THE EFFECT OF POLARITY STUDIED BY FINITE ELEMENT METHOD AT ULTRASONIC AIDED MICRO-ELECTRODISCHARGE MACHINING

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Abstract: The paper deals with the influence of polarity effect on technological performances at microelectrodischarge machining aided by ultrasonic longitudinal vibrations of electrode-tool (µEDM+US) through Finite Element Method (FEM). A comparison is made between the volume of material removed with positive polarity (by commanded pulses) and negative polarity (by relaxation pulses) and their effect on removal rate at classic µEDM and µEDM-US. In order to take advantage of bubbles collective implosion from frontal working gap ultrasonically induced, some technological recommendations are elaborated.

Keywords: electrodischARGE micromachining, ultrasonics, effect of polarity.

1. INTRODUCTION

The requested technological parameters in terms of machining rate, volumetric relative wear and roughness of machined surface can be attained at microelectrodischarge machining (µEDM) only if the effect of polarity is taken into account.

Several models of EDM material removal process approached this topic. One of the most known, Van Dijck’s model [1], was confirmed much later by experimental data provided by ultra speed cameras with more than 10⁶ frames/s of Schulze et al. [2], which allowed the observation of phenomena occurring at micrometric scale in the working gap.

On this basis, considering the assignment of power level at anode and cathode, it is useful to work with positive polarity, the electrode-tool as anode, when relative long pulses are applied. In this case, the commanded pulses (static pulse duration) are more appropriate, having pulse time greater than 1 µs. On the contrary, when working with relative short pulse duration lower than 1 µs, it is useful to have negative polarity, i.e. the electrode-tool is the cathode. In this case, the relaxation pulses are more suitable.

At µEDM aided by longitudinal ultrasonic oscillations of electrode-tool (µEDM +US), it is important to correlate the effect of polarity with elongation of the tool during an oscillation period in order to attain the requested technological parameters. Therefore the two cases of positive and negative polarity working modes will be approached in respect with the moment of collective implosion of the bubbles from the frontal working gap, which is produced at the end of an oscillation period after stretching semiperiod [3].

2. PHENOMENOLOGY

The assignment of power at anode and cathode can be described through the following model [1]. Thus the power dissipated on cathode surface \( P_c \) can be determined using the relation:

\[
P_c = i_c (U_c + U_{ion} - \Phi) - i_c \Phi \ [W]
\]

where: \( i_c \) is ionic current [A]; \( i_{ion} \) – electronic current [A]; \( U_c \) – potential fall at cathode [V]; \( U_{ion} \) – ionization potential of positive ions [V]; \( \Phi \) – extracting tension corresponding to cathode metal [V]; \( (i_c)\Phi \) - factor contributing to cathode cooling due to electronic emission [W].

The power dissipated at anode \( P_a \) can be determined from the following relation:

\[
P_a = P_{tot} - P_c - P_{col} \ [W]
\]

where \( P_{tot} \) is the power corresponding to a discharge, respectively.
\[ P_{\text{tot}} = \frac{W_e}{t_i} \quad \text{[W]} \quad (3) \]

where \( W_e \) is discharge energy [J]; \( P_{\text{col}} \) – power dissipated in plasma channel [W], estimated lower than 1% \( P_{\text{tot}} \); \( t_i \) - pulse time [s].

Taking into account the relations (1-3), fig.1.a presents a qualitative synthesis of EDM working parameters, which determines the anode/cathode distribution power, depending on polarity effect, explained in terms of current density \( J \). The curves of \( P_a/P_c \) and \( i_c^-/i_c^+ \) ratios depend on EDM spot temperature, which is strongly related to material boiling temperature as it will be presented below.

At small pulse time, the plasma channel has not sufficient time to develop and current density \( J \) is high, because electric loads are dissipated on small transversal area.

Therefore electronic current \( i_c^- \) is dominant, and the cooling factor \( (i_c^- \Phi) \) decreases the cathode power \( P_c \) and increases the anode power \( P_a \), according to relations (1), (2).

