MULTIPHYSICS 3D FINITE ELEMENT MODELLING OF MICRO-ELECTRODISCHARGE MACHINING AIDED BY ULTRASONICS

Daniel Ghiculescu¹, Niculce Ion Marinescu², Sergiu Nanu³ and Daniela Ghiculescu⁴
¹ Politehnica University of Bucharest, daniel.ghiculescu@nsn.pub.ro
² Politehnica University of Bucharest, niculce.marinescu@nsn.pub.ro
³ Politehnica University of Bucharest, sergiu.nanu@nsn.pub.ro
⁴ National Authority of Scientific Research, daniela.ghiculescu@ancs.ro

ABSTRACT: The paper deals with modelling through finite element analysis (FEA) of material removal mechanism of micro-electrodischarge machining (µEDM) aided by ultrasonics (US). Some essential requirements of this hybrid variant of EDM and some experimental data which fulfil these prerequisites are presented, and starting from these, a strategic approach is formulated. In this context, a multiphysics modelling is achieved, comprising a thermal component, corresponding to EDM and a mechanical component, related to ultrasonically induced cavitation within the working gap. On this basis, some improvements of main output technological parameters of micro electrodischarge machining aided by longitudinal ultrasonic oscillations of the electrode-tool are proposed in terms of machining rate and surface roughness.

KEY WORDS: finite element analysis, micro electrodischarge machining, ultrasonics.

1. INTRODUCTION

The goal of this introduction is to define the field of micro electrodischarge machining (µEDM). This is considered an updated technology with large spectrum of applications. Three versions of large scale use of µEDM are micro-die sinking (µ-die sinking), micro-wire electrical discharge machining (µ-WEDM) and micro-electrical discharge drilling (µ-ED drilling). The other µEDM variants have less industrial relevance [1]. This paper is focused on one of the most basically variant, µ-die sinking, studying the material removal process at micrometer scale with two components: thermal (due to EDM) and ultrasonic (due to ultrasonics assistance).

Generally, micro-machining defines the processes generating dimensions in the range of 1 to 999 µm, in agreement to CIRP committee of Physical and Chemical processes [2].

In terms of dimensional performances, the minimal structure widths that can be achieved by µ-die sinking are ranged between 20 µm and 40 µm [3], [4]. Other dimensions like channels can be of around 20 µm, corner radii, of 10 µm with aspect ratios of up to 25 and deviations of contouring precision of ±1 µm [3]. Taking into account these results, the µEDM technology is useful for microcomponents fabrication like micro-moulds, micro inserts, and overall, filigree structure up to 5 µm [5].

Concerning the materials that can be machined by micro-EDM, they must fulfil a minimal conductivity of k = 0.01 S/cm, being high temperature alloys, cemented carbide, and electro-conductive ceramics [4]. Thus micro-EDM offers some important break through in accomplishing micro-components from these kinds of materials, like shafts and gears, nozzle holes, slots etc.

In terms of energy delivered during a discharge, this variant of the EDM process justifies the name of micro because it utilizes very low discharge energies as 10… 10⁻³ µJ to remove very small volumes of material of around 0.05 – 500 µm³ [1], using even a single discharge.

2. STRATEGIC APPROACH AT MICRO-EDM AIDED BY ULTRASONICS

The strategy that we aimed to follow at micro-EDM is conceived on strict control of several items detailed below:

(1) Improved understanding of the influence of multitude of phenomenological factors that affect micro EDM and the more intricate process of microEDM aided by longitudinal oscillations of the electrode-tool (µEDM+US). These factors address mainly the thermal and mechanical properties of workpiece and electrode-tool materials related to phenomena occurring at micrometric time and space scales like melting, vaporization, boiling, resolidification produced by EDM, mechanical and hydraulic phenomena ultrasonically induced by cavitation within the working gap. Basically, this is our goal for present and further researches to carry on FEA studies at micrometer scale, validated by experimental data in order to better understand the complex material removal mechanism at µEDM+US and finally, to attain the optimization of working parameters - see the synthesis of factors from figure 1.

It always must be considered the other elements of technological system like electrodischarge machine, the devices for clamping the tool and workpiece in terms of assuring the precision of relative position between workpiece and electrode-tool, the interaction between the surfaces of the tool and workpiece during the machining process, influenced by electro-technological parameters and dielectric flushing.

(2) Discharge parameters: current (i), voltage (u) and pulse time (tₚ) (discharge level); pulse and pause (tₛ) time (discharge frequency). Under conditions of such low discharge energy in the order of µJ, a very small material volume can be removed at one single discharge working in very instable environment given by an extremely narrow gap between the tool and the workpiece, having width between 1 to 5 µm [6].

