

## CRITERION EQUATION FOR CALCULATION OF THE CURRENT LIMITING ELECTROCHEMICAL MACHINING BY FORMATION OF SPARKS

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The current density used in electrochemical machining can be increased only up to a certain value, above which the formation of electric sparks on the cathode (tool) is observed, whereby the latter and its insulation are damaged. The present work is devoted to the measurement of this critical current density for the case of electrochemical drilling of small holes by means of metal capillaries provided with an external insulation. The results are correlated by a criterion equation which gives the values of the limiting currents for sparking,  $I_S$ , with an average error of  $\pm 9\%$ .

The principle of electrochemical machining is the anodic dissolution of a workpiece in the medium of a flowing electrolyte. The shape of the tool as cathode is copied into the workpiece as anode with relatively small deviations given by the width of the gap between the material and the tool. The tool is not consumed during the process and if the working conditions are kept constant the accuracy in the shape of the workpiece is very high. By increasing the rate of removal, not only the process can be accelerated but the machined surface becomes smoother. However, the current density on the tool (cathode) can be increased only up to a certain limiting value given by the shape of the tool and hydrodynamic conditions. A further increase of the current density causes the formation of electric sparks on the cathode, whereby the latter and its insulation are damaged.

### ELECTRIC SPARKS IN ELECTROCHEMICAL DRILLING

We shall consider electric discharges in an apparatus for drilling small holes. The tool (cathode) is a metal capillary provided with a good external insulation; its end is ground in a plane perpendicular to the capillary axis. An electrolyte flows through the capillary into the gap between the workpiece and the tool.

When the voltage of the electrolyser is gradually increased, the current flowing through it attains a limiting value, which is approximately maintained during further increase of the voltage. In this phase, occasional electric sparks are observed on the surface of the cathode. When the voltage attains 45–55 V, the current increases

abruptly by 10–20% and begins to oscillate around a mean value which remains practically constant during increasing the voltage further. At the same time, acoustical and optical effects are observed; yellow-orange sparks or flames are visible on the cathode (Fig. 1). Its metallic surface does not change in form, only turns black. If the insulation of the cathode is from an organic compound it turns also black and is damaged (peals off under the action of the streaming electrolyte). This is illustrated by Fig. 2. If the electrolyte flow through the capillary is very slow (hence bad cooling) the metal at the orifice of the cathode melts and a deformation takes place.

Only a alumina ceramic insulation withstands the mentioned conditions. An insulation made of inorganic enamels lasts for a limited time. The mentioned phenomena are observed not only in oxidising media ( $\text{NaNO}_3$ ,  $\text{NaClO}_3$  or their mixture) but also in a neutral solution of  $\text{NaCl}$ . A typical dependence of current on time during sparking is shown in Fig. 3, and this at constant voltage. It follows from the observed  $i-t$  curves that the discharge has the character of sparks. The form of the dependence does not change with hydrodynamic conditions and is the same regardless of whether the electrode is in the free electrolyte or in the hole formed by drilling; and the same applies for the limiting current of sparking,  $I_s$ , which is constant to within  $\pm 20\%$ .

To explain this phenomenon, the following mechanism was proposed in accord with experiments reported in the literature<sup>1</sup>: With respect to the distribution of current density on the cathode<sup>2</sup> (the current density in the capillary is negligible), the electrochemical process is concentrated on the tip of the insulated metal capillary. The quantity of the evolved gas increases with the current density. At the same time, a considerable amount of heat is evolved at the electrode. Since the latter is thermally insulated by the applied ceramic or enamel, the heat is transferred to the electrolyte mainly by convection. Finally, the temperature of the electrolyte layer at the electrode attains the boiling point. Thus, together with the gas evolved electrolytically, a large number of bubbles appear on the electrode surface, and eventually at a certain current density a continuous layer of gas is formed<sup>1,3</sup>. The resistivity of the gas–electrolyte mixture on the cathode surface rises abruptly, while the current density remains practically constant regardless of the increasing voltage. When the latter attains a certain value, sparking takes place between the electrode and the electrolyte. The high temperature of the sparks causes then damage of the cathode tool and its insulation.

