Evaluating significance of relation between a material electroerosion resistance and electroerosive machining pulse energy

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Abstract. The paper presents results of research into dependence of electroerosion resistance on the energy of discharge impulses during electroerosive machining. A new criterion is proposed for evaluation of electroerosion resistance of materials. A direct dependence has been determined experimentally between the electroerosion resistance and the energy of discharge impulses. This relation is weak and close to linear. A mathematical model has been developed for this dependence. Scope of application is defined for the research results.

1 Introduction
It is known that tool-electrode wear during the electroerosive machining has a significance influence over precision of the machining. This wear depends on a multitude of factors: electrode material, electric machining modes, composition of inter-electrode fluid, process control system, presence and characteristics of process stabilization systems, etc. This paper is dedicated to the problem of accurately estimating the dependence of electroerosion resistance of a material on the energy of electric pulses supplied by the short-pulse generator to an inter-electrode gap [1-8].

2 Materials and methods
In practice, a degree of tool-electrode is evaluated by relative volumetric or weight wear (copying method), linear wear (piercing small-bore holes). However, when studying the physical nature of the wear process, it is more convenient to evaluate the electroerosion wear with a criterion:

\[ C = \frac{E}{V}, \]

where \( C \) is the electroerosion resistance, \( \text{J/mm}^3 \); \( E \) is the electric pulse energy, \( \text{J} \); \( V \) is the volume of the cavity, \( \text{mm}^3 \), resulting from the action of electric pulse with the energy of \( E \).

3 Research Results
It is easy to see that electroerosion resistance \( C \) under this criterion is numerically equal to the amount of electric pulse energy necessary to remove 1 \( \text{mm}^3 \) of tool-electrode material during the
electroerosive machining. It is evident that materials with higher electroerosion resistance require larger amounts of electrical pulse energy to remove the same volume of material.

Above we noted that among the factors influencing tool-electrode wear there are various electrical modes of operations, the most significant among them is the electrical pulse energy $E$. It is of practical and scientific interest to evaluate significance of relations between the pulse energy $E$ and electroerosion resistance $C$ of a tool-electrode material using the methods of mathematical statistics. To that end, we use the experimental data taken from [9], where a dependence of parameters (depth, diameter, volume) of isolated electroerosion holes in steel electrode (anode) on the electrical pulse energy when other parameters are constant (operating medium is kerosene, pulse generator type is $RC$). Table 1 shows the experimental data and results from calculating the electroerosion resistance of steel electrodes following the method stated above.

**Table 1.** Experimental data for parameters of isolated electroerosion holes and results of calculating electroerosion resistance of steel electrode for various discharge pulse energies

| No. of experiment | Discharge pulse energy, $E$, J | Hole depth, $H$, mm | Hole diameter, $d$, mm | Hole volume, $V$, $mm^3$ | Electroerosion resistance, $C$, J/mm$^3$ |
|-------------------|-------------------------------|--------------------|------------------------|--------------------------|---------------------------------|
| 1                 | 0.001                         | 0.015              | 0.1                    | 0.0000788                | 12.69                           |
| 2                 | 0.004                         | 0.018              | 0.15                   | 0.000218                 | 18.35                           |
| 3                 | 0.008                         | 0.020              | 0.22                   | 0.000507                 | 15.78                           |
| 4                 | 0.03                          | 0.022              | 0.45                   | 0.002325                 | 12.90                           |
| 5                 | 0.1                           | 0.025              | 0.75                   | 0.007360                 | 13.59                           |
| 6                 | 0.2                           | 0.028              | 0.95                   | 0.01322                  | 15.13                           |
| 7                 | 0.4                           | 0.033              | 1.20                   | 0.0249                   | 16.06                           |
| 8                 | 0.6                           | 0.037              | 1.40                   | 0.0379                   | 15.83                           |
| 9                 | 0.8                           | 0.040              | 1.55                   | 0.0505                   | 15.84                           |
| 10                | 1.0                           | 0.042              | 1.65                   | 0.0598                   | 16.72                           |
| 11                | 2.0                           | 0.050              | 2.00                   | 0.1046                   | 19.12                           |

Let us statistically assess the significance of relation between the electroerosion resistance $C$ and the pulse energy $E$ in the conditions of the above experiment. The strength of relationship between $C$ and $E$ is determined through a paired correlation coefficient $k$:

$$k = \frac{n \cdot \sum E \cdot C - \sum E \cdot \sum C}{\sqrt{n \cdot \sum E^2 - (\sum E)^2} \cdot \sqrt{n \cdot \sum C^2 - (\sum C)^2}}.$$

(2)

In order to calculate the value of $k$, let us construct a supporting Table 2.

