DETERMINATION OF THE EXCESS TEMPERATURE OF ELECTRICAL CONTACTS WITH CONTINUOUS CURRENT VARIATION

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An analytical solution is given of the heat conduction problem for a single-point contact in the closed position, under conditions of continuous variation of the current passing through it.

The thermal processes on the surfaces of electrodes determine to a considerable extent the reliable operation of electrical contacts. Such processes as weldability of contacts, breakdown of electrode surfaces due to electrical erosion, and spurious commutation are, among others, direct consequences of the action of electric current on the contacts. Therefore the study of thermal processes on the surface of contact electrodes is of considerable interest.

We shall assume that the contact elements are made of a single material, that the electrical contact is realized in one circular area of radius r_0, and that thermoelectric effects are absent. The contact elements are assumed to be symmetrical.

The resistance of the contact elements in a single, relatively small, contact area leads to a constriction of the current lines into places with good conduction. The region in which the current lines become nonparallel (Fig. 1) is called the neck region. A picture of the thermal and electric fields in the neck region is presented in Fig. 2. The circular contact area of radius r_0 is shown in the form of an infinitely thin disk, through which the current flows to a semi-infinite electrode. The equipotential and isothermal surfaces of the contact electrodes are semiellipsoids (lines 1), and the lines of current and heat flux (lines 2) run perpendicular to these semiellipsoids.

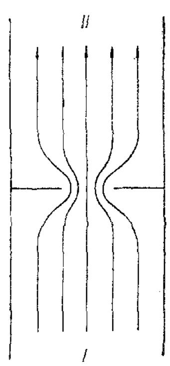

Fig. 1. Schematic representation of the constriction of current lines into a single circular conductor contact area.

The constriction of the current lines is due to the additional pinch resistance R_k; given constant resistivity of the contact material ρ, for one contact element we have

$$R_k = \rho/4r_0. \tag{1}$$

For the whole neck region at both contact elements

$$R_k = \rho/2r_0. \tag{2}$$

The mathematical calculation of the temperature field according to the exact model shown in Fig. 2, is very complicated and laborious. To simplify the mathematical problem, Holm [1] proposed a different model of the field in the region of the neck (Fig. 3). The straight radial lines denote lines of current and heat flux, and the circles are equipotential and isothermal surfaces. The contact surface is replaced by a sphere k of infinite conductivity and radius b.

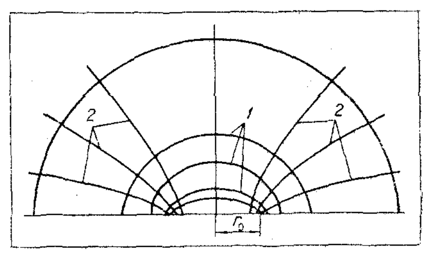

Fig. 2. Picture of the thermal and electric fields in the neck region.

The total pinch resistance R_k of the two contact electrodes in the simplified scheme (Fig. 3) is determined to be

$$R_k = \rho/\pi b. \tag{3}$$

It should be noted that the substitution was carried out by Holm on the condition that the same amount of liberated heat produces the same average temperature increase in the real and equivalent contacts. This condition is fulfilled if the value of the pinch resistance obtained from (2) and (3) is the same, i.e., the following basic condition for replacement of the one model by the other is fulfilled:

$$2r_0 = \pi b.$$

Heating of the electric contacts occurs due to liberation of energy in the active resistance of the contact and in the pinch resistance. The first part of the energy provides continuous heating of the whole volume of the contact material up to temperature $\Theta(x, y, z, t)$. This temperature is calculated according to known methods [3]. The second part of the energy provides additional heating of finite regions of the contact to the temperature T(x, y, z, t).

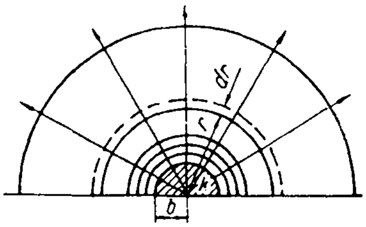

Fig. 3. Simplified model of constriction of the current lines.

The difference of these temperatures

$$T(x, y, z, t) - \Theta(x, y, z, t) = \vartheta(x, y, z, t)$$

is called the temperature excess of the contact.

The problem of determining the temperature excess ϑ (x, y, z, t) is met very often in practice: in calculating contact pressures, in determining welding of contact elements, in investigating resistance to erosion, in determining reliability of contacts, etc.

Let there be a continuous variation of current I, starting at time t = 0, according to the law

$$I = At,$$

where A is the rate of change of current (*a*/sec).

A current variation of this kind occurs in the commutation of high-speed dc apparatus in aeronautical equipment, in the chemical and metallurgical industries, in railroad substations, in subway, tramway and trolley yards, etc. In actual power systems the rate of change of current falls in the range $1-2 \cdot 10^6$ *a*/sec.