In this context, this last parameter is very important from the point of view of process stability at ultrasonic aiding, because oscillations amplitudes must be lower than gap width, in connection with acoustic pressure induced in the gap.
On the other hand, acoustic pressure must be high enough to exceed the cavitation threshold, which depends on working liquid nature and its homogeneity. The acoustic pressure \( p_{ac} \) is given by the following relation:

\[
p_{ac} = 2\pi \cdot c \cdot \rho \cdot f_{US} \cdot A \sin \alpha \quad \text{[MPa]} \quad (1)
\]

where: \( c \) is sound velocity in dielectric liquid \([\text{m/s}]\); \( \rho \) - density of dielectric liquid \([\text{kg/m}^3]\); \( f_{US} \) - ultrasonic frequency \([\text{Hz}]\); \( A \) - oscillation amplitude \([\text{m}]\); \( \alpha = 2\pi f_{US} \cdot [\text{s}^{-1}] \). The values from relation 1, corresponding to our real working conditions, under which cavitation was obtained, are: \( \rho=840 \text{ kg/m}^3 \); \( c=(E/\rho)^{1/2}=(1.35\times10^7/840)^{1/2}=1267.7\text{ m/s} \); \( f_{US}=40\text{ kHz} \), \( A=1\mu\text{m} \). So, the process stability could be attained relative to micrometer width of the gap, working with such low amplitude, facilitated by higher frequency of 40 kHz.

(3) **High precision of feed system.** At nowadays installations, the feed is achieved by a servo system with highest sensitivity and positional accuracy of 0.5 \( \mu \text{m} \) on the X, Y and Z axes movement [5]. In our case, during preliminary experiments, we used an electro-mechanical Z axis with resolution of 0.5 \( \mu \text{m} \), carried out through a construction having as central element a roller screw.

(4) **Wear of the tools and its compensation.** At micro-EDM very short discharge durations are used in the range of 10 ns - 2.5 \( \mu \text{ s} \) [1] and therefore, tool electrode is usually charged as cathode to reduce tool wear This is explained by the polarity effect, included in Van Dijck’s model [7] - the basis of FEM modelling in the present paper - and other more recent works as Piltz’s [8]. Even in case of very thermally resilient materials for electrode-tool like graphite, cemented carbides or tungsten-copper, the relative wear can be over 30% [8]. This is very apparent when machining part of surfaces generating high electric field intensity, e.g. edges and corners.

(5) **Improved working medium** – of utmost importance at \( \mu \text{EDM} \) - consists in high filtering fineness and efficacy of evacuation of the removed particles from the gap. This is in strong correlation with gap size and working of dielectric unit. Taking into account the gap width of several \( \mu \text{m} \), a filtering capacity under 1 \( \mu \text{m} \) is recommended and higher pressure of injected liquid than in case of classic EDM.

Beside the hydraulic parameters of EDM dielectric aggregate, the nature (characteristics) of dielectric liquid has to be considered too. A dielectric viscosity lower than 1.8 \( \times 10^{-6} \text{ m}^2/\text{s} \), suitable for micrometric gap width, has to be used in the micro-die sinking process [9].

Deionized water makes possible a better surface quality than dielectric oil [10] and higher material removal rate [8]. The surface quality is the results of generated crater shapes, which are more flat if the energy density in the discharge plasma channel is lower. The density of the water being lower, it allows the development of the plasma channel during discharge, and as a result, a lower energy density on EDM spot produced on workpiece surface is produced. The machining rate is an indirect consequence of improvement evacuation from the gap and decrease of withdrawals number of work head to avoid short-circuits. The water has higher conductivity determining the feed system to locate the work head (the frontal surface of the electrode-tool) at a greater distance from the frontal surface of the workpiece, enlarging the gap size and therefore producing an improved evacuation of the removed particles from the gap. When using water as dielectric, in order to avoid the secondary effect of electrolysis, negative polarity is recommended again, beside the wear decrease, aiming at additional anodic dissolution of the workpiece material, increasing the machining rate.

Several improved flushing modes have to be analyzed in connection with the strategic issue (5). The usual flushing modes, also called direct types, are used, mentioned in order of efficiency: injection (a), suction (b), and lateral flushing (c). The modes (a) and (b) involves tubular electrodes, which could be very expensive at transversal dimensions under 0.1 mm. The variant injection or suction through workpiece is also difficult to be applied at very small dimensions of micrometric level. The mode (c) is not so efficient in case of high hydraulic resistance, i.e. very narrow working gap, respectively high aspect ratio of machined surface.