Thus, ratios \( i_c^-/i_c^+ \) and \( P_a/P_c \) grow. When working with negative polarity, the electrode tool being the cathode, the result is that electrode wear decreases (its power being low) and removal rate at workpiece increases (its power being high).

At high pulse time, the current density lowers due to plasma channel development, and consequently the relative weight of ionic current against to electronic one grows. This determines increase of \( P_c \) due to \( i_c^+ \) grow (relation (1)), and decrease of \( P_a \).

When working with positive polarity (tool as anode) the removal rate to workpiece (cathode) increases and also volumetric relative wear decreases.

Nevertheless, \( V_w \) and \( \vartheta \) are strongly influenced by other working parameters, mainly pause time \( t_o \) flushing pressure, thermal physical properties of material couple (anode/cathode), carbon deposition on surface tool etc. [4].

The considerations from above are extended to specific phenomenology governing \( \mu \)EDM-US material removal process. From fig.1.b, it can be observed that certain polarity and pulse time values are appropriate to each ultrasonic semiperiod in order to improve \( V_w \) and \( \vartheta \). Technologically is very difficult to deliver different types of pulse in each semiperiod. Nevertheless, the commadned pulses are easier to be controlled but both types provide specific advantages.

The semiperiods have high influence on \( \mu \)EDM-US process, having different capillary phenomena within the frontal gap.

In the first semiperiod, when the pressure from the gap is positive, liquid compression is produced. In the second one, when \( p_{ht} \) pressure becomes negative, liquid stretching occurs. Total hydrostatic pressure \( (p_{ht}) \) depends on elongation \( (\gamma) \) through acoustic pressure \( (p_{ac}) \), which is determined by ultrasonic oscillations and working liquid characteristics [5].

Cumulative microjets are produced, developing pressure of MPa order in the end of stretching semiperiod. All bubbles from the gap collapse, generating shock waves parallel to machined surface [6]. Thus, roughness decrease could be explained.
Hence micropeaks having lower shear resistance are removed even in solid state, in agreement with FEM and experimental data.

Comparing to classic EDM, at US aiding, the bubble surrounding plasma channel has short life, until the final of an oscillation period (no more than 50 μs at ultrasonic frequency of 20 kHz). So the cumulative microjets remove more material melted by discharge and the margins of microcraters with low shear resistance due to high pressure developed by US; thus $V_W$ is much increased and machined roughness is decreased [5].

The high pressure of dielectric liquid because of liquid compression from the first semiperiod stops the plasma channel development. Consequently, $J$ density and $P_d/P_c$ ratio are increased. Taking account of polarity effect, negative polarity together with small time pulses are recommended in order to increase machining rate (anode power) and decrease electrode wear (cathode power) (fig.1).

The stretching semiperiod is favourable to plasma channel development because the pressure from frontal gap decreases. According to polarity effect, when current density $J$ lowers, the $P_d/P_c$ ratio also decreases. Hence, it is useful to work with positive polarity, in order to maximize the power to workpiece, which is the cathode in this case. Thus, the polarity effect helps to increase machining rate and decrease electrode wear (fig.1).

Obviously, the commanded pulses are recommended to be used because they could be controlled in terms of pulse durations and be delivered within stretching semiperiod synchronized with tool oscillations. A condition of optimization in case of both types of pulse is to maximize the number of discharges within an oscillation period in order to take advantage of cumulative microjets stage [7].

3. EXPERIMENTAL DATA

Some reference experimental data for FEM modelling validation - obtained when machining X210Cr12, tool steel, on Romanian ELER 01 machine with current step $I = 0.8A$, commanded pulse time with $t_l = 12μs$, pause time $t_p = 6μs$, positive polarity - were presented in [8]. It can be noticed that machining rate increase is more apparent at longer pulse time (more than 12 μs) and $R_a$ roughness decrease is more visible at shorter pulse time (lower than 12 μs).

Concerning relaxation pulses, other technological parameters values for machining rate, volumetric relative wear and surface roughness are presented in fig.2:

![Figure 2](image_url)

**Fig.2. Technological parameters improved by ultrasonic aided EDM.**

Analyzing the parameters from fig.2, it can be noticed that the major improvement induced by ultrasonic aiding is more apparent at higher discharge energies, i.e. higher capacity steps.

