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EROSION OF A COPPER CATHODE IN A NONSTATIONARY ARC SPOT. III. GENERALIZATION OF EXPERIMENTAL RESULTS AND MODELING OF THE INFLUENCE OF VELOCITY ON EROSION

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An extensive amount of experimental material on investigation of the dependence of the erosion of a copper cathode on the main operating parameters — the current, the electrode temperature, and the magnetic field — has been generalized with the use of the thermal macroscopic erosion model proposed earlier. It has been shown that the basic regularities of the erosion, modeled in such a manner, are confirmed experimentally with a satisfactory correlation.

Introduction. The results of experimental investigations of the basic regularities of the erosion of a copper cathode in an arc spot moving under the action of a magnetic field and of the influence of the magnetic field on the energy parameters of such a spot have been presented in [1, 2]. Below, we give a theoretical generalization of our results as well as those obtained by other authors.

The influence of a magnetic field on the erosion in setups with a magnetic movement of the arc has not been determined with a sufficient degree of confidence at present. There are many works in which a complex and often ambiguous influence of the magnetic field on the erosion has been shown (see [3, 4]). Therefore, here considerable attention is given to the employment of the thermal model for theoretical description of the behavior of the erosion with change in the magnetic field.

Theoretical Generalization of the Experiments. The basic equation of the thermal model employed for calculation of the erosion is a linear relationship between the volt-equivalent of the erosion energy $U_{er} = UW$ and the erosion g:

$$g = g_0 + \frac{UW}{h_{eff}} = g_0 + \frac{U_{er}}{h_{eff}} . \tag{1}$$

Here the dimensionless erosion energy W is a function of the dimensionless parameter of fusion f according to Eqs. (5) and (6) in [2]. Employing the experimental data and plotting U_{er} versus g, we can obtain h_{eff} and g_0 according to (1). In [2], we have made clear that the value of the microerosion g_0 weakly depends on the current

$$g_0 = 4.68 \cdot 10^{-12} I . \tag{2}$$

and is not strictly constant. Therefore, in the present work, we have taken g_0 from (1) as a function of the current I according to (2) and have not obtained it as a constant, as was done earlier in [5]. Then to find the effective enthalpy we represented the results of the experiments in the form $U_{er} = k(g - g_0)$, where, according to (1), the proportionality factor is equal to the effective enthalpy h_{eff}.

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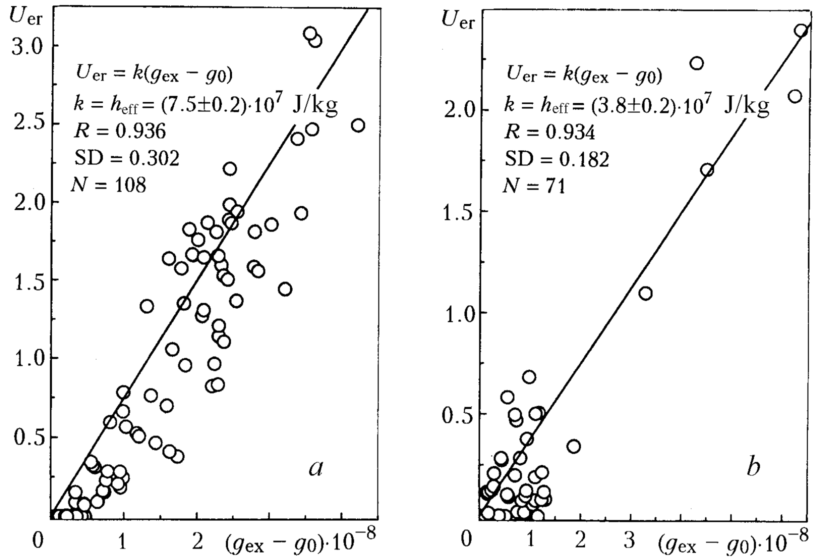

Fig. 1. Volt-equivalent of the erosion energy U_{er} as a function of the macro-erosion $g_{ex} - g_0$; the results have been obtained on the HMTI setup [5] (a) and the GWIP setup [1] (b). The parameters of linear regression are indicated in the margins of the figures.