We obtain the differential equations of heat conduction on the basis of a heat balance set up for a hemispherical shell with radii r and r + dr (Fig. 3):

$$\frac{\partial \vartheta}{\partial t} = a^2 \left[\frac{\partial^2 \vartheta}{\partial r^2} + \frac{2}{r}\frac{\partial \vartheta}{\partial r} + \frac{\rho A^2 t^2}{4\pi^2 \lambda r^4} \right]. \quad (4)$$

We choose the conditions for a unique solution of (4) as follows:

$$\vartheta(r, 0) = 0; \quad \left.\frac{\partial \vartheta}{\partial r}\right|_{r=b} = 0; \quad \vartheta(\infty, t) = 0.$$

To solve (4), we introduce the new variable

$$u = \vartheta r$$

and, in addition, putting

$$r = b(1 + x),$$

we obtain from (4)

$$\frac{\partial u}{\partial t} = \mu^2 \frac{\partial^2 u}{\partial x^2} + W(x)\mu^2 t^2,$$

where

$$\mu = a/b, \quad W(x) = \rho A^2 / 4\pi^2 \lambda b (1 + x)^3.$$

The conditions for the solution of (5) to be unique will have the form

$$u(x, 0) = 0; \quad \left.\left(\frac{\partial u}{\partial x} - u\right)\right|_{x=0} = 0; \quad u(\infty, t) = 0.$$

We solve (5) with the aid of an operational method [2]. For the most heated part of the contact, i.e., for x = 0, the solution in respect of $\vartheta(0, t)$ has the following form:

$$\vartheta(0, t) = \frac{u(0, t)}{b} = \frac{\rho A^2 \mu}{2\pi^2 \lambda b^2 (-\mu)^5} \psi(z), \quad (6)$$

where

$$z = \mu^2 t,$$

$$\psi(z) = \int_0^\infty \left[\exp(\varepsilon + z) \operatorname{erfc}\left(\frac{\varepsilon}{2\sqrt{z}} + \sqrt{z}\right) - \sum_{m=0}^{4} (-2\sqrt{z})^m i^m \operatorname{erfc} \frac{\varepsilon}{2\sqrt{z}} \right] \frac{d\varepsilon}{(1 + \varepsilon)^3}.$$

If we make the substitution in (6)

$$b = 2r_0/\pi, \quad \mu = \pi a / 2r_0,$$

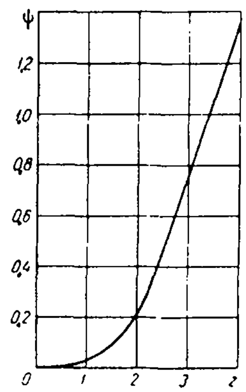

Fig. 4. Graph of the function $\psi(z)$.

then

$$\vartheta(0, t) = \frac{2\rho A^2 r_0^2}{a^4 \lambda \pi^4} \psi(z). \quad (7)$$

The function

$$\psi(z) = \vartheta(0, t) a^4 \lambda \pi^2 / 2\rho A^2 r_0^2$$

may be constructed (Fig. 4) once and for all for various values of z, and so the process of determining temperature $\vartheta(0, t)$ is considerably simplified.

We shall determine the temperature excess of the contact area of a high-speed dc switch with current varying at the rate $A = 10^6$ *a*/sec for a time interval $t = 3 \cdot 10^{-3}$ sec. The material of the contacts is copper. For the calculation we choose the following data: $a^2 = 1$ cm²/sec; $r_0 = 5.3 \cdot 10^{-2}$ cm; $\lambda = 3.8$ W/cm · · degree; $\rho = 1.75 \cdot 10^{-6}$ ohm · cm.

We determine the value of z:

$$z = \mu^2 t = a^2 t/b^2 = a^2 \pi^2 t/(2r_0)^2,$$

$$z = 1^2 \cdot \pi^2 \cdot 3 \cdot 10^{-3}/2^2 (5.3)^2 \cdot 10^{-4} = 2.6.$$

From the curve of Fig. 4 we find

$$\psi(2.6) = 0.53.$$

We determine the temperature of the contact area from (7):

$$\vartheta(0, t) = \frac{2\rho A^2 r_0^2}{a^4 \lambda \pi^4} \psi(z);$$

$$\vartheta(0, t) = \frac{2 \cdot 1.75 \cdot 10^{-6} \cdot 10^{12} \cdot (5.3)^2 \cdot 10^{-4}}{1^4 \cdot 3.8 \cdot 10^2} 0.53 = 13.7^\circ \mathrm{C}.$$

NOTATION

r_0—radius of contact area; R_k—pinch resistance; ρ—resistivity; b—radius of sphere; Θ(x, y, z, t)—bulk temperature of contact; T(x, y, z, t)—temperature of neck region of contact; ϑ(x, y, z, t)—temperature excess; t—time; I—current; A—rate of change of current; a^2—thermal diffusivity; λ—thermal conductivity.

REFERENCES

1. R. Holm, Electrical Contacts [Russian translation], IL, 1961.
2. A. V. Lykov, Theory of Heat Conduction [in Russian], 1952.
3. R. L. Aronov, Methods of Calculating Thermal Processes in Active Electrical Engineering Materials [in Russian], GEI, 1938.

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