BRIDGE TRANSFER ON ELECTRODES WITH FIBER STRUCTURE OF HEAT-PROOF COMPONENT

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The temperature field is investigated of a liquid bridge in a tungsten fiber immersed in copper. The feasibility is shown analytically, as well as experimentally, of minimizing bridge transfer by modifying the fiber dimensions.

It is known that the magnitude and direction of a bridge transfer depend on the thermophysical and electrical characteristics of the contact material [1], and also on the external conditions (medium, heat-dissipation intensity, etc.) [2, 3]. By proper selection of various contact materials [1, 2, 4] and by artificial heat dissipation from one of the electrodes [2, 3], one is able to minimize the transfer of the material from one electrode to another and even to achieve an inversion of erosion.

Considerable attention has recently been focused in the literature on the suitability of using in contact materials with a fibrous structure of the heat-proof component with normal distribution of the fiber towards the working surface of the contact [5-7]. It will be shown later that the application of the latter enables one to tackle the problem of self-restriction of the bridge erosion using a fundamentally different approach.

A simple fiber electrode is considered; in particular, a tungsten fiber immersed in a copper base. In this case the bridge erosion is a two-front problem (solid phase–melt of both components) with conditions of the fourth kind valid on the fiber surface [8].

To obtain one-dimensional estimates the cylindrical fiber is replaced by a ball of the same radius r_b. Then the contact surface copper–tungsten remains unchanged in the zone of intensive heating. The gap in the intensity of heat dissipation from the hemisphere surface and from the lateral cylinder surface is compensated to some extent by an additional heat dissipation from the base of the cylinder into the depth of the electrode. If one now adopts the contact resistance as constant and concentrated at the fiber center and ignores the density change of the matter when melting and also the dependence of thermophysical constants on the temperatures and on the phase state (Fig. 1a), one obtains for the temperature in the zones (in the quasistationary approximation) the following expressions [8]:

$$T_{1l} \sim \frac{q}{4\pi\lambda_1}\left(\frac{1}{r}-\frac{1}{a_1}\right), \tag{1}$$

$$T_{1s} = \frac{a_1 T_{me1}}{r_b - a_1}\left(\frac{r_b}{r}-1\right) + \frac{r_b T_b}{r_b - a_1}\left(1-\frac{a_1}{r}\right), \tag{2}$$

$$T_{2l} = \frac{r_b T_b}{a_2 - r_b}\left(\frac{a_2}{r}-1\right) + \frac{a_2 T_{me2}}{a_2 - r_b}\left(1-\frac{r_b}{r}\right), \tag{3}$$

$$T_{2s} = \frac{a_2 (T_{me2} - T_0)}{r} + T_0. \tag{4}$$

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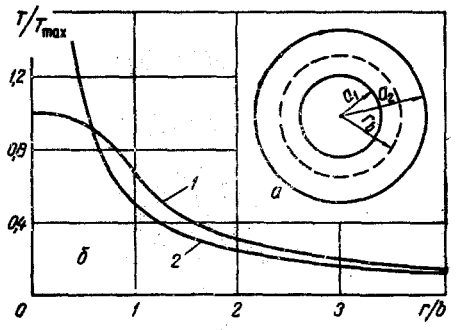

Fig. 1. a) Tungsten–copper interface versus fiber surface in the spherically symmetric case; b) stationary temperature field from a two-dimensional source (curve 1) and from a point source (curve 2) of equal strength.

On the boundary of the phase interface one has the relation [9]

$$\lambda_s \frac{\partial T_s}{\partial r} - \lambda_l \frac{\partial T_l}{\partial r} = \rho L \frac{da}{dt} . \tag{5}$$

Substituting (1)–(4) into (5), the energy balance is obtained on the phase boundaries and the fiber surface:

$$\frac{q}{4\pi a_1^2} - \lambda_1 \frac{T_{me1} - T_b}{r_b - a_1} \frac{r_b}{a_1} = \rho_1 L_1 \frac{da_1}{dt} , \tag{6}$$

$$\lambda_1 \frac{T_{me1} - T_b}{r_b - a_1} \frac{a_1}{r_b} = \lambda_2 \frac{T_b - T_{me2}}{a_2 - r_b} \frac{a_2}{r_b} , \tag{7}$$

$$\lambda_2 \frac{T_b - T_{me2}}{a_2 - r_b} \frac{r_b}{a_2} - \lambda_2 \frac{T_{me2} - T_0}{a_2} = \rho_2 L_2 \frac{da_2}{dt} . \tag{8}$$

