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STEP MODEL OF EROSION OF ELECTRODES. II. APPLICATION TO THE CASE OF SPECIAL REGIMES OF ELECTROEROSION TREATMENT

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The possibility of applying the step model of erosion of cold electrodes [Inzh.-Fiz. Zh., **76**, No. 2, 116–122 (2003)] *for special (optimized) regimes of electroerosion treatment of metals has been shown. A satisfactory agreement between the theoretical calculations and the experimental data of other authors* [J. Appl. Phys., **66**, No. 9, 4095–4103 (1989)] *in electroerosion treatment of steel has been obtained.*

Introduction. In electric-arc gas heaters, it is not practical to achieve conditions under which the arc spot moves over the electrode surface with a constant and controlled length of the step. The character of thermal action of a discharge which models the step motion of the spot most precisely can be attained in devices ensuring a controlled sequence of electric discharges. Such conditions can be implemented better, for example, in electroerosion-treatment (machining) plants (see, for example, [2]). The process of electroerosion treatment is widely used in industry for cutting off, 3D machining to a template, cutting out, piercing, grinding, finishing, marking, and hardening of the billet surface.

Erosion processes in electroerosion-treatment plants significantly differ from the processes in electric-arc heaters. The process of electroerosion treatment occurs in a working fluid which fills the space between the electrodes; one of the electrodes is a billet whereas the other is a tool. Below we will briefly describe the process of electroerosion treatment for the case where the billet is the cathode, and thereafter, using the experimental data [1], we will show that the equations of the step erosion model can be applied not only to electric-arc heaters but can also be extended to the cathode processes in electroerosion treatment.

Results and Discussion. The basic elements of an electroerosion-treatment plant are the electrodes divided by a liquid dielectric. A billet whose material fails (is treated) by the action of electric discharge is usually used as the cathode. The anode is an electrode tool and it must possess a high erosion resistance. The best anode materials for the conditions of electroerosion treatment are copper, brass, tungsten, aluminum, graphite, and graphite materials.

In the plant described in [2], a voltage of about 200 V is applied to an interelectrode gap of the order of 40 μm, which produces the breakdown of the dielectric. Thereafter the electrode voltage drops to 25 V while the discharge current increases to a constant (operating) value set by the operator. The discharge time τ_{pu} is usually no longer than 100 μsec. The expansion of the plasma channel is limited by the liquid dielectric and the incoming energy is concentrated in a very small volume.

As has been shown in [2], the density of the heat flux in the cathode spot can be considered to be constant in the discharge time τ_{pu}. This corresponds to the assumption on which the thermal erosion model is based (see [1]). To investigate the optimum regime of operation of the electroerosion plant, DiBitonto et al. [2] have developed a model in which the cathode spot is replaced by a point heat source.

In electroerosion treatment, the density of the heat flux on the billet surface is very high. Therefore, for the estimates given below we will disregard the quantity of heat removed from the surface over a short period of discharge and will assume that the entire heat adiabatically heats the volume of the molten metal. In accordance with [2], only a part of the molten volume is removed from the surface in the process of erosion. The ratio of the volume of

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TABLE 1. Experimental Data on the Electroerosion Treatment of a Steel Billet (the quantities I, τ_{pu}, τ_{pa}, V, and η are taken from Table 2 in [2])

I, A	$\tau_{pu}\cdot 10^{-6}$, sec	$\tau_{pa}\cdot 10^{-6}$, sec	$V\cdot 10^{-9}$, m^3/sec	η, %	h_{ef}, MJ/kg
2.34	5.6	1.0	0.005	2	4.816
2.85	7.5	1.3	0.027	9	4.971
3.67	13	2.4	0.052	14	5.09
5.3	18	2.4	0.14	24	4.861
8.5	24	2.4	0.39	36	4.362
10	32	2.4	0.53	41	4.336
12.8	42	3.2	0.84	50	4.284
20	56	3.2	1.5	54	4.144
25	100	4.2	2.08	60	4.19
36	180	4.2	3.77	74	4.19
44	240	5.6	4.1	66	4.197
58	420	7.5	5.77	70	4.194
68	560	10	9.32	96	4.174

removed metal to the volume of the melt calculated theoretically ("energy efficiency") has been called in [2] the "plasma flushing efficiency" (PFE).

