A NEW THERMOPHYSICAL MODEL FOR COLD ELECTRODES EROSION

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ABSTRACT

A simple formula is proposed for cold electrodes erosion calculation. The formula is based on the thermophysical model of erosion but modified to Arrhenius-Guile relationship form.

INTRODUCTION

Hitherto the methods of erosion calculations have been developed mainly for thermoionic cathodes, which operate under fixed arc attachments [1-2]. Anodes, and, for high power plasmatrons also, cathodes are manufactured from copper and are capable to operate only with fast moving arc attachments. Processes on its surface have unstationary character and are very various by nature [3-5]. It was shown by Guile et all, that the main role for copper cathode erosion play not complex physical, chemical or electrochemical processes in its oxide overlayer, but rather the trivial process of copper substrate fusion. Guile noted that a correlation exists between the logarithm of mass erosion and the specific heat of fusion for pure electrodes materials but not for their oxides. Guile et all proposed the using of Arrhenius-form relationship for calculations of mass erosion intensity [3]:

$$dm/d\tau = A \exp - (\Delta G_e / kNT) , \qquad (1)$$

where A is the "rate factor", ΔG_e is the activation energy of the erosion reaction of copper (which is close to the activation energy of interatomic bond loosening, i.e. fusion), k is the Boltzmann's constant, N is the Avogadro's number and T is the cathode surface temperature. This gives serious justification for the application of the thermophysical model to cold electrode erosion investigations.

THEORETICAL

The thermophysical model is based on the substitution of the real arc spot by a moving surface heat source [6-8]. A round form heat source is assumed with equal heat flux density within its area. Then the heat source flux density may be expressed as $q = jU$, where j - arc spot current density and U - near electrode voltage drop. The maximum time of electrode surface point heat exposure may be expressed as $\tau_{\max} = d/v$, where v - source displacement velocity, which is assumed constant and d - its diameter. For copper cathode the typical value of Fo number $Fo = a\tau_{\max}/d^2 \ll 1$. Due to this the solution of the one-dimensional problem for semi-infinite body may be applied for the calculation of electrode surface heating within the heat source (under $q = const$) [6-8]:

$$T(x,\tau) = T_0 + \frac{2q}{\lambda}\sqrt{a\tau}\,\mathrm{ierfc}\left(\frac{x}{2\sqrt{a\tau}}\right). \qquad (2)$$

The time of surface heating to the fusion temperature may be expressed from (2) as:

$$\tau_0 = \left[(T_f - T)\,\lambda/q\right]^2 \pi/4a, \qquad (3)$$

where T, T_f are the initial and the fusion cathode temperature, respectively, λ is the thermal conductivity and a is the thermal diffusivity of copper. During the time of τ_0 the heat source travels the distance $l_0 = v\tau_0$. If $l_0 < d$, a fusion zone arises within the heat source area. This zone is located at the distanse l_0 from its front edge (see scheme on Fig. 2). The dimensions of the fusion zone may be characterized by the parameter $f = l_0/d$. If $f \geq 1$, the fusion zone doesn't exist generally, if $l_0/d = 0$, the area of fusion zone is maximal. Developing of the fusion zone causes arizing of the difference between entered and removed electrode heat fluxes, because part of heat is spent on melting and overheating of liquid metal over the fusion temperature. So we take the hypothesis that the intensity of erosion may be expressed as function of this heat fluxes difference, which we'll name "erosion heat". The limited volume of this paper is inhibitory to give detailed description of the mathematical aspects of the mentioned problem. So we are giving only final theoretical expression for the value of heat erosion as function of melted zone dimensions and other parameters:

$$\begin{aligned} Q_{er} \;=\; & \frac{2}{\pi}\left\{IU\left(\arcsin\beta - f\beta\right) - 2\beta\left\{\frac{\lambda}{\pi^{0.25}}\sqrt{\frac{2v}{a}}\left(\frac{I}{j}\right)^{0.75}(T_f - T)\int_0^1\sqrt{\gamma(z) - f}\;dz\right.\right. \\ & \left.\left.-IU\left[\frac{2}{\pi}\left(\sqrt{f}\int_0^1\sqrt{\gamma(z)-f}\;dz - \int_0^1\gamma(z)\arctan\frac{\sqrt{f}}{\sqrt{\gamma(z)-f}}\,dz\right) + f\right]\right\}\right\} \qquad (4) \end{aligned}$$

where $\beta = \sqrt{1-f^2}$, $\gamma(z) = \sqrt{1 - z^2(1-f^2)}$ and $z = x\sqrt{\pi j/I(1-f^2)}$. Now erosion may be expressed as $g = Q_{er}/h_{ef}I$, where h_{ef} is the effective erosion enthalpy, which characterizes the consumption of energy for electrode material transforming from solid state to plasma one in the arc spot. If we calculate Q_{er} and measure g, it is possible to obtain the value of h_{ef}. But if thermophysical model and Guile-Arrhenius one have the same theoretical background, it should be possible to reduce the more universal but complicated relationships of thermophysical model to better for practice form (1). This paper is devoted to the search of such a possibility.

EXPERIMENTAL AND RESULTS

For erosion calculations it is necessary to know, in agreement with (4), the next main parameters: j - arc spot current density (or arc spot radius), U - near-electrode voltage drop, I - current, v - arc velocity and T - electrode surface temperature. The last three (I, v, T) were measured in the same experiments, which were carried out for erosion investigations. For defining of the first two, a special experiment was made. The measurement of near-electrode voltage drop immediately in a fast moving eletric arc is very difficult, that's why volt-equivalent of arc spot heat flux $U = Q_s/I$ was applied in this work. Here Q_s is the heat flux, which is introduced into the electrode body through arc spot area. A coaxial installation with magnetic arc deflection was used for obtaining Q_s (Fig. 1). Both electrodes of the installation were equipped with the copper rings separated one from another by thin spacers (near 0.5 mm), made by heat and electric insulating material. Electric current was fed only to one ring for each electrode (pos. 1 on Fig.1). At a small width of the ring it is possible to assume, that entering heat flux into the ring due to convection and radiation is proportional of its being heated surface area, but heat flux entered through the arc spot doesn't depend on ring surface area. This allows to extract the arc spot heat flux from the integral one. To ensure that the arc spot heat flux was dominant, rings of a small width (3-5 mm) and small interelectrode gaps (1.5-3 mm) were used. Every ring was supplied with a thermocouple, and heat flux was then obtained from the record of ring heating curve (unstationary method). This method was also used with some modification, which consisted in measuring of heat fluxes to three adjacent rings, with only one of these current-fed. This method allowed to obtain dependence of anode and cathode volt-equivalents on magnetic field and gas pressure (volt-equivalents grow with increasing of the last two ones). Due to the lack of space we are not giving here the tables of results. The cathode volt-equivalent value for the experimental conditions will be taken in the calculations as equal to ≈ 6.5 V.

The same experimental installation (see Fig. 1) was applied to estimate the effective heat diameter of arc spot. For this goal a thermocouple was placed near inner being heated surface of outer electrode (at the distance ≈ 1 mm). The ring dimensions and durations of experiments were chosen so to obtain the regular heat conduction regime. For regular regime a linear temperature-time dependence takes place, if heat flux is constant. As it is seen from Fig. 2, such experimental dependence is linear really in a wide range of temperatures. After electrode being heated to a certain temperature, this linearity is violated, so that derivative $dT/d\tau$ is being decreased gradually with the temperature growth. That evidenced on the decreasing of heat flux into the electrode. The most probable reason for such decreasing may be the onset of surface fusion within the arc spot. Proceeding with such assumption, it is possible to obtain the relationship for the estimation of effective heat diameter of arc spot, using the above presented expressions for $\tau_{\max}, \Delta T, \tau_0$ and U :

$$d = \frac{4}{\pi}\left(\frac{I^2U^2a}{(T_f - T)^2\,\upsilon\lambda^2}\right)^{1/3}, \qquad (5)$$

where T - temperature of ring inner surface, which corresponds to the moment of $dT/d\tau$ decreasing (marked by arrows on Fig. 2).