It is not difficult to show [10] that specific times of heat conduction and of melting for tungsten and copper are of the order 10^{-7}–10^{-8} sec. Consequently, instability of thermal conductivity and phase transition are only essential in the initial part of bridge forming and can be ignored at the instant of bridge breaking down ($\tau_M \sim 10^{-3}$–10^{-2} sec). Then in agreement with (6)–(8) the melt radius a_1 for the tungsten can be expressed in the terms of the fiber radius r_b in the following manner:

$$a_1 = \bar{a}_1 \left[1 + \frac{T_{me2} - T_0}{T_{me1} - T_0} \left(\frac{\lambda_2}{\lambda_1} - 1 \right) \frac{a_2}{r_b} \right]^{-1} . \tag{9}$$

By analogy with the corresponding relations for homogenous materials the expression for the melting isotherm a_1 and, by the way, for any other isotherm can be written asfollows:

$$a_1 = \frac{q}{4\pi \lambda_{eff} (T_{me1} - T_0)} , \tag{10}$$

where the effective value of the coefficient of thermal conductivity is given by

$$\lambda_{eff} = \lambda_1 \left[1 + \frac{T_{me2} - T_0}{T_{me1} - T_0} \left(\frac{\lambda_2}{\lambda_1} - 1 \right) \frac{a_2}{r_b} \right] . \tag{11}$$

It should be mentioned that the bridge center can be located with equal probability at any point of the fiber surface, different points contributing in a different way to the total heat flux. The latter can be taken into account by replacing r_b in the formula (12) by its average,

$$\bar{r}_b = \frac{1}{3} r_b \left[1 + 2 \left(\frac{a_1}{r_b} \right)^2 \right] . \tag{12}$$

Thus by employing the model of a point source, the approximate formula (11) has been obtained for the effective thermal conductivity λ_{eff} of the component material as a function of the fiber radius r_b and of the coefficients of thermal conductivity of the components λ_1 and λ_2. For $r_b \to \infty$, one has $\lambda = \lambda_1$, and for $r_b = a_1$ one has $\lambda = \lambda_2$, that is, in the interval $a_1 \leq r_b < \infty$ the function λ is bounded ($\lambda_1 \leq \lambda_{eff} \leq \lambda_2$), if reasonable values at both ends are assumed.

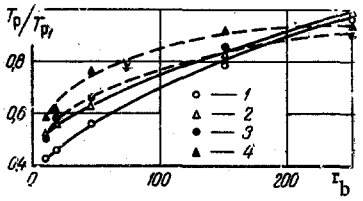

Fig. 2

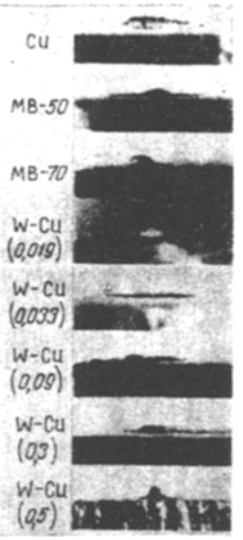

Fig. 3

Fig. 2. Experimental (curves 1 and 2) and theoretical (curves 3 and 4) values of reduced temperatures of bridge breakdown on fiber electrodes W–Cu versus fiber radius r_b for J_p = 40 A (curves 1 and 3) or J_p = 20 NA (curves 2 and 4), r_b, μm.

Fig. 3. Manifestation of erosion on negative electrodes of copper and metal ceramics MB-50 and MB-70 and on fiber electrodes W–Cu for J_p = 40A after $2 \cdot 10^4$ disconnections (in brackets the diameters of tungsten fibers are shown in mm).

We now proceed to determine the temperature of bridge breakdown as a function of the fiber radius; it should be mentioned that for $r_b > a_1$ the heat dissipation from the melt (λ_{eff}) takes mainly place at the expense of the region $r > r_b$ which can be verified on a model of a point sources, whereas the breakdown is determined by the hottest region ($r < r_b$), the fact that the source is a distributed one being essential. The coefficient of thermal conductivity of the component material λ_{eff} is therefore adopted as in (11), and the temperature distribution in the fiber is considered with finite dimensions of the source taken into account.