## EXPERIMENTAL

During electrochemical drilling, it is necessary to ensure that the current does not surpass the limiting value above which the sparking begins,  $I_s$ . Since this depends on hydrodynamic conditions, we measured the dependence of  $I_s$  on the Reynolds number  $Re$ , and this for four electrodes

\* See insert page 2792.

whose outer diameters (without insulation) were in the range 0.43–1.50 mm. The insulation was made either of alumina ceramics or inorganic enamel. The description of the electrodes is apparent from Table I and Fig. 4. The velocity of electrolyte flow was in the turbulent region ( $Re > 2\,300$ ), its upper limit was given by the maximum pressure of 10 MPa in the apparatus. Physical data about the electrolytes used are given in Table II; the temperature of the electrolyte at the inlet was 20°C. The method of work was the following. First the rate of flow of the electrolyte through the cathode was set as desired; the attainment of the stationary state was indicated by a record of the pressure in the apparatus. Then the electric current was switched on and the voltage was gradually raised. The instant when the sparks began to form on the cathode was determined visually in a damped light. The value of  $I_S$  was determined as the current which passed at a voltage lower by 1 V than that at which the sparking began. Two dependences of  $I_S$  on  $Re$  were measured for each electrode–electrolyte combination. The cathode was placed either in the bulk of the electrolyte (case  $\alpha$ ) or an insulating plate was placed at a distance 0.2 mm from the orifice perpendicular to the capillary axis (case  $\beta$ ), in which case the outflowing electrolyte was forced to change its direction abruptly. Since no dependence of the value of  $I_S$  on the character of flow near the capillary orifice was observed, the results for both cases  $\alpha$  and  $\beta$  were evaluated together. In total, 139 pairs of data (cases  $\alpha$  and  $\beta$ ) were measured for all electrode–electrolyte combinations; some of them are given in Table III.

## RESULTS AND DISCUSSION

In evaluating the measured data, we assume that the whole process is governed by heat transfer. Since the streaming was turbulent, we assume the validity of the

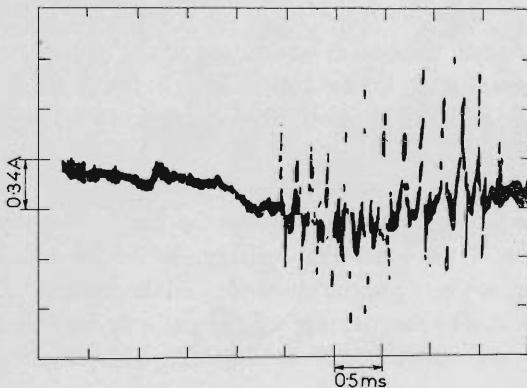


FIG. 3

Dependence of current on time of sparking. Vertical division corresponds to 0.34 A, horizontal division to 0.5 ms, sparking frequency 6–8 kHz

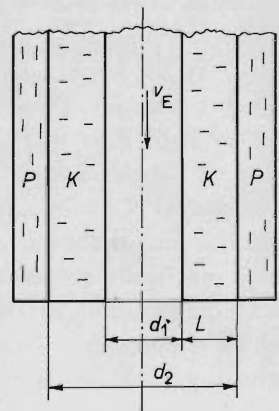


FIG. 4

Scheme of the cathode. K metal capillary, P insulation; arrow denotes direction of electrolyte flow