To investigate the regimes of electroerosion treatment (in particular, the optimum duration of the discharge τ_{opt} corresponding to the maximum rate of treatment of the billet) DiBitonto et al. [2] employed steel as the billet material and the electrode tool manufactured from copper. The original values of the parameters obtained in [2] are given in Table 1.

With the data of the table, we can estimate the value of the effective enthalpy of erosion h_{ef} (i.e., the quantity of heat accumulated in a unit mass of the removed electrode material) using the expression

$$h_{ef} = \frac{\eta U I \bar{\tau}}{\rho V}, \quad (1)$$

in which the relative discharge time $\bar{\tau}$ is

$$\bar{\tau} = \frac{\tau_{pu}}{\tau_{pu} + \tau_{pa}}. \quad (2)$$

In expression (1), it is assumed that the removed metal contains a quantity of heat $\eta U I \bar{\tau}$ that must be expended on heating it to the fusion temperature. In calculations, we used the following data [2]: density of the steel ρ = 7545 kg·m^{-3} and cathode volt-equivalent $U = 0.183U_d$ yielding U = 4.575 V for the discharge voltage U_d = 25 V.

In Table 1, we present the values of the effective enthalpy h_{ef} determined from formula (1). As follows from the table, for the operating regimes presented h_{ef} remains constant, in practice 4.144–5.09 MJ·kg^{-1} (for the average value h_{ef} = 4.507 MJ·kg^{-1}), despite the change of several orders of magnitude in the discharge duration τ_{pu}. It is necessary to note that in this case a constant, in practice, value of h_{ef} has been obtained with the optimum (from the viewpoint of the productivity of electroerosion treatment) duration of the discharge τ_{pu}. This fact enables us to compare the experimental results of Table 1 and the calculations based on the one-dimensional thermal erosion model [1], using the concept of constancy of h_{ef}.

Unfortunately, DiBitonto et al. [2] do not indicate the data on the value of the current density in the cathode spot of the discharge. However, the experimental data of Table 1 and the thermal erosion model [1] enable us to determine the approximate value of the effective density of the current j in the cathode spot. In accordance with the propositions of the thermal model, the beginning of microerosion corresponds to the condition $f = \tau_0/\tau_s = 1$, which enables us to calculate j from the formula

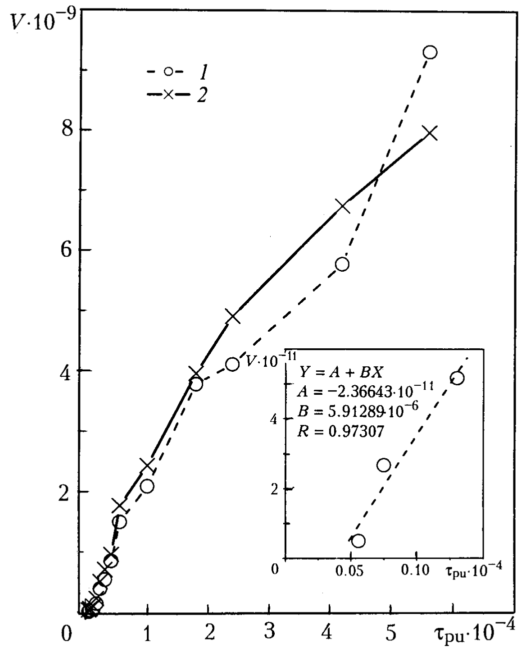

Fig. 1. Amount of removed material of the billet V as a function of the duration of the discharge τ_{pu} for electroerosion treatment: 1) experimental data [2]; 2) theoretical calculation, according to Eqs. (2) and (6)–(8), for $j = 2.28{\cdot}10^9$ A/m^{-2} and $h_{ef} = 4.49$ $MJ{\cdot}kg^{-1}$ (see the text and Fig. 2). On the inset: linear approximation of $V(\tau_{pu})$ for the first three points with a minimum τ_{pu} used for calculation of τ_0 from the condition $\tau_0(V) = \tau(0)$.

$$j = \frac{\pi^{0.5}\,\lambda\,(T_f - T_0)}{2a^{0.5}\,\tau_s^{0.5}\,U}\,. \qquad (3)$$

In the case where the residence time τ_s (time of stay of the spot at a certain point of the surface) is known, we can obtain the effective current density j from the expression

$$\tau_0 = \frac{\pi}{4a}\left[\frac{(T_f - T_0)\,\lambda}{q_0}\right]^2, \qquad (4)$$

taking into account that $q_0 = jU$.