Taking into account the advantages and disadvantages of classic flushing modes discussed above, indirect flushing strategies have to be considered in case of \( \mu \text{EDM} \). These suppose relative motion between the tool electrode and the workpiece, during machining process. The relative motion can be: (a) longitudinal or transversal oscillation with high or low frequency or (b) a rotary motion of the tool electrode.

The variant (b) is similar to the planetary motion at classic EDM, contributing to discharge energy on a larger spot due to relative motion between tool and workpiece.

The variant (a), with a particular case, is developed in our researches. Thus, the efficiency of the flushing is increased by

---

**Figure 1.** Controlled parameters of technological system at ultrasonic aiding microEDM
a translatory vibration with amplitude between 4 μm and 20 μm and a frequency of 50 - 300 Hz [9].

Figure 2. Variation of tool elongation (z) and total hydrostatic pressure (pht) in the frontal gap at μEDM+US

Nevertheless experimentally, it has already demonstrated that low frequency vibrations are inferior to ultrasonic ones in terms of machining rate [11]. So, ultrasonic aiding μEDM can be considered also an indirect flushing strategy. By all means, ultrasonics aiding brings many more advantages related directly to material removal process as it will be highlighted.

Many researchers reported significant improvement of technological performances at micro-EDM, using ultrasonic assistance of the machining process. Among others, H. Huang at al. increased spectacularly the machining rate at μEDM+US, up to 60 times, drilling microholes in Nitinol (intelligent material from Ni and Ti alloy) [12]. J.C. hung at al. used both variant of indirect flushing, combining ultrasonic vibration and rotary movement of electrode-tool at machining microholes by μEDM [9].

Several machines performing μEDM exist on the market today [1], many of them using RC circuits, delivering pulses, discharges with duration in the order of 10 nano-seconds, and consequently, very low level of discharge energy is produced. But, in the frame of our strategy at μEDM+US, aiming at synchronization between tool ultrasonic oscillation and ignition moments, this solution is not useful because relaxation pulses cannot be controlled in terms of delivery moments. Therefore, the lowest values of static pulse durations, which are more suitable for US aiding, are 2.5 μs in the state of the art [1]. Then the value of 2 μs used in our preliminary experiments is framed in requirements for μEDM. The current used of 0.9 A is compatible with values provided by mentioned above installations.

The moment of commanded pulses must be placed as much as possible close to cumulative microjets phase (CMP), which occurs at the final of a stretching semiperiod (fig. 2). Nevertheless, from our previous researches, the final of these pulses have to range within 1-1.5 μs before the collective implosion from the gap (CMP), which is very difficult to achieve. So, under those conditions, a more realistic approach is to overlap the pulse duration on CMP as it is illustrated in figure 2. The two curves show the variation of elongation of tool (on z direction), and the total hydrostatic pressure pht from the gap, calculated with the relation:

$$ p_{ht} = p_{ac} + p_{hd} \quad \text{(MPa)} \quad (2) $$

where: $p_{ac}$ is acoustic pressure and $p_{hd}$ – local hydrostatic pressure.

CMP produces shock waves in the order of 100 MPa oriented along the working gap, against the cases when the space between two solid walls is much greater, milimetric order [14].

3. EXPERIMENTAL DATA

FEM modelling validation was done considering some experimental data as reference, synthesized in table 1:

Table 1. Craters mean dimensions at micro-EDM with and without US aiding

<table>
<thead>
<tr>
<th>Machining</th>
<th>μEDM</th>
<th>μEDM+US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crater dimensions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (μm)</td>
<td>3</td>
<td>1.6</td>
</tr>
<tr>
<td>Radius (μm)</td>
<td>3.7</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Workpiece material: X210Cr12; tool material: Cu 99.5; static pulse duration with pulse time $t_i=2μs$, pause time $t_{p/MIT}$ = 2μs, positive polarity, current step I=0.9A

These are obtained on Romanian ELER 01 machine interfaced with dedicated equipment for μEDM+US, consisting in a specialized EDM generator, a feed system with 0.5 μm resolution, and adaptive 40 kHz frequency control ultrasonic generator, and 100 W consumed power on acoustic chain. The crater diameters mean values were determined by a photo-microscope Neophot – Zeiss with 500:1 magnifier. The crater depths were measured using a surface roughness measurement apparatus, “Surtronic” Rank Taylor Hobson.