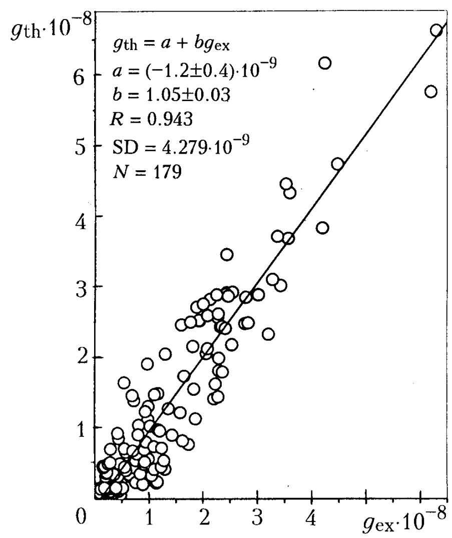

Fig. 2. Comparison of the erosion calculated from the thermal model (g_{th}) and measured in the experiments (g_{ex}). The parameters of linear regression are indicated in the margins of the figure.

Since we considered in [1, 2] two groups of experiments conducted with different cathode materials and on different setups, we processed them separately to determine h_{eff}. We recall that in the experiments on the HMTI setup, we employed copper of grades M_1 and M_2 according to the All-Union State Standard-859-78. In the experiments on the GWIP setup, we employed commercial copper of an unknown grade. In generalizing all the experiments, we employed formulas (3) and (9) from [2] for the dependence of the main energy parameters of the cathode spot U and j on the magnetic field. Figure 1 shows respectively the two groups of experiments in the form of the dependence $U_{er} = h_{eff}(g_{ex} - g_0)$ between the volt equivalent of the erosion energy U_{er} and the specific erosion g_{ex} obtained experimentally with account for the linear function $g_0(I)$ according to (2). The specific enthalpy of the erosion h_{eff} was 37.7 $MJ\cdot kg^{-1}$ for the experiments on the GWIP setup, whereas it was 75.15 $MJ\cdot kg^{-1}$ for the experiments on the HMTI

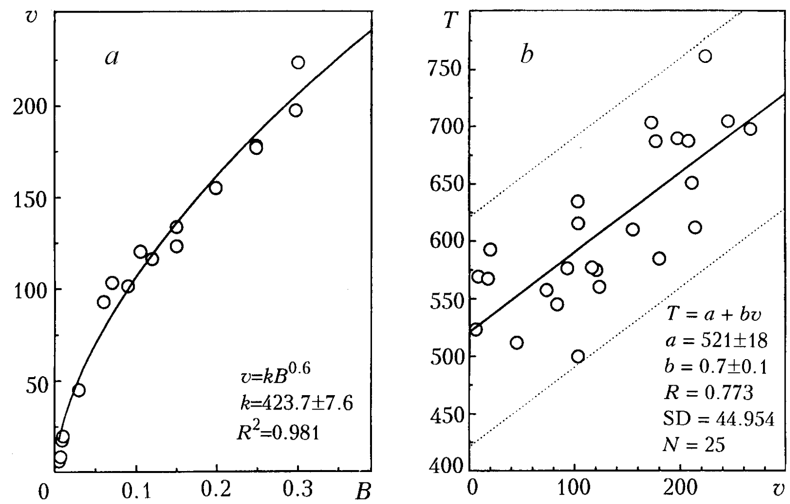

Fig. 3. Empirical approximations employed in theoretical representation of the results of the experiments on investigating erosion: a) nonlinear approximation of the arc velocity v as a function of the magnetic induction B; b) linear approximation of the surface temperature of the electrode T vs. the velocity of movement of the arc v. The range of variation of the temperature (±100 K) is shown dotted. The parameters of linear regression are indicated in the margins of the figures.

setup. The correlation coefficients R were identical, in practice, for the two sets of experiments and were about 0.93. Employing these values of h_{eff} and relation (2) for g_0, we have calculated the theoretical values of the erosion for all the experiments on both setups. The theoretical g_{th} and experimental values of the erosion g_{ex} are compared for them in Fig. 2 (a total of 179 points) as $g_{\mathrm{th}} = a + bg_{\mathrm{ex}}$. It is clear that there is quite a satisfactory correlation between these two samples: the correlation coefficient R is equal to 0.94 for an angular coefficient close to unity (b = 1.05) and a constant term close to zero ($a \approx 10^{-9}$), which confirms the correctness of the model.

Modeling of the Influence of Velocity on Erosion. In [1], it has been shown that there is a region of optimum magnetic fields and arc velocities with a minimum erosion in the case of magnetic movement of the arc. Here we model these regimes, employing a theoretical description based on the thermal model, and compare the results obtained to the experiments of [1] and to the experiments of other authors.