A comparison between the crater dimensions obtained with commanded pulses and relaxation pulses in both cases of classic $μ$EDM and $μ$EDM+US is presented in table 1 and 2. This also represents the referential in order to validate the FEM modelling.
Table 1. Craters mean dimensions at commanded pulses obtained on Romanian ELER 01 ED Machine with current step I=0.8A, pulse time t_i=12 μs, pause time t_0=6 μs, consumed power to supply the acoustic chain P_{cUS}=100W.

<table>
<thead>
<tr>
<th>Machining</th>
<th>EDM</th>
<th>EDM+US</th>
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<tbody>
<tr>
<td></td>
<td>3.6</td>
<td>4</td>
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Table 2. Craters mean dimensions at relaxation pulses – obtained on Romanian ELER 01 ED Machine with capacity step C=1, supply current step I_s=1, consumed power to actuate the acoustic chain P_{cUS}=70W.

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<tr>
<td></td>
<td>2</td>
<td>8.5</td>
<td>1.6</td>
<td>6.5</td>
</tr>
</tbody>
</table>

As it can be observed, the craters resulted when working with relaxation pulses are more flat and the ultrasonic aiding can remove crater margins decreasing their depths and diameters.

3. FEM MODELLING

FEM modelling of material removal process using commanded and relaxation pulses was achieved in order to emphasize the polarity effect at μEDM and μEDM+US.

Aiming at computational resource saving, 2D geometry was created due to the symmetry of approached phenomena (fig.3). The workpiece was 10 mm width square; it could be noticed that these dimensions order have no influence on FEM results [8]. The EDM spot was applied on initial surface with craters produced by previous discharges. Major errors are produced in terms of crater dimension modelling when initial surface is plane [9].

In case of commanded pulses simulation, the EDM spot was applied on the symmetry axis of microgeometry, comprising two adjacent previous craters of 3.6 μm depth, on the interval x=[-7.25;7.25] μm, points PT3, PT4 (fig.3). The geometry also includes the resolidified material on crater border as semicircles of 0.5 μm diameter, PT1, PT2 - due to difficult evacuation from a deep molten volume, specific to commanded pulse [3].

The extension of gas bubble of 0.2 mm diameter formed around plasma channel was defined by PT5 and PT6 points, placed on the superior surface of the workpiece.

For relaxation pulses simulation, another 2D geometry was created (fig.4). The EDM spot was applied on the axis of microgeometry formed by two previous flat craters of 2μm depth produced by relaxation pulses defined by the points PT2, PT3, PT4, placed on the interval x=[-16;16] μm. The margins of the craters have lower shear resistance (PT4) than in case of commanded pulse, no material being resolidified on them as the evacuation of molten material is easier from a flat crater. The margins of the gas bubble around the plasma channel have the same dimensions as in previous case, defined by the points PT1, PT5.

Meshing was based on Lagrange-T_2J, triangular elements. A finer meshing in the zone adjacent to EDM spot was applied within the volume thermally affected by discharge. Aiming at computational resource saving, the meshing was ordinary on the rest of workpiece volume without influencing the results.

Thermal properties of X210Cr12 (D3 DIN) were loaded from Comsol Multiphysics library as temperature dependent, increasing the precision of FEM results.

For boundary settings, in case of commanded pulse, the anodic EDM spot was
placed on a radius of $R_{\text{spot}}=3.5\ \mu\text{m}$ at 3473K taking into account the assumption that during the pulse time the melted material is overheated above boiling temperature (around 3000 °C at steel) with 200°C due to increased pressure produced by plasma channel [6]. Similarly, the cathodic EDM spot radius in case of relaxation pulse was $R_{\text{spot}}=8\ \mu\text{m}$. Thus, the following FEM results sustain Conn’s Hypothesis of plasma channel narrowing in the cathodic zone [1]. The adjacent zones to EDM spot were considered as insulated due to gas bubble influence. The rest of boundaries belonging to workpiece were set at dielectric liquid temperature, which usually is 313 K.