4. MULTIPHYSICS MODELLING OF MICRO-EDM AIDED BY ULTRASONICS

The characteristics of micro-electrodischarge machining impose the study of material removal mechanism taking into account the shape of microgeometry during the machining process. Therefore, the specific EDM surface with multiple craters generated by micro-discharges was considered as starting point for process modelling with Comsol Multiphysics 4.2 release.

Two components (physics) were used, corresponding to electrodischarge machining and ultrasonic longitudinal oscillations of electrode-tool: Heat Transfer in Solids and Solid Mechanics, both in time dependent variant. The thermal load time was equal to pulse time $t_i=2μs$ at classic micro-EDM and 1 μs at micro-EDM+US in case when the pulse is overlapped on cumulative microjets stage. Our recent experiments proved that discharges, visualized on the oscilloscope as current variation within the working gap are cut by the shock waves produced by collective implosion from the gap. The mechanical load acted for 1 μs, which is the approximate time when cumulative microjets work.

A parametric modelling was achieved with the variables assigned in the global definitions as it is presented in fig. 3.

Figure 3. Parametric assignation of multiphysics modelling of μEDM+US process
Previous researches highlighted that chosen workpiece dimensions – a cube with the size of \( l_p = 10 \text{ mm} \) – have no significant influence on modelling results.

The modelling geometry was created by several Boolean operations as it is presented in fig. 4.a. The microgeometry of initial surface is composed by four craters whose dimensions are defined by the semi-axes of semi-ellipsoids, \( ax, by, cz \), which are in the order of \( \mu \text{m} \) (fig. 4.b). The gas bubble radius formed around the plasma channel is much greater, in the order of 0.1 mm and drawn in the front work plane (fig. 4.c).

![Figure 4. 3D geometry for µEDM+US modelling](image)

The workpiece material was D3 (UNS T30403), corresponding to X210Cr12, taken from Comsol library and completed with needed temperature dependent thermo-physical properties for the two modules (physics) applied - thermal and mechanical ones.

For boundary conditions related to heat transfer module, it was used the Van Dijck’s overheating model [7], agreed by Lazarenko and Zolotich, parents of EDM, i.e. temperature on discharge spot is 200-300 K, over boiling temperature, maximum possible during pulse time, due to high pressure exerted by plasma channel. Therefore, this represents 3473 K, assigned to symmetry centre (peak) of the geometry - fig. 5:

![Figure 5. Maximum temperature 3473 K on EDM spot](image)

The zone around the EDM spot, covered by the gas bubble, formed around plasma channel was considered thermal insulated, as it is pointed out in fig. 6:

![Figure 6. Thermal insulation, corresponding to the gas bubble](image)

The rest of the workpiece surfaces are considered immersed in dielectric liquid, having a temperature of 313 K.

So, the surrounding liquid acts through convective cooling with a heat transfer coefficient taken 10 W/(m\(^2\)·K).

![Figure 7. Convective cooling at the contact with the dielectric liquid](image)

For Solid Mechanics module, several boundary conditions were adopted: fixed constraint at the inferior part of the workpiece, assimilated to the case when a vertical fixing force is used, and the workpiece is oriented on the inferior plane in contact with the EDM machine work table (fig. 8); a load created by cumulative microjets of 100 MPa, on one flank of the peak produced by the four previous discharges (craters) – fig. 9:

![Figure 8. Fixed constraint, corresponding to a fixing force on the superior plane](image)

![Figure 9. Boundary load on the lateral surface of the peak](image)

![Figure 10. Meshing with free tetrahedral elements](image)
The mesh was made with free tetrahedral elements – its statistics revealed an average quality of 0.81 on a scale 0-1 – being finer only in the interest zone (fig. 10), aiming at computational resources saving without affecting calculation precision.

For modelling validation, a simulation of 2µs single discharge, under conditions of classic µEDM was achieved. The temperature distribution, using one slice facility in yz plane is represented in fig. 11:

As it can be noticed, the almost entire initial peak is removed, and a levelling at the bottom of the microcavity is achieved, resulting a crater with maxim depth on a circular zone with the radius of 2.6 µm. The results highlighted the dimensions of the crater obtained, the volume bordered by boiling isothermal of 3273K at steel, according to overheating theory, which emphasizes that material reaches a temperature with 200-300 K, higher than boiling point under normal conditions, due to high pressure created by plasma channel over the spot zone [7]. Basically, the material removal mechanism through boiling remains the main one under EDM classic conditions. The removal of melted material is not possible after discharge because the action of hydraulic forces of dielectric liquid is blocked by the gas bubble formed around the plasma channel. The images from the gap taken by ultraspeed camera pointed out that gas bubble still exist after more than 100 µs after the pulse end [15]. By this moment, the melted material is relative long time ago resolidified, even after 1-2 µs after pulse end [16]. The margins of the volume with 3273 K indicated z=3.1 µm and y=3.8 µm (error of 0.1 µm) – fig. 11.b – in good agreement to experimental reference data (see table 1).