In [6], it has been shown that the dependence of the velocity of motion of the arc on the magnetic field in an annular interelectrode gap has the form of a power function with an exponent of 0.6:

$$v = kB^{0.6} . \tag{3}$$

For our experiments we have determined the values of k in Eq. (3) directly by approximation of the experimental data for a more accurate modeling of the function $g(v)$. The results of such a nonlinear approximation are shown in Fig. 3a. A good correlation (R^2 = 0.98) is seen. The velocity of movement of the arc spot substantially influences the temperature of the cathode surface. Such a dependence is shown in Fig. 3b and is characterized by a substantial spread in experimental points, which makes it impossible to identify any nonlinearities with a sufficient degree of confidence. Therefore, within this spread, we have approximated $T(v)$ by the linear function

$$T(v) = a + bv . \tag{4}$$

According to Fig. 3b, we have a = 521 ± 18 and b = 0.7 ± 0.1 for the correlation coefficient R = 0.77. This dependence have been adopted for further theoretical modeling of the experimental results. As is clear from Fig. 3b, the spread in experimental points totally falls in a corridor of ±100 K relative to (4). This corridor has been adopted for modeling of the limits of the corresponding variation of the erosion. Furthermore, in modeling, we took account of the dependences of the thermal volt-equivalent of the cathode spot $U(B)$ and the current density $j(B)$ on the magnetic field

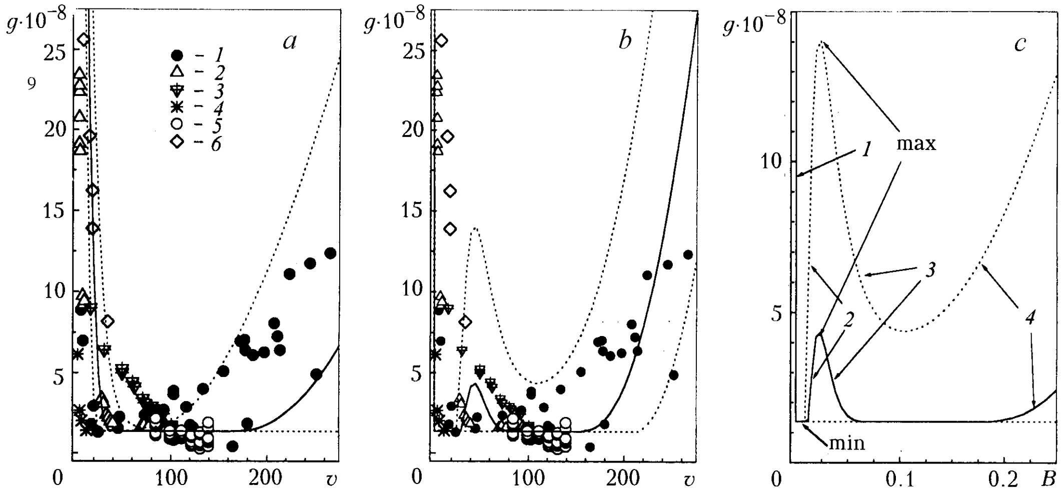

Fig. 4. Erosion g vs. velocity of movement of the spot v and magnetic field B: a and b) comparison of the theory with the experiments of different authors as a function of the spot velocity; c) theoretical representation of the initial portion of the plot as a function of the magnetic field on an enlarged scale. Experimental points: 1) of the present authors for air; 2) argon–nitrogen mixture [11]; 3) pure nitrogen [12]; 4) air in purely gasdynamic movement of the arc with the use of a vortex [13]; 5) air [14]; 6) mixture of argon with titanium tetrachloride and metal-ceramic cathode [15]; solid curve, modeling with the thermal model with the use of the function $j(B)$ according to Eq. (8) from [2] (a) and of the same function according to Eq. (9) from the same work (b, c). Dotted curves, the same with variation of the cathode-surface temperature within ±100 K; max and min, local maximum and minimum of erosion; 1–4) characteristic portions of increase and decrease in the erosion (see text for details).

according to Eqs. (3) and (9) in [2]. Additionally, we carried out modeling with the use of the dependence $j(B)$ obtained in [7] by the nonstationary method and represented in [2] in the form of Eq. (8).

