SOME ASPECTS OF FINITE ELEMENT MODELLING OF MICRO-EDM AND ULTRASONIC EDM WITH TIME DEPENDENT RADIUS OF PLASMA CHANNEL

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ABSTRACT: The paper deals with finite element method (FEM) modelling of thermal removal mechanism at micro electrical discharge machining (EDM), comparing the following cases: classic (EDM) and ultrasonic (US) aiding EDM with time dependent and constant plasma channel radius on different initial microgeometries. The results obtained through FEM are compared to relevant experimental data in case of X210Cr12 machining in terms of crater dimensions. Some remarks are formulated concerning the adequacy of different modelling and some technological measures to improve material removal process are conceived.

KEY WORDS: Finite element modelling, ultrasonics, electrical discharge, plasma channel.

1. INTRODUCTION

Several models of thermal removal process of electrical discharge machining (EDM) are conceived in order to explain its very complex phenomenology, and based on these, some technological solutions are designed, leading to output process parameters improvement. Nowadays, the research interest is focused on micro(µ)-EDM, supposing achieving dimensions in the range 1-999 µm [1], working in a gap size with less than 5 µm, and delivering energies of $10^{-9} - 10^{-5}$ J [2]. The elaboration of a model as much as close to real process represents a question of utmost importance for µEDM development.

2. THERMAL MODELS FOR MATERIAL REMOVAL PROCESS FROM THE STATE OF THE ART

The parameters of interest in the frame of thermal modelling are presented in fig. 1:

![Figure 1. Modelling parameters at µEDM in the proximity of electrical discharge between tool and workpiece](image)

where: $r_{CA}$ is radius of removed volume by discharge from anode; $h_{CA}$ – depth of removed volume from anode; $r_{CA}$ – radius of EDM spot on anode; $q_A$ – heat flux entering the anode; $r_{CS}$ – radius of EDM spot on cathode; $q_C$ – heat flux entering the cathode; $r_{dc}$ – radius of the discharge channel; $r_{gb}$ – radius of gas bubble; $h_{gap}$ – size of frontal gap; both polarities can be used, the effect of polarity being very important at short pulses and micromachining.

As a result of transient and random characteristics of EDM material removal process, all the parameters from fig. 1 are time dependent. Apparently the most important input parameter is channel radius, due to its influence on EDM spot dimensions and energy density on the surface to be machined. A model that includes the time variation of plasma channel transversal section is our actual objective.

Basically, the model of over heating with 200-300K, above the normal boiling temperature - i. e. 3473 K in case of steel machining - owed to increased pressure produced by plasma channel formation during pulse time, was used in FEM modelling of the volume removed by a single discharge. The rapid drop of the pressure just at the end of pulse produces the material removal at classic EDM [3]. Under these conditions, the crater volume is bordered by 3273 K boiling isothermal in case of steel.

The overheating model was the topic of many discussions in scientific community during the time. Switching off the discharge current causes a collapse of the plasma channel. According to Lazarenko and Zolotich, parents of EDM, an induced low pressure reduces the boiling temperature of the melted material on the electrodes surfaces and the material
is vaporized or explosively erupted by hydro-mechanical forces [4–7]. So, this is in agreement with Van Dijck’s model [3], but this one is more complex, including the calculation of plasma channel radius development, the life duration of the gas bubble around the plasma channel, the temperature distribution inside the electrode-tool and workpiece, and the material removal mechanism.

Regarding the plasma channel evolution, there are different relations through which the plasma channel radius could be calculated.

Patel, Barrufet, Eubank, and DiBitonto, (1989) considered that discharge channel radius can be estimated using the following relation [8]:

$$r_{dc}(t) = K \cdot t^n$$  \hspace{1cm} (2)

where: t is pulse duration; K, n - empirical constants with the following values, K=0.788 and n=0.75.