Our experimental data proved also that is possible that gas bubble collapses when another discharge occurs in the vicinity of the previous EDM spot (the conductivity in the gap at the previous spot zone remains high), generating high pressure. But at such energy level characterizing microEDM, a delay time necessary to ignition is approximately 100 µs. So, even under this assumption, the long life time of gas bubble makes boiling the main mechanism of material removal.

Taking into account the very fast mechanism of material resolidification presented above, the strategic approach to improve the material removal rate at µEDM+US is to overlap relative longer pulses (static pulse duration) over the cumulative microjets stage in order to shorten the gas bubble life time, and to permit the access of the dielectric liquid to molten material. In this context, the results provided by FEA are presented in fig. 12:

At micro-electrodischarge machining aided by ultrasonics (µEDM+US), the material volume removed is bordered by 1683 melting isothermal (melting point in case of X210Cr12 steel). Therefore, the volume thermally removed under conditions of ultrasonically induced cavitation within the gap is much greater, i.e. almost five times, according to FEA results, which is in the agreement with our experimental results of increase of machining rate at some working modes [16].

Our experimental data proved also that is possible that gas bubble collapses when another discharge occurs in the vicinity of the previous EDM spot (the conductivity in the gap at the previous spot zone remains high), generating high pressure. But at such energy level characterizing microEDM, a delay time necessary to ignition is approximately 100 µs. So, even under this assumption, the long life time of gas bubble makes boiling the main mechanism of material removal.

Taking into account the very fast mechanism of material resolidification presented above, the strategic approach to improve the material removal rate at µEDM+US is to overlap relative longer pulses (static pulse duration) over the cumulative microjets stage in order to shorten the gas bubble life time, and to permit the access of the dielectric liquid to molten material. In this context, the results provided by FEA are presented in fig. 12:

At a distance > 20 µm from EDM spot the temperature is equal to dielectric liquid temperature

Figure 11. Temperature distribution in yz plane after a pulse time t=2 µs at classic µEDM

Figure 12. Temperature distribution in yz plane after 1 µs from the pulse beginning at cumulative microjets stage of µEDM+US

Figure 13. Temperature distribution in the vicinity of discharge spot in yz plane after 1 µs from the pulse beginning at cumulative microjets stage at µEDM+US
The FEA results in the proximity of the EDM spot, from figure 13, demonstrate that even close – at a distance in the order of 10 μm - to the thermally attacked zone by a single discharge, the temperature is equal to that of the working environment of the dielectric liquid. So, the overall dimensions of the model are correctly chosen, not affecting the temperature distribution.

The contribution of ultrasonics to material removal mechanism is revealed by von Mises stress distribution after 1 μs of mechanical load produced by cumulative microjets (fig. 14).

**Figure 14.** Von Mises stress [MPa] distribution produced after 1 μs by 100 MPa mechanical load due to cumulative microjets stage at μEDM+US

As it can be noticed, the microgeometry peak is removed in proportion of approximately 50% in agreement with our experimental data (see table 2). In case of μEDM+US, the ultrasonic cavitation is produced within the very narrow working gap width in the range of several micrometers. In such narrow spaces between solid walls the shock waves are oriented along the surface against the cases with spaces having larger width in the order of mm, where normal orientation occurs [14]. This orientation of mechanical load at μEDM facilitates the micropores removal with lower shear resistance, reducing the machined surface roughness through trimming effect, but also increasing the machining rate. The amplitude of the tool ultrasonic oscillations, and consequently the power delivered on the acoustic chain is the subject of experimental optimisation, strongly dependent on working conditions.

5. CONCLUSIONS

A strategic approach is proposed in order to improve main output technological parameters – machining rate and surface roughness – at micro-electrodischarge machining aided by ultrasonic longitudinal vibrations of electrode-tool. This is based on Finite Element Analysis results validated through experimental date, consisting mainly in two solutions: (1) overlapping relative long commanded pulse on cumulative microjets phase, i.e. collective implosion of the gas bubbles from the gap ultrasonically induced in order to remove the material in melted state; (2) actuate with optimum value of the acoustic chain to remove material in solid state, i.e. the peaks of microgeometry, but also maintaining the stability of machining process.

6. ACKNOWLEDGEMENTS


7. REFERENCES