INVESTIGATING THE TEMPERATURES OF CONTACT ELEMENTS ON SEPARATION

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Solutions are presented for the heat-conduction equations of the liquid-bridge—solid system which is set up on separation of electrical contacts. The conditions are given for the selection of contact materials to ensure minimum erosion of one of the electrodes.

Electrical contacts find extensive application in various branches of engineering and much effort has been devoted to their study. Of particular interest are the problems associated with the melting of contact materials when circuits are opened.

We know that there exists a period during the last stage of the opening of contacts in which the density of the current passing through the contact surface attains values which causes the melting of the metal in one of the electrodes. A further shift in the contact elements does not result in the breaking of the circuit, since a neck of molten metal has been formed between the contact and it continues to pass current (see figure).

For the solution of a large number of important practical problems, we have to determine the distribution of temperature in the contact elements, all the way to the breaking of the electrical circuits.

The coordinate origin is set at the point of contact between two electrodes prior to separation, and the x-axis is made to coincide with the axis of electrode symmetry (see figure). We assume that the contact elements have been made from various materials.

The heat-conduction equation for the liquid bridge can be written in the form [1]

$$\frac{\partial \vartheta_1}{\partial t} = a_1^2 \frac{\partial^2 \vartheta_1}{\partial x^2} + h_1,$$

$$t > 0, \quad -\alpha_1 \sqrt{t} < x < 0, \tag{1}$$

where α_1 is the coefficient for the melting of the material in the first electrode; in a spherical system of coordinates we can write the heat-conduction equation for the solid electrode in the form [2]

$$\frac{\partial \vartheta_2}{\partial t} = a_2^2 \left(\frac{\partial^2 \vartheta_2}{\partial r^2} + \frac{2}{r} \frac{\partial \vartheta_2}{\partial r} + \frac{q_2}{r^4} \right),$$

$$t > 0, \quad b < r < \infty, \tag{2}$$

where

$$h_1 = \frac{\rho_1 I^2}{\gamma c F^2}; \quad q_2 = \frac{\rho_2 I^2}{4\pi^2 \lambda_2}.$$

Conditions for the unique definition of solutions (1) and (2) can be expressed by the following system of equations:

$$\vartheta_1(-\alpha_1 \sqrt{t}, t) = \vartheta_{1m}, \tag{3}$$

$$\vartheta_2(r, 0) = \psi(r), \tag{4}$$

$$\vartheta_1(0, t) = \vartheta_2(b, t), \tag{5}$$

$$\lambda_1 \frac{\partial \vartheta_1}{\partial x}\Big|_{x=0} = \lambda_2 \frac{\partial \vartheta_2}{\partial r}\Big|_{r=b}, \tag{6}$$

$$\vartheta_2(\infty, t) = 0, \tag{7}$$

where $\psi(r)$ is a known function derived on solution of the heat-conduction equations for solid contact elements prior to the instant at which the electrodes melt and is equal to [3]

$$\psi(r) = \frac{B}{r} - \frac{q_2}{2r^2} = \vartheta_{1m}; \tag{8}$$

B is a coefficient which is a function of the thermal conductivity of the solid electrodes, of the magnitude of the current, of the radius of the surface covered, etc.; the determination of this coefficient can be found in [3]; ϑ_m is the temperature of the solid contact element at the point of contact with the liquid phase of the first electrode.

The solution of the system of equations (1)–(7) is assumed in the following form:

$$\vartheta_1(x, t) = h_1 t + A_1\left(t + \frac{x^2}{2a_1^2}\right) + C_1 \int_0^t \frac{\sqrt{\tau} \exp\left[-\frac{x^2}{4a_1^2(t-\tau)}\right]}{(t-\tau)^{1/2}} d\tau + \vartheta_{1m} + N_1 x + P_1 \int_0^t \frac{\exp\left[-\frac{x^2}{4a_2^2(t-\tau)}\right]}{(t-\tau)^{1/2}} d\tau + 4M_1 t i^2 \operatorname{erfc} \frac{x}{2a_1\sqrt{t}}; \tag{9}$$