To determine τ_0 we have used the linear extrapolation by the first three points of the dependence of the volume erosion V on the pulse duration τ_{pu}, which were obtained for the shortest discharge times (dashed line in the inset in Fig. 1). Assuming that the instant of time $\tau = \tau_0$ corresponds to $V = 0$, we will have $\tau_0 = 4{\cdot}10^{-6}$ sec from the extrapolation and the corresponding effective current density $j = 2.28{\cdot}10^9$ $A{\cdot}m^{-2}$ from Eq. (4). In calculating, we used the values (just as in [2]) of the thermal conductivity $\lambda = 56.1$ $W{\cdot}m^{-1}{\cdot}K^{-1}$ and the thermal diffusivity $a = 1.3{\cdot}10^{-5}$ $m^2{\cdot}sec^{-1}$ average in the range of temperatures from $T_0 = 298$ K to $T_f = 1808$ K (the thermal diffusivity was obtained from the relation $a = \lambda/\rho C_p$ for the specific heat of the employed steel $C_p = 575$ $J{\cdot}kg^{-1}{\cdot}K^{-1}$ and $\rho = 7545$ $kg{\cdot}m^{-3}$).

To compare the experimental data and the results of the calculations according to the step erosion model we will disregard the effect of preheating of the billet surface by the previous discharge and will take the cathode temperature to be equal to the ambient temperature $T_0 = 300$ K. In accordance with the thermal model, the specific erosion g can be represented as

$$g = g_0 + \frac{UW_s}{h_{ef}}\,. \qquad (5)$$

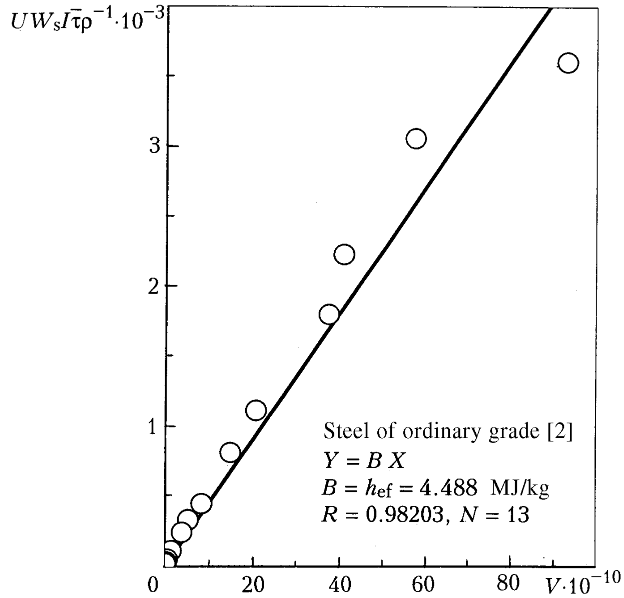

Fig. 2. Linear approximation through the origin of coordinates of the dimensionless group $UWI\bar{\tau}\rho^{-1}$ as a function of the volume erosion V for determination of the effective enthalpy of erosion h_{ef}.

In electroerosion treatment, the erosion is determined in terms of the volume of the billet material removed per unit time. Disregarding the microerosion g_0 because of its smallness as compared to macroerosion (see [1]) and using the relation $g = \rho V/(I\bar{\tau})$, we obtain from (5) the expression for the volume erosion

$$V = \frac{UW_s I\bar{\tau}}{\rho h_{ef}}, \tag{6}$$

in which (see [1])

$$W_s = \frac{2}{\pi}\left(\arctan\sqrt{\frac{1-f_s}{f_s}} - \sqrt{f_s\,(1-f_s)}\right) \tag{7}$$

is a function of the dimensionless parameter of fusion $f_s = \tau_0/\tau_s$:

$$f_s = \frac{\pi}{4a\tau_s}\left[\frac{(T_f - T_0)\,\lambda}{jU}\right]^2. \tag{8}$$

Formula (6) enables us to determine the amount of material removed in the discharge time $\tau_s = \tau_{pu}$ at fixed values of T_0, T_f, and U.