It is known [8] that if heat is supplied to a semiinfinite body through a circle of radius b (with a uniform heat flow distribution over the circle surface area) temperature distribution in the body is established and is of the form

$$T = \frac{q}{2\pi\lambda_{eff} b} \int_0^\infty \exp\{-vz\} I_0(vr) I_1(vb) \frac{dv}{v}. \tag{13}$$

Hence the temperature distribution over the contact surface or over the electrode depth or the maximal temperature are given, respectively, by the following:

$$T(r, z=0) = \frac{q}{2\pi\lambda_{eff} b} F\left(\frac{1}{2}, -\frac{1}{2}, 1, \frac{r^2}{b^2}\right), \tag{14}$$

$$T(r=0, z) = \frac{q}{2\pi\lambda_{eff} b^2} [(z^2 + b^2)^{1/2} - z], \tag{15}$$

$$T_{max} = T(r=0, z=0) = \frac{q}{2\pi\lambda_{eff} b}. \tag{16}$$

The stationary temperature field of a two-dimensional source evaluated by using the formula (16) is shown by curve 1 in Fig. 1b. It is seen clearly that inside the bridge ($r/b < 1$) the temperature field of a two-dimensional source is quite different from that of a point source (curve 2 in Fig. 1b), and varies from the value T_{max} at the center up to $T \approx 0.637$ at $r = b$. Outside the melting zone the temperature fields of the two-dimensional source and the point source approach each other asymptotically with r increasing.

It is known [1-4, 11] that the breakdown of the bridge occurs when in the highest heating zone the breakdown temperature T_B is reached. One can estimate the value of T_B and its dependence on the fiber radius r_b by setting $T_B = T_{max}$ in the formula (15). In the case of solid tungsten electrodes ($r_b \to \infty$) one has

$$T_{max} = T_{B_1} = \frac{q}{2\pi\lambda_1 b} . \tag{17}$$

Consequently,

$$\frac{T_B(r_b)}{T_{B_1}} = \frac{1}{1 + \frac{T_{me2} - T_0}{T_{me1} - T_0}\left(\frac{\lambda_2}{\lambda_1} - 1\right)\frac{a_2}{r_b}} . \tag{18}$$

Using Eqs. (14) and (15) it is not difficult to determine the radius and the depth (r_{me} and z_{me}) of the melt bath within the tungsten fiber as dependent on r_b; this is done by setting the right-hand sides of these equations equal to the melting temperature of tungsten, T_{me}.

If one regards the melting zone as half of an ellipsoid of rotation, it is easy to determine the reduced volume of the liquid phase by using the formula

$$V' = \frac{r_{me}^2 z_{me}}{b^3} . \tag{19}$$

To verify experimentally the quantities determined by Eqs. (18) and (19) experiments were conducted on the bridge transfer on electrodes of a fiber structure of the W–Cu type in the medium of an inert gas (He). The radii of the reinforcing fibers of tungsten were 9.5; 16.5; 45; 150 and 20 μm with about $\sim 70\%$ tungsten content in the specimens. The switching current was implemented by an installation described in [7]. The magnitude of the contact erosion was determined gravimetrically with an error of $\sim 10^{-4}$ g. During the disconnection process carried out with the aid of the CI-54 oscillogram, the voltage on the contacts was kept constant. Using the same oscillograms the breakdown voltage U_B and the duration τ^*_M of the bridge were determined.

It is known [11] that the breakdown temperature T^*_B of the bridge is related to the breakdown voltage U_B by the following relation:

$$T_B^* = AU_B, \quad A \approx 3200\ ^\circ\mathrm{K}/b.$$

For solid tungsten electrodes one has $T^*_{B_1} = AU_{B_1}$ and, consequently,

$$\frac{T_B^*}{T_{B_1}^*} = \frac{U_B}{U_{B_1}} . \tag{20}$$

In Fig. 2 the theoretical (T_B/T_{B_1}) values and the experimental ($T^*_B/T^*_{B_1}$) values are shown of the dependence of the reduced temperatures of the bridge breakdown on the fiber radius r_b for switching currents of 20 and 40 A. It can be seen that the discrepancy between the experimental and the evaluated data is insignificant and remains basically within the limits of 15-20%. This shows that the model used above is suitable for estimating the quantity λ_{eff} and the temperature field in the tungsten fiber.

