# Micro EDM process modelling and process Capability

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***Моделиране и възможности на микро-електро-ерозийния процес**: Статията поставя основите на аналитичното моделиране на микро-електро-ерозионния процес. Съществено променените условия на ерозионния процес предполагат и промяна на същността на процеса. Той вече не е на базата на разтопяването на метала и разликата в наляганията, предизвикващи изхвърлянето му в диелектрика, а се основава на частичното локално изпаряване на метала. Аналитичното решаване на задачата води до провеждане на експерименти с метали с висока чистота. В резултат на извършения статистически анализ в статиаята е направено и заключение за полето на разсейване, което може да се очаква от този процес.*

***Ключови думи**: микро-електро-ерозиен процес, износване на електрод, точност, възможности на процеса.*

## 1. Introduction

In Micro Electrical Discharge Machining for the production of 3D cavities, the use of EDM milling technology, employing simple-shape electrodes is the preferred strategy, compared to the traditional die sinking methods. However, because of the physical size of the features, the accuracy required for the methods used in micro EDM milling, wear compensation is much higher. The electrodes wear adversely [1] affecting the accuracy of the machined micro features and causing distortion of the original electrode shape. Electrode shape deformation and especially its random variations together with the volumetric wear ratio are the two main factors affecting the applicability of wear compensation methods. This paper studies some specific examples of the electrode wear during the micro EDM process and the effect of the electrode wear on the accuracy of the machined surfaces. Many electrode wear compensation methods have been studied and applied more or less successfully in research laboratories [2], however their introduction into an industrial manufacturing environment is not easily implemented. In addition the modelling tasks of the EDM process may change when very quick and very low energy sparks are involved which is the case of micro EDM process.

## 2. Assumptions and relative wear ratio modelling in micro EDM

For the modelling purpose it is assumed that the spark pulses are as shown in the figure 1. Time for the discharge pulse is one of the most crucial parameters in the process. For the micro EDM process is used as the main control parameter for the spark energy [3].

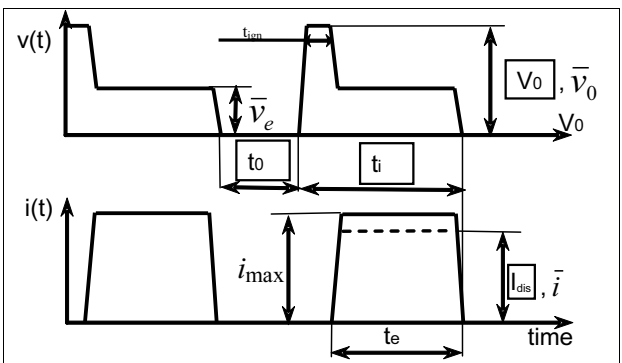


Figure 1 Voltage current assumption for the modelling

Control over the discharge current and voltage is limited as they are dependant on other process parameters such as dielectric strength, material properties etc. Typically in micro EDM, discharge times of 1μs or less are applied [3]. Most of the EDM process models regard the material removal as a combination of melting and vaporization, where the volume of material that has been removed through melting is much larger than the volume of material that has been removed through vaporisation. Verification of these models 'suffer' big discrepancies especially in the low

energy sparks with very quick discharge times. The assumption in this paper is that with low energy sparks and quick discharge times there is negligible amount of molten material and the majority of the spark energy goes for the vaporization of the material. Therefore the energy of the discharge is given by equation (1) where: $t_e$ is the time of the discharge, *Ve* is the discharge voltage and $I_{dis}$ is the discharge current. The total discharge energy of the spark is divided into 3 sections [3]. Part of it goes to the anode, part of it goes to the cathode and part of it goes to the dielectric [4] (2). The energies that go to the anode and the cathode melt and mainly vaporise small volumes from the electrodes.

$$E_{dis} = \int_0^{t_e} I_{dis}(t) V_e(t) dt \qquad (1)$$

$$E_{dis} = E_{dis}^{anode} + E_{dis}^{cathode} + E_{dis}^{dial} \qquad (2)$$

The logical assumption made in this paper is that the volumes removed from the electrodes are proportional to the share of the energy going to the relevant electrode.

$$V_{dis}^{anode} = K_1 E_{dis}^{anode} \qquad V_{dis}^{cathode} = K_2 E_{dis}^{cathode} \qquad (3)$$

The Volumetric wear ratio (ν) for a predetermined time period is the ratio of the volumes removed from both electrodes.

$$\nu = \frac{V_{total}^{anode}}{V_{total}^{cathode}} = \frac{K_1 E_{total}^{anode}}{K_2 E_{total}^{cathode}} \qquad (4)$$

The minimum energy required to melt and vaporise one unit of mass is given by the enthalpy of melting and vaporisation (9 and 10)

Enthalpy of melting and vaporization:

$$H_m = \int_{T_0}^{T_m} c_p dT + L_m^e \quad \text{and} \quad H_V = \int_{T_0}^{T_m} c_p dT + L_m + \int_{T_m}^{T_v} c_p dT + L_V \qquad (5)$$

Where: $c_p$ is the specific heat capacity (J/kg °C); $L_m$ and LV are the latent heats for melting and vaporization (J/kg); $T_0$ initial temperature (°C); $T_m$ melting temperature (°C); $T_v$ temperature of vaporization (°C).