In this context, the mentioned above authors considered that for the first time (1993), quantitative evidence that superheating is the dominant mechanism at EDM is provided [9].

Shuvra et. al. (2003) pointed out that plasma radius varies with time as the following relation shows [10]:

$$r_{dc} = k \cdot t^3$$  \hspace{1cm} (7)

where: t is pulse duration [µs]; k – proportionality constant.

More recently, Marafona and Chousal (2006) concluded that discharge channel radius ($r_{dc}$) is proportional to discharge current, pulse duration, workpiece materials, dielectric liquid properties and proportionality constants and indices (depending on gap size), according to the following relation [11]:

$$r_{dc}(t) = K \cdot Q^n \cdot t^m$$  \hspace{1cm} [µm]  \hspace{1cm} (1)

where: Q is discharge current [A]; t – pulse duration; m, n, K – empirical constants that take account of working conditions mentioned above.

Salonitis et. al. (2007) considered the following relation to compute discharge channel radius [12]:

$$r_{sp} = 2040 \cdot I^{0.43} \cdot t_{on}^{0.44}$$  \hspace{1cm} [µm]  \hspace{1cm} (8)

where: I is the current [A]; $t_{on}$ - the pulse on time [µs].

Some of presented above relations were used in our FEM modelling of material removal mechanism at µEDM aided and unaided by ultrasonics under specified conditions.

3. EXPERIMENTAL DATA

Micro electrical discharge machining using ultrasonic longitudinal vibrations (normal on machined surface) of electrode with frequency 20 kHz, amplitude 2 µm were achieved on Romanian installation ELER 01, and some experimental results in comparison with classic EDM, under the same working conditions are presented in fig. 2-5.

Figure 2. Microtopography at EDM (x500) with I=0.8 A, pulse time $t_{on}$=12 µs, pause time $t_{off}$=6 µs  

Figure 3. Craters mean dimensions at EDM (x500), current step I=0.8 A, pulse time $t_{on}$=12 µs, pause time $t_{off}$=6 µs

Figure 4. Microtopography at EDM+US (x500) with I=0.8 A, ultrasonic consumer power $P_{cUS}$=200W $t_{on}$=12 µs, $t_{off}$=6 µs

Figure 5. Microtopography at EDM+US (x500) with I=0.8 A, ultrasonic consumer power $P_{cUS}$=200W $t_{on}$=12 µs, $t_{off}$=6 µs
The crater diameters mean values were determined by Neophot – Zeiss photo-microscope with 500:1 magnifier. The crater depths were established by surface roughness measurement apparatus, “Surtronic” Rank Taylor Hobson.

The samples presented above were from X210Cr12 steel, the machining being achieved with Cu 99.5 tool material, flat end electrode, positive polarity, and static pulse durations (commanded pulses) with effective pulse time of 11 µs. The previous experimental data were utilized as reference for FEM modelling validation.

4. FEM MODELLING

Comsol Mutiphysics 4.2, Time Dependent module of Heat Transfer in Solids was used for finite element modelling of thermal material removal mechanism at micro-electrical discharge machining in several variants.

The first approach was the time dependent radius variation given by Patel et al. relation [8]. The relation (2) was converted in the following one, needed for the compatibles measure units used in Comsol modelling of channel radius (r_{ch}) variation:

\[ r_{ch} = 0.024942 \cdot t_i^{0.75} \text{ [m]} \]  

(9)

where: \( t_i \) is pulse time [s].