**Table 2.** Supporting table for calculation of the coefficient $k$

| Experiment number | $E$, J | $C$, J/mm$^3$ | $E/C$ | $E^2$ | $C^2$ |
|-------------------|--------|--------------|-------|-------|-------|
| 1                 | 0.001  | 12.69        | 0.01269 | 0.000001 | 161.0361 |
| 2                 | 0.004  | 18.35        | 0.0734  | 0.000016 | 336.7225 |
| 3                 | 0.008  | 15.78        | 0.12624 | 0.000064 | 249.0084 |
| 4                 | 0.03   | 12.90        | 0.387   | 0.0009  | 166.41 |
| 5                 | 0.1    | 13.59        | 1.359   | 0.01    | 184.6881 |
| 6                 | 0.2    | 15.13        | 3.026   | 0.04    | 228.9169 |
| 7                 | 0.4    | 16.06        | 6.424   | 0.16    | 257.9236 |
| 8                 | 0.6    | 15.83        | 9.498   | 0.36    | 250.5889 |
| 9                 | 0.8    | 15.84        | 12.672  | 0.64    | 250.9056 |
| 10                | 1.0    | 16.72        | 16.72   | 1.0     | 279.5584 |
| 11                | 2.0    | 19.12        | 38.24   | 4.0     | 365.5574 |
| Σ                 | 5.143  | 172.01       | 88.538  | 6.211   | 2731.316 |
Then,
\[ k = \frac{11.88.538 - 5.143 \cdot 172.01}{\sqrt{11 \cdot 6.211 - 5.143^2 \cdot \sqrt{11 \cdot 2731.316 - 172.01^2}}} = 0.645354. \]

As the coefficient \( k > 0 \), then the relation between \( C \) and \( E \) is direct. When \( 1 > |k| > 0 \), the relation may be significant or insignificant. To assess significance, we calculate Student’s \( t \)-test value:
\[ t_p = \frac{k \cdot \sqrt{n} - 2}{\sqrt{1 - k^2}} = \frac{0.645 \cdot \sqrt{11} - 2}{\sqrt{1 - 0.645^2}} = 2.5345, \]
where \( n \) is the number of experiment attempts, \( n = 11 \).

The obtained calculated value \( t_p \) is compared against the tabulated \( t_r \), defined for the number of degrees of freedom \( f = n - 2 = 11 - 2 = 9 \) and confidence coefficient \( P_g = 0.95 \). We get \( t_r = 2.26 \) [10].

It is evident that the correlation between \( C \) and \( E \) is at the limit of significance: for the confidence coefficient of 0.95 it is significant (\( t_p = 2.53 > t_r = 2.26 \)), but for the confidence coefficient of 0.97 it is insignificant (\( t_p = 2.53 < t_r = 2.62 \)).

Dependence \( C = f(E) \) was modeled with a linear approximation and a least square method:
\[ C = a \cdot E + b, \]
where coefficients \( a \) and \( b \) are:
\[ a = \frac{n \cdot \sum E \cdot C - \sum E \cdot \sum C}{n \cdot \sum E^2 - (\sum E)^2} = 2.132, \]
\[ b = \frac{1}{n} \left( \sum C - a \cdot \sum E \right) = 14.64. \]

From that we get \( C = 2.132 \cdot E + 14.64 \).

Table 3 shows calculated and experimental values of electroerosion resistance, while Figure 1 shows superimposed graphs of calculated and experimental values \( C = f(E) \).

| Table 3. Calculated and experimental values of electroerosion resistance for various pulse energies |
|-----------------------------------------------------|
| The nature of \( C \) | Electroerosion resistance \((J/mm^3)\) at the pulse energy of \( E \) (J) |
|------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Calculated             | 14.64               | 14.65               | 14.66               | 14.70               | 14.85               | 15.07               | 15.49               | 15.92               | 16.35               | 16.77               | 18.90               |
| Experimental           | 12.69               | 18.35               | 15.78               | 12.90               | 13.59               | 15.13               | 16.06               | 15.83               | 15.84               | 16.72               | 19.12               |

**Conclusions**

1. For given conditions of the experiment (steel anode, kerosene as a working medium), electroerosion resistance insignificantly increases with increasing discharge pulse energy. Statistically, the dependence is significant at a confidence coefficient of 95% or less, but at a confidence coefficient of 97% it loses its significance. It is evident from simple calculations: when pulse energy is increased from 0.001 J to 2 J (by a factor of 2000), the electroerosion resistance is increasing only by a factor of 1.5. This fact shall be taken into account in further studies.

2. Dependence of electroerosion resistance of material on pulse energy is close to linear for pulse energies of \( E > 0.2 \) J. At \( E < 0.2 \) J there is a high dispersion in experimental data (Figure 1), evidently related to a high measurement error for volume of isolated electroerosion microscopic holes.
3. For the given conditions (steel anode, kerosene as a working medium), it is preferable to use larger energies in electroerosive machining, however, it limits process optimization as it increases the surface finish (roughness).

![Graph showing material electroerosion resistance](image_url)

**Figure 1.** Calculated and experimental graphs showing dependence of a material electroerosion resistance \( C \) on the discharge pulse energy \( E \): 1 is a calculated linear model \( C = f(E) \); 2 is an experimental curve \( C = f(E) \)

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