Figure 4 compares the results of modeling of the erosion g as a function of the arc velocity v with the use of both formulas for the current density. Figure 4a shows the results of modeling with formula (8) from [2]. Here three theoretical curves are presented in the corridor of temperatures $T(v) \pm 100$, where $T(v)$ corresponds to formula (4). This corridor of temperatures covers all the experimental points with their considerable temperature spread (see Fig. 3b). As is clear from Fig. 4a, on the lower edge of the temperature corridor at the temperature $T(v) - 100$ the increase in erosion with velocity is currently absent, which is inconsistent with the results of the experiments, and the curve calculated from the center of the temperature corridor lies on the lower edge of the region occupied by the experimental points. This suggests that formula (8) from [2] yields j values understated for thermal calculations of the erosion. Possible reasons for the lower nonstationary values of the current density have been discussed in [2]. It has been shown there that the values of j, obtained by thermosphysical methods without diagnostics of the character of movement of the spot, yield an "apparent" value of the density, which includes the influence of the character of motion on measurement results. And this character is different in nonstationary and stationary experiments in view of the dissimilar states of the cathode surface for a strongly differing duration of the experiment. Therefore, to calculate the erosion it is more preferable to employ data on the current density, obtained directly in stationary erosion experiments.

Figure 4b gives the results of modeling with the use of formula (9) from [2, 8] for $j(B)$ which has been obtained in stationary experiments. Quite satisfactory agreement between theory and experiment is seen — the behavior of the theoretical curves on both edges of the temperature corridor $T(v) \pm 100$ corresponds to the behavior of the experimental points. Furthermore, a region of nonmonotonic change in the erosion with increase in the velocity has manifested itself on the $g(v)$ curve. For the sake of convenience this region is shown in Fig. 4c as a function of the magnetic field on an enlarged scale. Here the local maximum of erosion max for a magnetic field of about 0.025 T and the additional minimum of erosion min for very low (less than 0.01 T) magnetic fields are clearly seen. If we compare this figure to Fig. 6 in [2] for the dependence of the current density on the magnetic field $j(B)$, we can explain the reason for the nonmonotonic behavior of the erosion in the region of low magnetic fields.

According to the thermal model, in the limiting case for $v \to 0$ we have $f \to 0$ and $W \to 1$ and the erosion here is maximum. According to this model, the erosion begins to decrease as the velocity increases from zero (portion 1 in Fig. 4c). However, in the region of magnetic fields from B = 0 to B = 0.025 T, the current density increases so rapidly (see the solid curve in Fig. 6 in [2]) that its effect dominates over the effect of increase in the velocity, and as a result the erosion here begins to increase (see portion 2). When the magnetic fields are higher than 0.025 T, the growth in the current density as a function of the magnetic field is strongly retarded (see Fig. 6 in [2]) and the erosion accordingly begins to decrease on portion 3. As the magnetic field/velocity increases further, the erosion begins to increase again on portion 4 because of the increase in the temperature with arc velocity. On the lower edge of the temperature corridor $T(v)$ – 100 in question (dashed line), the local maximum of erosion max disappears since, according to the thermal model, the fusion temperature on the electrode surface is not attained even with the indicated rapid growth in the current density with magnetic field in the arc spot (i.e., $f > 1$).

Such a nonmonotonic dependence of the erosion on the magnetic field and the arc velocity has been noted in experiments by other authors (see [3, 4]). They explained this phenomenon on the basis of the change in the thickness and state of the oxide film on the cathode surface, and it was inferred in [4] that the variations indicated depend rather on the magnetic field than on the arc velocity. Indeed, the magnetic field influences both the dynamic characteristics [9] and the energy parameters of the spot: the current density and the thermal volt-equivalent [2, 8], which can have an effect on the kinetics of formation and destruction of the oxides on the cathode surface.

As follows from the modeling of erosion with the thermophysical macromodel, the erosion can vary for a purely thermal reason because of the change in the behavior of the function $j(B)$ in different ranges of the magnetic field; the manifestation of the irregularity of the erosion depends on the thermal regime of the cathode. Because of this, the behavior of the erosion as a function of the velocity in the region of magnetic fields of about 0.025 T is distinguished for its particular instability and sensitivity to a change in the operating parameters since a local maximum of erosion (it is denoted as max in Fig. 4c) can appear or disappear here depending on these parameters. Its appearance and value depend on the cathode temperature and on the energy parameters of the arc spot, which are determined by the material of the cathode and the composition of the plasma atmosphere. The most stable to a change in the operating parameters is the erosion minimum occupying an extensive zone in the region near B = 0.1 T (see Fig. 4c). Therefore, we can assume that this zone must be the most reliable for stable operation of the copper cathode of an arc heater.