Figure 2 shows the calculated values of the dimensional group $UWI\bar{\tau}\rho^{-1}$ (J·m^3·sec^{-1}·kg^{-1}) as a function of the volume erosion V. The angular coefficient of linear approximation of $UWI\bar{\tau}\rho^{-1}(V)$ represents the effective enthalpy h_{ef}. Using the value $h_{ef} = 4.488$ MJ·kg^{-1} obtained from Fig. 2, in accordance with Eq. (6) we calculated the theoretical values of the erosion $V(\tau_{pu})$ for the experimental points of Fig. 1. As is clear from Figs. 1 and 2, the step erosion model agrees with experiment rather well, which proves not only the possibility of applying the model to electric-arc heaters but also its capacity to explain certain features of the process of electroerosion treatment.

Moreover, from Table 1 it follows that for the effective current density $j = 2.28\cdot 10^9$ A·m^{-2} the Fourier number Fo $= a\tau_s/d^2$ takes on values from Fo $= 5\cdot 10^{-2}$ for the first point (minimum $\tau_s = \tau_{pu}$) to the value Fo $= 19\cdot 10^{-2}$ when the discharge time τ_{pu} is maximum. The low values of Fo substantiate the applicability of the one-dimensional thermal model to the case of electroerosion treatment, in particular, to cathode erosion.

The lower value of h_{ef} obtained for the process of electroerosion treatment ($h_{ef} \approx 4.5$ MJ·kg^{-1}) as compared to h_{ef} = 70–80 MJ·kg^{-1} for the copper electrode of an electric-arc heater [1] demonstrates that electroerosion treatment is characterized by the more powerful mechanism of erosion than the electrodes of the electric-arc heater, which is a positive factor for electroerosion treatment.

CONCLUSIONS

It has been shown that the step erosion model [1] can be used for description of the erosion process in electroerosion treatment. Unlike electric-arc heaters, in electroerosion-treatment plants one can reproduce more accurately the conditions described by the step erosion model owing to a more accurate sequence of discharge pulses with a prescribed duration. For analysis we used the experimental data obtained by other authors in electroerosion treatment of steel under conditions optimum from the viewpoint of the rate of removal of the billet material. The application of the step model enabled us to determine the basic characteristics of the process of electroerosion treatment, such as the effective density of the current in the cathode spot of the discharge $j \approx 2 \cdot 10^9$ A·m^{-2} and the effective enthalpy of erosion $h_{ef} \approx 4.5$ MJ·kg^{-1}. We obtained a satisfactory agreement between the values of the erosion calculated according to the model and those obtained experimentally.

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NOTATION

Fo, Fourier number; I, discharge current, A; η, energy efficiency of electroerosion treatment; T_0, initial temperature of the electrode surface, K; T_f, fusion temperature, K; U, volt-equivalent of the heat flux in the arc spot, V; U_d, drop of the discharge voltage, V; V, volume erosion, rate of removal of the material, m^3·sec^{-1}; W_s, dimensionless energy of erosion in the step model; a, thermal diffusivity, m^2·sec^{-1}; C_p, specific heat, J·kg^{-1}·K^{-1}; f_s, dimensionless parameter of fusion in the step model; q, specific erosion, kg·C^{-1}; g_0, specific microerosion, kg·C^{-1}; h_{ef}, effective enthalpy of erosion, J·kg^{-1}; j, effective density of the current in the discharge spot, A·m^{-2}; τ_{opt}, optimum pulse time, sec; λ, thermal conductivity, W·m^{-1}·K^{-1}; ρ, density, kg·m^{-3}; τ, time, sec; $\bar{\tau}$, relative duration of the discharge; τ_0, time of heating of the surface to the fusion temperature; q_0, density of the heat flux supplied to the electrode through the arc spot, W·m^{-2}; τ_{pu}, discharge duration, sec; τ_{pa}, duration of a pause between pulses, sec; τ_s, time of existence of the spot at a given point (residence time) for the step motion, sec. Subscripts: 0, characteristic value of the quantity (for example, initial temperature T_0, time of heating to the fusion temperature τ_0); f, fusion; s, parameter for the step motion of the spot; ef, effective value; opt, optimum value; pu, pulse; pa, pause; d, discharge parameter.

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