The energy required to melt ($E_m$) and to vaporize ($E_v$) certain amount of material (mass) will be: $E_m = mH_m$, $E_V = mH_V$. The vaporized mass can be expressed by the total vaporized volume and the density of the material ρ (kg/m$^3$), $m = V_{total}\rho$.

The relative wear ratio (ν), for this period of time will be given by the ratio of the vaporized volumes. Therefore from equations (6) follows:

$$\nu = \frac{V_{total}^{anode}}{V_{total}^{cathode}} = \frac{E_{vap}^{anode}}{E_{vap}^{cathode}} * \frac{\rho^{cathode} H_V^{cathode}}{\rho^{anode} H_V^{anode}} \qquad (6)$$

Based on equation 6 and considering equation 4, the proportionality coefficients $K_1$ and $K_2$ can be determined.

$$\rho^{anode} H_V^{anode} \approx const = K_2 \qquad \rho^{cathode} H_V^{cathode} \approx const = K_1 \qquad (7)$$

In the case of electrode material and workpiece material being the same, from equation 6 follows that the wear ratio will be proportional only to the energy distribution between the anode and the cathode. Still from this model is not clear whether the energy distribution further depends on the material being used as electrodes. This paper further investigates the behaviour of pre-selected pure metals in order to study the wear ratios, variations of the wear ratios and make conclusions about the process capabilities.

### 3. Experimental set-up

A number of electrode materials were selected in order to investigate the energy distribution ratio (6) and the effect of the electrode material on the electrode wear ratio and its variation. The following materials, with purity equal or higher that 99.95%, were

selected: Titanium (Ti), Cobalt (Co), Copper (Cu), Silver (Ag), Gold (Au) and Tungsten (W). All electrode materials were in the shape of ∅1mm wire. To block the cross material influence on the process and following the findings in equation 6, the experiments were conducted using the same electrode material for the anode and the cathode. The set up of the machine was selected to deliver the minimum discharge energy per pulse to the spark gap. On the basis of Masuzawa [4], this condition is sufficient to place this investigation in the domain of micro-manufacturing. The detailed generator set up is summarised in Table 1.The dielectric used in this experiment was a commercially available, purpose designed hydrocarbon with the main physical properties shown in Table 2.

Table 1 Set up parameters of the EDM generator

| Parameter, symbol | Unit, symbol | Value |
|---|---|---|
| Open circuit voltage, V0 | Volt, V | 80 |
| Average current from the generator, I | Ampere, A | 0.5 |
| Duration of the pulse of voltage at V0, T-on | microsecond, μs | 1 |
| Programmed time interval between adjacent pulses of voltage, T-off | microsecond, μs | 1 |
| Reference voltage of the servo system | Volts, V | 50 |

Table 2 Main physical properties of the hydrocarbon dielectric

| Parameter, symbol | Unit, symbol | Value |
|---|---|---|
| Density at 15 °C, ρ | Grams over cubic centimetres, g/cm3 | 0.765 |
| Kinematic viscosity at 20 °C, v | Centistokes, cSt | 1.8 |
| Flash point °C (Pensky-Martens close cup), fp | Degree Celsius, °C | 63 |
| Aromatic content, ac | Per cent in weight,% | 0.003 |
| Disruptive voltage kV at 2.5mm | Kilovolts, kV | 58 |

Although the most appealing measurement of wear ratio for manufacturing purposes should be based on volumes, the complexity of the measuring task led to an alternative method of assessment being used, which calculated the wear ratio by the measurement of mass (weight). Both the cathode and anode electrodes were weighted before and after electric discharge machining. The ratio of mass removed from the anode and cathode by the machining was measured. The weighting system was an analytical balance with a capacity (maximum measurable mass) of 210 g. and readability (resolution) of 0.1 mg. The weighting procedure was carried out in clean room condition of class 6. [5]. A control chart for the standard deviation ([6], pp 211-221) was designed. On the one hand, this resulted in a quantitative assessment of the variability of the measuring system employed in this investigation and on the other hand, the availability of control chart data made provision for an estimation of the capability of the measuring system itself, which is a pre-requisite for the subsequent analysis of the variability of the wear ratio. [7].