The parameters utilized in the frame of this approach (similar in the following models) are presented in fig. 6 as they were defined in global definitions:

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_p )</td>
<td>10[mm]</td>
<td>0.01 m</td>
<td>workpiece dimension</td>
</tr>
<tr>
<td>( a_{cr} )</td>
<td>5e-6</td>
<td>5.0e-6</td>
<td>axis x dimension of crater</td>
</tr>
<tr>
<td>( b_{cr} )</td>
<td>3.2e-6</td>
<td>3.2e-6</td>
<td>axis y dimension of crater</td>
</tr>
<tr>
<td>( r_{ms} )</td>
<td>0.15e-6</td>
<td>1.5e-7</td>
<td>radius of resolidified material</td>
</tr>
<tr>
<td>( r_{ch} )</td>
<td>0.024942 \cdot t_i^{0.75}</td>
<td>0</td>
<td>radius of plasma channel</td>
</tr>
<tr>
<td>( t_i )</td>
<td>0</td>
<td>pulse time</td>
<td></td>
</tr>
<tr>
<td>( r_{bg} )</td>
<td>0.1[mm]</td>
<td>1.0e-4 m</td>
<td>radius of gas bubble</td>
</tr>
</tbody>
</table>

The parameters used at time variation of plasma channel modelling of micro EDM

The EDM was applied on a micropeak of \( Ra = 0.8 \mu m \) initial surface, taking into account the data presented in fig. 3 and dependence relation between \( Ra \) and \( Rz \) roughness. Under these conditions, the following boundary conditions were set up. The temperature on EDM spot was 3473 K, based on overheating Van Dijck’s model [3], constant and maximum value attainable on steel under these process conditions (fig. 7 – dynamic boundaries, a - at early moment, b – at pulse time end).

The model achieved corresponds to an EDM process in deployment where the craters are overlapped.

The gas bubble around plasma channel, whose life time lasts much longer than pulse time, with dimensions (\( r_{bg} \)) in the range of 0.1 mm was set up as thermal insulation as it is presented in fig. 8.

The periphery of machined workpiece was set up at dielectric liquid temperature, of 313 K as convective cooling.

The meshing was achieved with free triangular elements, much finer in the interest zone, adjacent to EDM spot, and coarser toward workpiece periphery (fig. 10.a). Meshing statistics is presented in fig. 10.b.

![Figure 6. Parameters used at time variation of plasma channel modelling of micro EDM](image)

![Figure 7. Boundary conditions on EDM spot](image)

![Figure 8. Boundary conditions related to gas bubble](image)

![Figure 10. Mesh parameters](image)
The thermo-physical properties of X210Cr12 steel were temperature dependent provided by Comsol library.

The relative deep craters produced by commanded pulses determine a resolidification of melted material on the margins, phenomenon characterized by the radius of crater margin (rms) from fig. 6.

The temperature distribution obtained through Patel’s relation of plasma channel radius variation (9) is presented in fig. 11, the volume removed by discharge being bordered by boiling isothermal.

\[ r_{ch} = k \cdot \sqrt{t_i} \quad [\mu m] \] (10)

where: \( t_i \) is pulse time [\mu s].

The previous relation was converted in the suitable form for Comsol modelling as it follows:

\[ r_{ch} = 0.0014 \cdot \sqrt{t_i} \quad [m] \] (11)

where: \( t_i \) is pulse time [s].

The dimension of crater produced by the single discharge are more sensitive on radius (increase of 0.28 \( \mu m \)) than in depth direction (increase of 0.07 \( \mu m \)). Globally, the results in case of first modelling are closer to real reference data from fig. 3.

Another approach was made starting from the assumption of Kiyoshi Inoue, that the variation of radius \( r_{ch} \) can be expressed like [15]:

\[ r_{ch} = k \cdot \sqrt{t_i} \quad [\mu m] \] (10)

where: \( t_i \) is pulse time [\mu s].

The temperature distribution after pulse end is presented in fig. 14. Generally, the results emphasized even closer dimensions reported to reference data from fig. 3, in comparison with the previous modelling approaches. Reported to Patel’s relation based modelling, a decrease of 0.08 \( \mu m \) is recorded on depth, and 0.11 \( \mu m \) on radius direction.
The influence of initial surface microgeometry was studied by comparison between modelling of the single discharge on very low roughness surface $Ra=0.1$ µm, and EDMed surface of $Ra=1.6$ µm presented above. The temperature distribution on such surface after 11 µs single commanded pulse is presented in fig. 15. It can be observed that the depth dimension is more sensitive than the radius one. Comparing to the variant of initial roughness $Ra=0.8$ µm, based on Inoue’s relation, a significant decrease of 2 µm in depth of removed volume was obtained, and only of 0.07 µm on radius direction.