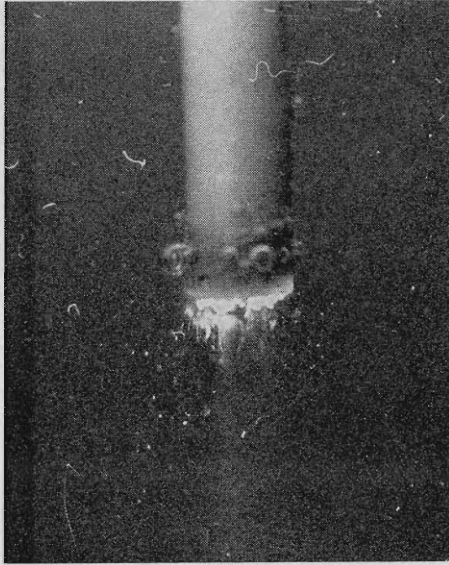


FIG. 1

Electric discharge on the cathode

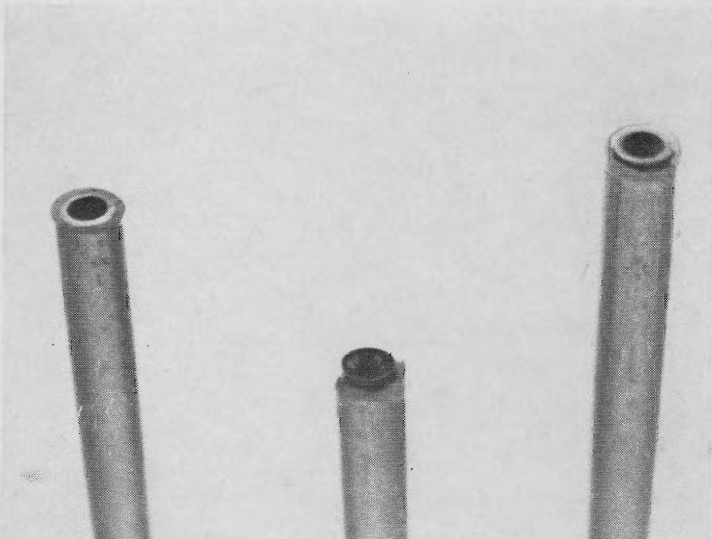


FIG. 2

Electrodes damaged by electric discharges in electrolyte. An electrode before use is shown on the right for comparison

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equation

$$Nu = Re^Q Pr^{0.4} (L/d_1)^P, \quad Re > 2300. \quad (1)$$

The Nusselt number is given as

$$Nu = qd_1/\lambda \Delta T, \quad (2)$$

where for the case of the formation of sparks we express the heat flow density as the formation of heat in a unit volume multiplied by the characteristic length,  $L$ :

$$q = i_S^2 L / \kappa. \quad (3)$$

Hence,

$$Nu = i_S^2 d_1 L / \kappa \lambda \Delta T. \quad (4)$$

TABLE I

Characteristics of electrodes used

Symbol	$d_1$ , mm	$d_2$ , mm	Insulation
A	1.07	1.50	enamel 0.06 mm
B	0.66	0.99	ceramics 0.3 mm
C	0.28	0.51	enamel 0.06 mm
D	0.21	0.43	ceramics 0.2 mm

TABLE II

Characteristics of electrolytes used (20°C)

Symbol	Composition	$\kappa$ $\Omega^{-1} \text{ m}^{-1}$	$\rho'_E$ $\text{kg/m}^3$	$\lambda$ W/m K	$\mu \cdot 10^3$ kg m s
1	15% NaNO <sub>3</sub> 20% NaClO <sub>3</sub>	18.0	1 329	0.550	1.60
2	25% NaCl	21.4	1 191	0.572	1.81
3	20% NaCl	19.6	1 148	0.578	1.58
4	15% NaCl	16.4	1 109	0.584	1.28
5	10% NaCl	12.1	1 071	0.590	1.14
6	5% NaCl	6.7	1 034	0.594	1.09

The limiting current density for sparking is defined as

$$i_s = 4I_s/\pi(d_2^2 - d_1^2). \quad (5)$$

The symbol  $d_1$  denotes the inner diameter of the cathode,  $d_2$  its outer diameter (without insulation). We set the value of  $L$  equal to