**4. Results**

A dedicated R package for statistical process control was employed [9]. The variability of the weighting system was quantitative assessed [8] All the values of standard deviation obtained are therefore been considered as originated by the same process. Consequently, the unknown variance of the weighting variability, $\sigma^2$, was estimated by pooling together all the available sample information (148 samples).

$$\hat{\sigma}^2_{\text{balance}} = \overline{S}^2 = \frac{(n_i - 1)\cdot S_i^2}{\sum_{i=1}^{m}(n_i - 1)} = 0.006643\ mg^2 \qquad \hat{\sigma}_{balance} = 0.08151\ mg \tag{8}$$

Each of the six sample metals were machined six times. Therefore 36 measurements of wear ratio were obtained. The results are displayed in the notched box plots [10] of Figure 2. This figure supports qualitatively the idea that the wear ratio for the different

materials is different. In particular, the medians of the wear ratio data for each metal appear, to be significantly to one another. However the same figure induces the suspicion that the probability density function of the wear ratio is asymmetrical around the median and this is strongest for Ag and W. Two of the measurements of wear ratio 1.257 and 3.609 for Co and Cu, respectively, show a condition of remoteness from the other homologous data. A search for potential contaminating effects that might have been causing such deviation was carried out and no evident reason causing this remoteness was identified. In fact, the median calculation is extremely insensitive to the removal of remote values ([11] page 126,127).

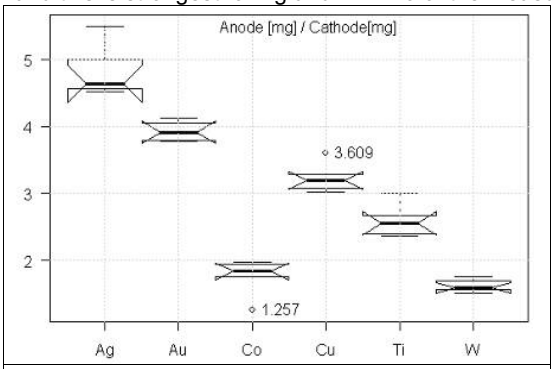

Fig. 2 Wear ratio in mass (anode/cathode removal).

The potential effect of the materials on the variability of the wear ratios has been tested by using the modification of the Levene's test [12] that uses the medians to centre the variables and where the p value has been computed on the basis of the Fisher's distribution. The simulation studies showed that the significance level of Levene's test is below its nominal value, especially for small sample sizes. This means that the I type error is smaller than the nominal. The calculated p value is equal to 62.63%. It is therefore not possible to reject the hypothesis of equal dispersions of the wear ratios. In this case the experimental evidence supports the fact that the variability of the wear ratio does not depend on the metals eroded in this study.

Following the above findings, a more stable (reliable) estimation of the spread of the wear ratio is obtained by aggregating all the experimental results:

$$\hat{\sigma}^2_{total} = S^2_{total} = \frac{\sum_{i=1}^{6} \cdot S_i^2}{6} = 0.05634 \qquad (9)$$

In reality, equation (9) represents an estimate of the variance, $\sigma^2_{total}$, resulting by both the EDM manufacturing process, $\sigma^2_{EDM}$, and by the mass measurement process, $\sigma^2_{balance}$ where the two processes are completely separated. There is no apparent reason for suspecting a correlation between them. They are therefore assumed independent. Moreover, from equation (8) and (9), it is noticed that the variability of the measuring system is about one order of magnitude smaller than the overall variability. Hence, it is qualitatively argued that the measuring process utilised appears suitable for the performed measuring task.

$$\sigma^2_{total} = \sigma^2_{EDM} + \sigma^2_{balance} \qquad (10)$$

Assuming that the estimate $\hat{\sigma}^2_{balance}$ derived from equation (8) is so close to the unknown parameter $\sigma^2_{balance}$ that they can be considered equal. Then from equation (10) it results in:

$$\hat{\sigma}^2_{EDM} = \hat{\sigma}^2_{total} - \hat{\sigma}^2_{balance} = 0.05634 - (0.08151)^2 = 0.04970\,\mathrm{mg}^2 \qquad (11)$$

$$\hat{\sigma}_{EDM} = \sqrt{\hat{\sigma}^2_{total} - \hat{\sigma}^2_{balance}} = 0.2230\,mg \qquad (12)$$

Equation 12 gives the process capability for micro EDM in mass and based on this and specific material density, it is possible to calculate for practical purposes the dimensional error caused by this process.

## 5. Conclusions

Understanding of the electrode wear process and influencing factors is the key to more accurate and reliable micro EDM. The above investigation shows that variations of the wear ratio in micro EDM due to uncontrolled factors are not negligible and that the energy distribution between the anode and cathode further depends on the material. The equal wear ratio variability for the different materials shows that the material removal phenomenon was the same for all the materials and is the key to the ultimate process capabilities. The above does not justify the use of compensation methods relying on the wear ratio staying fixed. Any electrode wear compensation method should allow for machining tolerances due to the variation of the volumetric wear ratio. When using any new combination of electrode/workpiece materials, tests should be done on the machine to measure the wear ratio and assess its repeatability. The results should be used to justify the chosen compensation method and enable the production of more accurate micro parts.

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**Докладът е рецензиран.**