It became evident that during the contact process a transfer of material takes place from the anode to the cathode (Fig. 3). If one knows the quantity of erosion for the anode Δm^*_k and for the cathode $-\Delta m^*_k$ (the sign $-$ indicates that the electrode weight has increased), it is easy to evaluate the volume V^*_{tr} of the transferred material in one full on–off cycle:

$$V_{tr}^* = \frac{\Delta m_a^* + \Delta m_k^*}{2\rho} . \tag{21}$$

The volume of the evaporated material V^*_{ev} during one cycle can be represented in the form

TABLE 1. Characteristic Parameters of Bridge Transfer versus Fiber Size

I_B, A	$x = \frac{r_b}{a_2}$	a_2, $\cdot 10^4$ cm	a_1, $\cdot 10^4$ cm	r_b, $\cdot 10^4$ cm	r_{me}/b	z_{me}/b	V'	V, cm^3	V^*_{tr}, cm^3	V^*_{ev}, cm^3	$\bar{\tau}^*_M \times 10^3$ sec
40								copper transfer			
	9,5	18,47	14,19	9,5	0	0	0		$6,8 \cdot 10^{-9}$	$1,06 \cdot 10^{-9}$	1,8
	16,5	18,47	14,19	13,6	0,4	0,04	0,015	$3,28 \cdot 10^{-10}$	$1,35 \cdot 10^{-10}$	$3,9 \cdot 10^{-10}$	0,04
	45	18,47	14,19	18,0	0,73	0,18	0,10	$2,24 \cdot 10^{-9}$	$6,75 \cdot 10^{-9}$	$1,55 \cdot 10^{-9}$	7,7
	150	18,47	14,19	50,0	1,01	0,67	0,68	$1,52 \cdot 10^{-8}$	$3,1 \cdot 10^{-9}$	$1,04 \cdot 10^{-9}$	4,2
	250	18,47	14,19	83,0	1,03	0,78	0,83	$1,86 \cdot 10^{-8}$	$2,95 \cdot 10^{-9}$	$0,66 \cdot 10^{-9}$	3,3
	∞	18,47	14,19	∞	1,06	1,06	1,13	$2,52 \cdot 10^{-8}$	$2,85 \cdot 10^{-9}$	$0,26 \cdot 10^{-9}$	2,4
20	9,5	9,40	7,36	7,04	0,52	0,07	0,02	$5,4 \cdot 10^{-11}$	$8,3 \cdot 10^{-11}$	$8,3 \cdot 10^{-11}$	0,14
	16,5	9,40	7,36	7,70	0,62	0,11	0,04	$1,08 \cdot 10^{-10}$	$7,8 \cdot 10^{-10}$	$2,6 \cdot 10^{-10}$	2,9
	45	9,40	7,36	15,80	0,97	0,45	0,42	$1,14 \cdot 10^{-9}$	$7,4 \cdot 10^{-10}$	$1,7 \cdot 10^{-10}$	3,1
	150	9,40	7,36	50,0	1,04	0,90	0,97	$2,62 \cdot 10^{-9}$	$7,2 \cdot 10^{-10}$	$0,73 \cdot 10^{-10}$	2,7
	250	9,40	7,36	83,0	1,05	0,96	1,01	$2,72 \cdot 10^{-9}$	$4,7 \cdot 10^{-10}$	$0,78 \cdot 10^{-10}$	2,2
	∞	9,40	7,36	∞	1,08	1,11	1,20	$3,34 \cdot 10^{-9}$	$5,9 \cdot 10^{-10}$	$0,62 \cdot 10^{-10}$	1,8

$$V^*_{ev} = \frac{\Delta m^*_a - \Delta m^*_k}{2\rho} \tag{22}$$

under the assumption that the evaporation rate is independent of the electrode polarity.