A similar installation, but equipped with water-cooled electrodes, was applied for cathode erosion investigations. The width of water-cooled ring was 5 mm. Besides erosion, the arc velocity, electrode temperature and current were measured. The experimental results are presented on Fig. 3 for the range of arc velocities 48-270 m/s and cathode temperatures 380-1070 K. It is seen, that erosion intensity is growing fast beginning from some critical value of current, which depends on electrode diameter (see points enclosed in frames). If we suppose, that the reason of abrupt increasing of erosion at critical current value is the fusion onset in arc spot, it is possible also to estimate the arc spot heat diameter and current density in accordance with (5). Such estimations were made for points in frames on Fig. 3. Due to limitations of paper volume the table of results are not being given here, but they are rather close to the ones obtained by unstationary method. For further calculations the mean value of current density 1.3×10^5 A/cm^2 in cathode spot was applied. Calculations in accordance with previous formula gave values $f \geq 1$ ($Q_{er} = 0$) for the points, where erosion was almost constant with current ($g' = 3 - 4 \times 10^{-9}$ kg/C approximately). For regimes where $f \leq 1$, $Q_{er} \geq 0$, it is possible to calculate the erosion, using a modification of the above presented expression,

$$g = g' + Q_{er}/h_{ef}I. \tag{6}$$

The results of experiments were processed in the form: $g_{ex} = f(g)$, where g_{ex} is the experimentally measured erosion. The best matching is obtained with $h_{ef} = 66 \times 10^6$ J/kg, $g' = 4 \times 10^{-9}$ kg/C. Then the numerical analysis of thermophysical model in Guile-Arrhenius relationship coordinates (1) was carried out (dm/dC instead of $dm/d\tau$ was used, where C is the amount of electrical charge passed through the electric arc spot). The results are presented on Fig. 4. We see a series of curves, originated from the same initial point, coordinates of which are the fusion temperature of copper and some initial value of specific erosion, which is equal $\approx 10^{-7}$ kg/C. This value is in agreement for the maximal erosion level for vacuum cathode spot [11]. The curves differ one from another only by the parameter $s = \sqrt{I}/v$, which is proportional to the d/v ratio. If we replace these curves with direct lines originating from the same initial point, it is possible to get a simple expression for thermophysical model in Guile-Arrhenius relationship form:

$$g = g_0 \exp -K \left(\frac{1}{s+a} - b\right)\left(\frac{T_f}{T} - 1\right). \tag{7}$$

We have obtained the best correlation (7) with experimental data for $a \approx 0.6$ and $b \approx 0.4$, ($K = 2.65$, $g_0 = 8 \times 10^{-8}$ kg/C). A comparison of the experimental data generalizations in accordance with (7) and (1) is presented on Figs. 5 and 6 for the experimental points, for which $Q_{er} > 0$ and, in this case, the thermophysical model is valid. All points were divided into four groups in accordance with the range of parameter s and marked on this figures. The separation of points acording to s value is clearly seen on Fig. 5. This causes decreasing of correlation coefficient in comparison with Fig. 6. As for erosion calculations for the regimes where $Q_{er} = 0$, it is possible to take $g' \approx 3 - 4 \times 10^{-9}$ kg/C for cathodes made by technical copper, which was used in our experiments.

