta)$, specific volumetric heat capacity; $\lambda(\vartheta)$, thermal conductivity; $\rho(\vartheta)$, electrical resistivity of the material of the contacts; $\delta(r, z, t)$, current density in the region of constriction; $f(t)$, radius of contact microarea; r, z, space coordinates; t, time; $a_T^2 = \lambda/C_V$, thermal diffusivity of the material of the contacts; $A_T(t)$, position of the boundary of the region of integration of Eq. (1) with respect to the variables r, z; $\sigma(r, t)$, tunneling resistivity of the oxide film on the contact surface; $H(\vartheta)$, hardness of the contact material; F_K, contact pressure; μ_0, magnetic permeability of air; i(t), current flowing through the contacts; R, radius of the broad side of the contact; K, coefficient taking into account the magnitude of the external electrodynamic forces; $\vartheta_{max}(r, 0, t)$, maximum temperature attained on the contact surface by the instant t; ϑ_M, maximum temperature on the contact surface at the instant t; r_M, radius of the isotherm with the maximum temperature; $P_H(\vartheta_M)$, saturated vapor pressure at the temperature ϑ_M; P_{at}, atmospheric pressure; m, atomic mass; ν_0^*, corrected frequency of normal atomic vibrations; k_B, Boltzmann constant; L, Lorenz constant; p_n, volume fraction of the n-th component; $(Q\gamma)_n$, latent heat of fusion of the n-th component; ϑ_n, melting point of the principal component, the matrix; $\vartheta_{\pi n}$, melting point of the n-th component; σ, parameter characterizing the degree of concentration of the additional heat capacity; i, k, number of the grid node by coordinates r and z; j, number of the time layer; h, step on the space coordinates; τ, step in time; Δ_π, thickness of the oxide film.

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