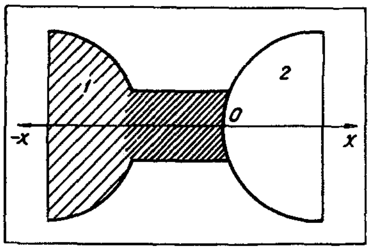
$$\vartheta_2(r, t) = \frac{B}{r} + \frac{K_2}{r} \int_0^t \frac{\exp\left[-\frac{(r-b)^2}{4a_1^2(t-\tau)}\right]}{(t-\tau)^{1/2}} d\tau - \frac{q_2}{2r^2}, \tag{10}$$

where

$$i^2 \operatorname{erfc} z = \frac{1}{4}\left\{\operatorname{erfc} z - 2z\left[\frac{1}{\sqrt{\pi}} \exp(-z^2) - z \operatorname{erfc} z\right]\right\};$$

$$z = \frac{x}{2a_1\sqrt{t}};$$

A_1, C_1, N_1, M_1, P_1, and K_2 are the coefficients whose determination has been carried out on the basis of conditions (3)–(7).



Schematic representation of liquid bridge consisting of one material.

From (3) and (9) we obtain

$$\vartheta_{1m} = h_1 t + A_1 t\left(1+\frac{\alpha_1^2}{2a_1^2}\right) + C_1\varkappa_1 t + \vartheta_{1m} + P_1\delta_1\sqrt{t} - N_1\alpha_1\sqrt{t} + M_1\gamma_1 t, \qquad (11)$$

where ϑ_m

$$\varkappa_1 = \frac{\pi}{2}\left(1+\frac{\alpha_1^2}{2a_1^2}\right)\operatorname{erfc}\frac{\alpha_1}{2a_1} - \sqrt{\pi}\,\frac{\alpha_1}{2a_1}\exp\left(-\frac{\alpha_1^2}{4a_1^2}\right);$$

$$\gamma_1 = \operatorname{erfc}\left(-\frac{\alpha_1}{2a_1}\right) + \frac{\alpha_1}{a_1}\left[\exp\left(-\frac{\alpha_1^2}{4a_1^2}\right)\frac{1}{\sqrt{\pi}} + \frac{\alpha_1}{2a_1}\operatorname{erfc}\left(-\frac{\alpha_1}{2a_1}\right)\right];$$

$$\delta_1 = 2\left[\exp\left(-\frac{\alpha_1^2}{4a_1^2}\right) - \frac{\alpha_1\sqrt{\pi}}{2a_1}\operatorname{erfc}\frac{\alpha_1}{2a_1}\right].$$

The unknown coefficients A_1, C_1, M_1, N_1, P_1, and K_2 can be found on the basis of the solution of the system of equations (3)–(8):

$$K_2 = \frac{\frac{\lambda_2}{b}\left(\frac{q_2}{b} - B\right)}{\left(\frac{\lambda_2}{a_2} + \frac{\lambda_1}{a_1}\right)\sqrt{\pi} + \frac{\lambda_1}{\alpha_1}\delta_1};$$

$$P_1 = \frac{K_2}{b};\quad N_1 = \frac{\delta_1}{\alpha_1 b}K_2;$$

$$A_1 = \left[\frac{h_1\lambda_1}{a_1}\left(\sqrt{\pi} - \frac{2\varkappa_1}{\sqrt{\pi}}\right) + \frac{\lambda_2}{b^2}(\gamma_1\pi - 2\varkappa_1)K_2 + \frac{h_1\lambda_1}{a_1}\sqrt{\pi}(1-\gamma_1)\right]\times \left[\frac{\lambda_1}{a_1}\left[\frac{2\varkappa_1}{\sqrt{\pi}} + \gamma_1\sqrt{\pi} - 2\sqrt{\pi}\left(1+\frac{\alpha_1^2}{2a_1^2}\right)\right]\right]^{-1}$$

$$C_1 = \frac{\frac{\alpha_1^2\lambda_1 h_1}{a_1^3\sqrt{\pi}} + \frac{2\lambda_2}{b^2}K_2\left(1+\frac{\alpha_1^2}{2a_1^2} - \gamma_1\right)}{\frac{\lambda_1}{a_1}\left[\frac{2\varkappa_1}{\sqrt{\pi}} + \gamma_1\sqrt{\pi} - 2\sqrt{\pi}\left(1+\frac{\alpha_1^2}{2a_1^2}\right)\right]};$$

$$M_1 = \frac{\frac{\alpha_1\lambda_1 h_1\sqrt{\pi}}{2a_1^3} + \frac{2\lambda_2}{b^2}K_2\left[\varkappa_1 - \frac{\pi}{2}\left(1+\frac{\alpha_1^2}{2a_1^2}\right)\right]}{\frac{\lambda_1}{a_1}\left[\frac{2\varkappa_1}{\sqrt{\pi}} + \gamma_1\sqrt{\pi} - 2\sqrt{\pi}\left(1+\frac{\alpha_1^2}{2a_1^2}\right)\right]}$$