![Figure 15. Temperature [K] distribution after 11 µs commanded pulse in case of Inoue’s relation based of plasma channel radius variation on Ra=0.1 µm surface](image)

This emphasizes the strong influence of microgeometry shape on removed volume. High micropeaks can well absorb the thermal discharge energy, which is dissipated on a smaller volume than in case of a flatter surface.

The thermal modelling in case of ultrasonic aided micro-EDM ($\mu$EDM+US) is related on the strategy to overlap the pulse time on the cumulative microjets stage, produced by collective implosion of the gas bubbles at the end of stretching ultrasonic semiperiod. Consequently, the gas bubble formed around the plasma channel is destroyed by the pressure, in the range of 100 MPa, developed by this cavitation phenomenon. This is able to interrupt the discharge, as our experiments pointed out, and allows the dielectric liquid to enter the melted material zone and remove it. So, in terms of material removal mechanism, the melting isothermal is of interest in case of EDM+US, i.e. 1683 K for X210Cr12 steel. The temperature distribution after 4 µs from the pulse beginning, when the cumulative microjets stage is produced, is presented in fig. 16. One can notice the 3.4 times increase of depth of removed volume and 1.55 of radius through ultrasonic aiding in comparison with the similar thermal modelling of 11 µs single commanded pulse.

![Figure 16. Temperature [K] distribution at $\mu$EDM+US after 4 µs from pulse beginning at cumulative microjets stage occurrence in case of Inoue’s relation based modelling](image)

The huge potential of ultrasonic aiding in terms of machining rate is pointed out. Beside this thermal component of material removal mechanism, EDM+US has also a hydraulic one that is able to remove the micropeaks in solid state, due to shock waves orientation parallel to machined surface.

The evolution of temperature distribution during the pulse time interval is presented fig. 17. A thermal shock is revealed because after only 1.1 µs from the pulse beginning, a machining depth of 3.3 µm is attained, i.e. approximately 90% from the whole depth of removed crater volume.

![Figure 17. Evolution of temperature [K] distribution during pulse time at modelling of channel radius variation based on Inoue’s relation](image)
5. CONCLUSIONS
A relevant model of plasma channel development is very difficult to achieve because this is strongly dependent of the characteristics of EDM generator, the profile of discharge energy delivered. The plasma channel radius is dependent not only on pulse time but also on the variation of energy density delivered on EDM spot. The small dimensional variation pointed out by different studied models is of utmost interest for µEDM since its demands of precision and surface quality are permanently increased. The revealed thermal shock on machined material just from the pulse beginning imposes the decrease of energy level in this stage of discharge.

The measures of material removal process improvement address the two major stages of EDM in terms of machining depth, resulted from different variants of modelling. In the first stage, if the surface has very low initial roughness, the craters formed are very flat. In the second stage, when the depth of machining is increased, the craters produced by EDM are overlapped and their depth is increased. The machining rate is highly maintained in the second stage if depth and shape of macrorgeometry do not affect the EDM stability - fine and complex surfaces with high aspect ratio, more than 10:1.

At EDM+US the possibility of superimposing the pulse duration on cumulative micro jets stage is considered, when using relative long durations of pulse time, comparable to a semiperiod of ultrasonic aiding at high oscillation frequency. The hydraulic removal component is able to remove the micropeaks in solid state, contributing to machining rate increase and surface roughness decrease. Further researches will be focused on experiments aiming at clarification of modelling assumptions.

6. ACKNOWLEDGEMENTS
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7. REFERENCES