DISCUSSION

If we include into the correlation the points with $Q_{er} = 0$ (especially points for low currents), the difference of correlation coefficients between (1) and (7) formulae decreases. It is possible, that the relationship (1) is related to regimes, where

Q_{er} = 0 (Guile's and Szente's [3-5] experiments were made at currents $\approx$ 100 A), but (7) - to ones, where $Q_{er} > 0$. It should not exclude the possibility of two erosion mode occurrence, as two kinds of cathode spots occur ("thermal" and "explosive", or first and second kind spots [10,11]). Unfortunately, many authors are not giving all parameters (I, v, T), which is necessary for thermophysical model applying. Besides, cathode materials are also different in many works, and it is very difficult to compare all results presented.

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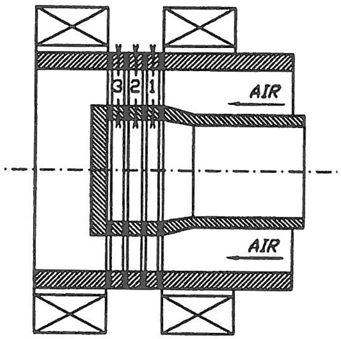

Fig.1: Scheme of experimental installation. 1 - current-fed rings.

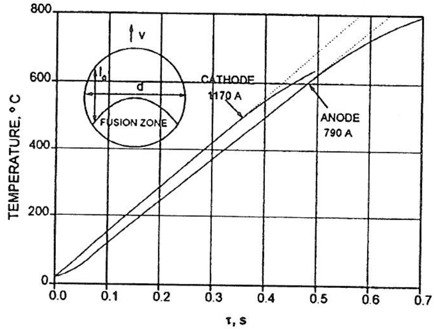

Fig. 2: Electrodes heating records and scheme of surface heat source.

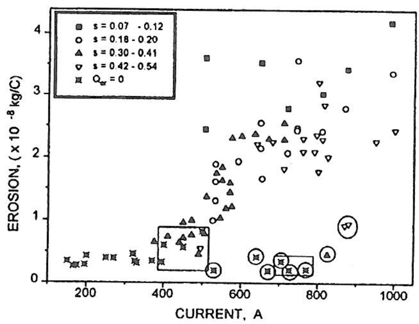

Fig. 3: Experimental data on copper cathode erosion. Cathode diameter 50 mm, points in circles 90 mm.

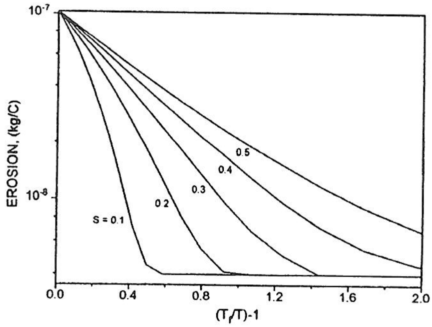

Fig. 4: Formulae (4,6) in Guile-Arrhenius coordinates.

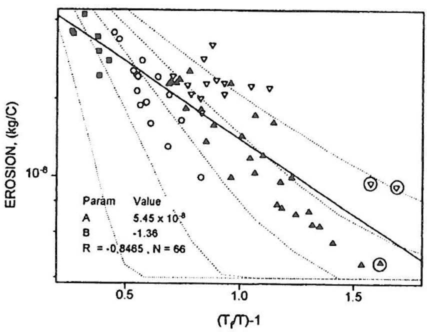

Fig. 5: Experimental points according (1). Symbols see Fig. 3. Dotted lines: formulae (4,6).

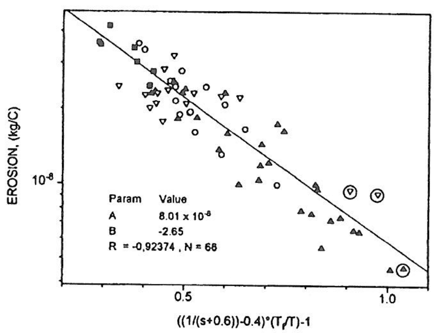

Fig. 6: Experimental data according (7). Symbols see Fig. 3.