Of significant interest is the temperature at the point of contact between the liquid bridge and the solid body of the second electrode: $\vartheta_2(b, t)$. The time variation of this temperature can be determined from (10), assuming that $r = b$:

$$\vartheta_2(b, t) = \frac{B}{b} - \frac{q_2}{2b^2} + \frac{K_2}{b}\int_0^t \frac{d\tau}{(t-\tau)^{1/2}} = \frac{B}{b} - \frac{q_2}{2b^2} + \frac{2K_2}{b}\sqrt{t}. \qquad (12)$$

The first two terms in Eq. (12) define the initial value of the temperature $\vartheta_2(b, 0)$, while the third term gives the variation in the temperature of the contact surface during the process of liquid-bridge formation at the first electrode.

If the temperature at the surface of the solid electrode $r = b$ does not reach the melting point during the time $t = t_c$ of the existence of the liquid bridge, the material of the second electrode will not melt and only one electrode will be subject to erosion. To satisfy this condition the materials of the contact elements must be chosen so as to satisfy the following condition:

$$\vartheta_2(b, t_c) < \vartheta_{2m}, \qquad (13)$$

where ϑ_{2m} is the melting point of the second electrode.

With consideration of (12)

$$\frac{B}{b} - \frac{q_2}{2b^2} + \frac{2K_2}{b}\sqrt{t_c} < \vartheta_{2m} \qquad (14)$$

Assuming that at the instant $t = 0$ for $r = b$, the temperature

$$\vartheta_2(b, 0) = \vartheta_1(0, 0) = \vartheta_{1m}, \qquad (15)$$

with consideration of (8) we obtain

$$\frac{B}{b} - \frac{q_2}{2b^2} = \vartheta_{1m}. \qquad (16)$$

From (13)–(16) we can write

$$\vartheta_{2m} - \vartheta_{1m} > \frac{2K_2}{b}\sqrt{t_c}. \qquad (17)$$

Proceeding from the fact that $\vartheta_{2m} > \vartheta_{1m}$, we have

$$K_2 > 0 \qquad (18)$$

or

$$\frac{\frac{\lambda_2}{b}\left(\frac{q_2}{b} - B\right)}{\left(\frac{\lambda_1}{a_1} + \frac{\lambda_2}{a_2}\right)\sqrt{\pi} + \frac{\lambda_1}{a_1}\delta_1} > 0,$$

where

$$B = \frac{q_1(2\lambda_1 + \lambda_2) + q_2\lambda_2}{2b(\lambda_1 + \lambda_2)}.$$

In the case under consideration, during the initial commutation cycles, we find that only the material of the anode melts, which is possible when

$$\rho_1 < \rho_2$$

or

$$q_2 - q_1 > 0.$$

Consequently, to satisfy inequality (18) we must have

$$\lambda_2 \leqslant \lambda_1.$$

Thus, to satisfy condition (13) the contact materials should be selected on the basis of the following inequalities:

$$\vartheta_{1m} < \vartheta_{2m}, \ \rho_1 < \rho_2, \ \text{and} \ \lambda_1 \geqslant \lambda_2.$$

The following combination can serve as an example:

Ag (anode)	W (cathode)
$\vartheta_{1m} = 960°$ C	$\vartheta_{2m} = 3400°$ C
$\rho_1 = 1.65 \cdot 10^{-6}$ ohm · cm	$\rho_2 = 5.5 \cdot 10^{-6}$ ohm · cm
$\lambda_1 = 4.18$ W/cm · deg	$\lambda_2 = 2{,}2$ W/cm · deg

The relationships derived here can be used in selecting the contact materials for low-load dc relays.

NOTATION

I is the current; ϑ is the superheat temperature; ρ is the specific resistance; λ is the thermal conductivity; γ and c are the specific weight and heat capacity, respectively; F is the cross-section of the liquid bridge. Symbols: 1 liquid phase; 2 is the solid phase.

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