In the region of a narrow local irregular minimum of erosion at $B < 0.01$ T, both the movement of the arc and the behavior of erosion are unstable, which can be caused by the smallness of the Lorentz driving force as compared to the force of surface resistance to the movement of the arc [10]. In the experiments with a copper cathode operating in air, we were able to obtain just two points on portion 1 (Fig. 4a) because of the instability of arc movement; these points confirmed a decrease in the erosion with increase in the velocity in this region. When the decrease in the velocity was excessive, we observed emergency regimes with an instantaneous local burnout of the cathode which were, probably, related to the too long shutdowns of the arc. Szente et al. [11] have been able to obtain a fairly large number of points in this region (points 2 in Fig. 4a and b) by extending the range of control of the velocity due to the change not only in the magnetic field but in the composition of the gas (proportion of components of the argon–nitrogen mixture) as well. The $g(v)$ points obtained by them with pure nitrogen in just magnetic control of the velocity (point 3 in Fig. 4a and b) [12] appear very close to portion 3 and we can assume that these points belong to it. Employing the vortex gasdynamic movement of the attachments of the arc without a magnetic field, An'shakov et al. [13] have obtained data on the erosion in the region of very low velocities (points 4). Points 5 were obtained in a considerable range of magnetic fields (0.1–0.35 T); the change in the erosion in these experiments [14] turned out to be slight and close to the spread in experimental points. Data in the region of low fields (points 6) have been obtained with a metal-ceramic cathode (whose regime and properties can strongly differ from those of a copper cathode) in an atmosphere of a mixture of argon and titanium tetrachloride [15]. Thus, the most reliable range of magnetic fields with a minimum erosion for the copper cathode in an air medium can be the range near 0.1 T.

Such a complex dependence of the erosion on the arc velocity is characteristic just of the magnetic movement of the arc. As the magnetic field increases, in addition to the increase in the heat flux through the arc spot $q_0 = j(B)U(B)$, we have an increase in the convective flow, which is caused by the growth in the turbulence of the gas flow, which leads to the effects considered above.

In structures with a purely vortex rotation of the arc, the increase in the arc velocity always leads to a decrease in the erosion. Here not only does the increase in the arc velocity due to the increase in the tangential vortex velocity decrease the time of stay of the spot at a given point of the electrode surface but it also reduces the heat flux into the electrode owing to the features of vortex flows [16].

CONCLUSIONS

The use of the thermal macroscopic erosion model has made it possible to generalize all the available experimental data on the erosion of a copper cathode in an air medium (about 180 experimental points) with a satisfactory correlation between theoretical and experimental results (correlation coefficient 0.94). Different values of the effective erosion enthalpy — from 0.38 to 75 $MJ \cdot kg^{-1}$ — have been obtained for different grades of copper. The character of the dependence of the specific erosion on the velocity of motion of the arc spot is also consistent with the predictions of the thermal model. There is an optimum range of magnetic fields for operation of the copper cathode in an air medium, which is near 0.1 T.

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NOTATION

a, b, and k, coefficients of linear regression; B, magnetic induction, T; f, dimensionless parameter of fusion in the thermal erosion model; g, specific erosion, $kg \cdot C^{-1}$; g_0, specific microerosion, $kg \cdot C^{-1}$; g_{th} and g_{ex}, specific erosion calculated theoretically and measured experimentally, $kg \cdot C^{-1}$; h_{eff}, effective enthalpy of erosion, $MJ \cdot kg^{-1}$; I, current, A; j, current density, $A \cdot m^{-1}$; N, sample volume; q_0, density of the heat flux in the arc spot, $W \cdot m^{-2}$; R, correlation coefficient; SD, standard deviation; T, temperature, K; U, volt-equivalent of the heat flux in the arc spot, V; U_{er}, volt-equivalent of the erosion energy, V; v, arc velocity, $m \cdot sec^{-1}$; W, dimensionless erosion energy in the thermal model. Subscripts: er, erosion; th, theoretical value; ex, experimental value; eff, effective value.

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