In Table 1 the values are shown of the quantities appearing in the relations (10)-(22) for switching currents of 20 and 40 A. Comparing the values of V, V^*_{tr}, V^*_{ev} and $\bar{\tau}^*_M$ for various contacts it is easily found that they are interrelated and one observes their effect on the magnitude of the erosion. Thus, for J_p = 40A in the case of electrodes with r_b = 9.5 μm the material is transferred mainly at the cost of the melted component, since $V' \sim 0$ and $a_1 < r_b$. For electrodes with r_b = 16 μm the bridge is made inside the fiber, the melted volume V, however, and $\bar{\tau}^*_M$ are relatively small, since $T_B \leq T_{me_1}$. Therefore, there is very little erosion of such electrodes in the described state (Fig. 3).

For longer radii r_b of the fiber the volume of the melt bath also increases, and one now has $T_B > T_{me_1}$. In this case the magnitude of the bridge erosion has proved to be dependent to a considerable extent on $\bar{\tau}^*_M$, which thus determines the amount of the transported volume V^*_{tr}.

One can also apply similar considerations for J_p = 20A.

Thus, at the instant of the electric circuit breaking down, the temperature in the region of the maximum heating of contacts with fibrous structure of the heat-proof component is, in the final analysis, determined by the degree of dispersion (the value of r_b) and the bridge transfer can be minimized ($T_B \sim T_{me_1}$) by modifying the sizes of the fibers for given values of the switching currents.

NOTATION

T, temperature, °K; q, rate of heat releases, cal/sec; λ, coefficient of thermal conductivity, cal/cm · sec · deg; T_{me} melting temperature, °K; T_f, temperature at the fiber boundary, °K; T_B, temperature of bridge breakdown, °K; T_{bo} boiling temperature °K; T_0, initial temperature °K; a, radius of the melt cm; r, radius vector of current point in the region under investigation; index 1 refers to tungsten, 2 to copper; indices l and s refer to liquid and solid phases, respectively; t, current time; L, latent heat of melting, cal/g; $\bar{a}_1 = 9/4\pi\lambda_1(T_{me1} - T_0)$ and $\bar{a}_2 = 9/4\pi\lambda_2(T_{me2} - T_0)$, radii of melt in homogenous samples of W and Cu, respectively; I_0, I_1, Bessel functions of the zeroth and the first order, respectively; $F(\alpha,\beta,\gamma, r^2/b^2)$, hypergeometric function; b, radius of contact; V', reduced volume of melt; V, volume of melt, cm^3; U_B, voltage of bridge breakdown, v; U_{me}, voltage of bridge melt, v; T*, temperature evaluated from experiments, °K; τ^*_{M*}, mean lifetime of bridge evaluated experimentally, sec; ρ, density of eroded electrode material, g/cm^3; Δm_a, and Δm^*_k, erosion of anode and cathode per one cutoff, g; V^*_{ev}, volume of evaporated material from each electrode per one cutoff, cm^3; J_p, switching current, A.

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HEAT EXCHANGE IN THERMALLY INITIAL PORTION OF TUBE WITH VARIABLE WALL TEMPERATURE

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An asymptotic solution is obtained for the laminar heat-exchange problem with variable wall temperature.

The heat problem for the boundary layer on the surface whose temperature follows the law

$$T_w = T_0 + Ax^\nu, \tag{1}$$

possesses a self-similar solution; it was studied in detail in [1] primarily by asymptotic methods.

The thermally initial portion of the tube where the liquid temperature varies from its value at the wall T_W to the temperature of the flow core, T_0, is equal to the incoming temperature; this takes place in the region $\delta \ll d$ (see Fig. 1), and can be analyzed in the same way as a boundary layer; the self-similar solution of the heat problem can also be obtained.

In the case of T_W = const [$\gamma = 0$ in (1)] this solution was obtained first by Leveque [2]. Attempts to generalize this solution to the variable case were made by Leveque himself [2] and also by others in [3, 4] although Nu as a function of γ was not available as is the case in a boundary-layer problem.

In the present article the Leveque solution is directly generalized to the case of the wall temperature following a power law.

The heat equation for the thermally initial portion is given by [5]

$$\rho c_p u \frac{\partial T}{\partial x} = \lambda \frac{\partial^2 T}{\partial y^2}. \tag{2}$$

In a thin heat-exchange layer the liquid velocity can be regarded as proportional to y:

$$u = \beta y. \tag{3}$$

In particular, for laminar flow in a circular tube one has [5]

$$\beta = 8\bar{u}/d. \tag{4}$$

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