The position of boiling temperature (the bottom of fig.5) obtained after 12 μs commanded pulse is in agreement with experimental data (table1, classic μEDM).

![Fig.5. Temperature distribution after 12 μs commanded pulse, positive polarity](image)

After 0.8 μs relaxation pulse, the position of boiling isothermal is presented in fig.6. Its radius and depth are in accord with crater dimensions from classic μEDM (table 2). In both cases, the FEM results confirmed that boiling is the main mechanism of material removal at classic μEDM.

The experimental results for commanded pulses and relaxation pulses indicated that ultrasonic aiding greater improvement of technological parameters occurs for longer pulse time since the probability increases that discharges are located closer to cumulative microjets stage on time axis (fig.1.b).

This is confirmed by FEM results since the process of resolidification of molten material is very fast under 2 μs after pulse end [8]. At μEDM+US, the machining rate could be increased by thermal removal mechanism (1683K melting isothermal for X210Cr12 is located close to EDM spot) if the pulse time is overlapped on the cumulative microjets stage, phenomenon more probable to occur at longer pulse time.

![Fig.6. Temperature distribution after 0.8 μs relaxation pulse, negative polarity](image)

Taking into account the considerations from above, the most reliable mechanism that could explain the technological improvement provided by experimental data is the one of removing the margins of the craters by high pressure created through collective implosion of the bubbles from the gap. Stagnation pressure produced by cumulative microjets stage could lead to values of 10 MPa order during less than 1 μs [6].

![Fig.7. Von Mises stresses [Pa] distribution within crater margins](image)

Experimentally, the consumed power to actuate the acoustic chain at using of commanded pulses was 100W, greater than
in case of relaxation pulses of only 70 W (fig.2). This is explained by the fact that craters margins produced by commanded pulses (fig.3) are harder to be removed.

In order to study the US effect on removal mechanism, thermal transient analysis was coupled with mechanical homologous one, having temperature \( T \) as common variable and using same triangular elements.

As boundary conditions, follower load of 14 MPa (greater than in relaxation pulses case) was applied on the craters profile on \( x \) direction because US shock waves are oriented parallel to machined surface [6]. Fixed constraints were applied on lateral and inferior sides of workpiece, according to workpiece clamping [9].

The depth of volume removed by US shock waves was more than 2 \( \mu \)m (fig.7). X210Cr12 austenitized and tempered to hardness of 50 HRC had ultimate tensile strength of 1500 MPa [10]. Thus, the depth of crater could be reduced to more than 1.6 \( \mu \)m and its radius to 3 \( \mu \)m, close to experimental data from table 1. Our experimental data proved that roughness (\( R_b \)) of machined surface at EDM+US can be decreased with up to 50% compared to classic EDM if acoustic pressure (\( P_{ac} \)) is minimized. This could validate the FEM results. Nevertheless, \( P_{ac} \) must be higher than cavitation threshold. Nevertheless, optimum power to actuate US chain must be experimentally found for each machining type. However, only when craters overlap is achieved (enough EDM time), i.e. crater margins having low width, ultrasonic removal becomes effective [9].

4. CONCLUSIONS

FEM modelling applied in case of \( \mu \)EDM and \( \mu \)EDM+US validated by experimental data concerning the dimensions of craters produced by commanded and relaxation pulses demonstrated that effect of polarity on removal mechanism is essential. Thus, in order to ultrasonically improve technological parameters - machining rate, volumetric relative wear and surface roughness – comparing to classic \( \mu \)EDM, in case of positive polarity (commanded pulses), it is useful to have longer pulse time located on time axis closer to cumulative microjets stage or overlapped on it. In case of negative polarity (relaxation pulses), the maximization of discharges number within an oscillation period could potentiate the ultrasonic removal of crater margins. The pressure to actuate the acoustic chain needs to be lower with 30% than in case of machining with commanded pulses. FEM results also led to some clarifications of some previous hypotheses addressing phenomenology and material removal mechanism at \( \mu \)EDM and \( \mu \)EDM+US.

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REFERENCES