$$L = \frac{1}{2}(d_2 - d_1). \quad (6)$$

TABLE III

Measured and calculated limiting currents for sparking

Symbol <sup>a</sup>	Re	$I_{s,\alpha}$ A	$I_{s,\beta}$ A	$I_{s,c}$ A
A/3	3 926	1.39	1.52	1.43
	5 533	1.56	1.60	1.58
	7 079	1.62	1.64	1.69
	8 609	1.72	1.70	1.79
	10 125	1.80	1.78	1.88
	11 662	1.88	1.86	1.96
	13 198	1.93	1.96	2.03
	14 736	1.97	1.98	2.10
16 273	2.00	2.06	2.16	
B/4	4 707	1.01	0.94	0.92
	7 573	1.06	0.98	1.06
	10 673	1.18	1.07	1.17
	13 655	1.32	1.31	1.25
	16 607	1.42	1.40	1.33
	19 531	1.50	1.48	1.39
C/5	3 280	0.38	0.38	0.39
	4 484	0.39	0.42	0.42
	5 766	0.42	0.45	0.45
	7 017	0.43	0.45	0.48
	8 268	0.45	0.49	0.50
	9 520	0.46	0.50	0.53
	10 771	0.47	0.53	0.55
D/6	2 705	0.28	0.21	0.24
	4 430	0.35	0.23	0.27
	6 056	0.36	0.28	0.30
	7 786	0.38	0.29	0.32

<sup>a</sup> Symbols correspond to electrodes and electrolytes in Tables I and II.

The quantity  $\Delta T$  in Eq. (2) is the characteristic temperature difference related to the given phenomenon; in our case it is constant. This quantity involves also the change of the electrolytic conductivity  $\kappa$  with temperature and gas evolution in the boundary layer, as well as the change of other properties of the electrolyte with temperature. The Reynolds and Prandtl numbers in Eq. (1) are defined in the usual way as

$$Re = v_E d_1 \rho'_E / \mu, \quad Pr = c_{pE} \mu / \lambda. \quad (7), (8)$$

We denote  $\kappa$  the specific conductivity of the electrolyte,  $\lambda$  its heat conductivity,  $\rho'_E$  its density,  $\mu$  its dynamic viscosity, and  $c_{pE}$  its specific heat. All quantities refer to the temperature of the bulk of the electrolyte. Finally,  $v_E$  is the linear velocity of the electrolyte flowing through the cathode (the hollow needle). The measured data were correlated by Eq. (1). The exponents  $Q$ ,  $P$  and the characteristic temperature difference  $\Delta T$  are considered as unknowns, whose values were determined from 278 experiments by using the least squares method with Eq. (1) as follows:  $\Delta T = 88.3$  K,  $Q = 0.58$ ,  $P = -0.49$ . Hence, for  $Re > 2\,300$  we have

$$Nu = Re^{0.58} Pr^{0.4} (d_1/L)^{0.49}. \quad (9)$$

The calculated limiting currents for sparking,  $I_{s,c}$ , from Eq. (9) are given in Table III together with their relative errors. Accordingly, this equation gives the limiting current for sparking with an average error of  $\pm 9\%$ ; only 5% of the calculated data had a deviation larger than  $\pm 20\%$ , all combinations of electrolytes and electrodes under study being involved. It can be concluded that Eq. (9) is suitable for proposing the working conditions for electrochemical drilling of small holes.

#### LIST OF SYMBOLS

$c_{pE}$	specific heat of electrolyte, J/kg K
$d_1$	inner diameter of cathode, m
$d_2$	outer diameter of cathode without insulation, m
$i_s$	limiting current density for sparking, A/m <sup>2</sup>
$I_s$	limiting current for sparking, A
$L$	characteristic length, Eq. (6), m
$Nu$	Nusselt criterion, Eq. (4)
$P, Q$	exponents, Eq. (1)
$Pr$	Prandtl criterion, Eq. (8)
$q$	density of heat flow, W/m <sup>2</sup>
$Re$	Reynolds criterion, Eq. (7)
$\rho'_E$	electrolyte density, kg/m <sup>3</sup>
$\Delta T$	characteristic temperature difference, K
$v_E$	linear velocity of electrolyte flow through cathode, m/s
$\kappa$	specific conductivity of electrolyte, $\Omega^{-1} \text{ m}^{-1}$

$\lambda$  heat conductivity of electrolyte, W/m K

$\mu$  dynamic viscosity of electrolyte, kg/m s

Subscript  $\alpha$  refers to electrode in the bulk of the electrolyte,  $\beta$  to electrode in 0.2 mm distance from insulator plate,  $c$  to value calculated from Eq. (9).

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