FINITE ELEMENT METHOD STUDY ON MACHINED SHAPE INFLUENCE AT ULTRASONIC AIDED AND NOT AIDED MICROELECTRODISCHARGE MACHINING

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Abstract: The paper deals with study through Finite Element Method (FEM) concerning microgeometry shape influence at microelectrodischarge machining aided by ultrasonics (µEDM+US) and comparatively at classic finishing, µEDM and EDM+US. The technological performances and requirements of µEDM were extensively analyzed. Microhole as well as microprotuberance shapes were considered in order to establish their influence on crater volumes, and implicitly, to removal mechanism. Two cases are compared: micromachining with and without ultrasonic aiding. Some recommendations aiming at improved control of material removal process were formulated.

Keywords: microgeometry shape, ultrasonics, microelectrodischarge machining.

1. INTRODUCTION

Thermal, electro-physical and chemical micro-machining processes have important places in micromanufacturing due to their no contact material removal mechanisms. Electrodischarge Machining (EDM) is particularly appropriate for micromachining due to its thermal material removal process. This occurs almost as force-free machining not dependent of the mechanical properties of the processed material. Its applications have broadened much farther than dies/molds fabrication to a large range of micro-components [1].

2. MICROEDM TECHNOLOGY PERFORMANCES, REQUIREMENTS

Micro-machining defines the processes that achieve products in the range of 1 to 999 μm, according to CIRP committee of Physical and Chemical processes [2]. The present trend of ultra miniaturization of mechanical components led to µEDM applications at microscopic mechanical components and devices.

In this respect, the µEDM technology is helpful for conventional precision machining as well as for microcomponents fabrication like micro-molds, micro inserts, and in general, filigree structure up to 5 μm [3]. For this type of machining, the energy must be minimized and consequently, also the size of the gap at a width of 1 μm. A specific EDM strategy is applied by the authors that permits setting of a minimized discharge gap. Working with increments of under 1 μm of the feed system, which are effectuated gradually, after a short delay (sample time), as gap increases, this µEDM requirement is attained.

A large range of products can be achieved like fuel injector valves, parts and components for medical devices, fiber optic connectors, micro-molds, stamping tools, micro-electronic parts etc. [4], [5]. The Asian zone has an advance in this field. MicroEDM is considered a very flexible machining process due to its different variants. Three versions of big industrial applications 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 with less industrial relevance are micro-electrical discharge milling (µ-ED milling), micro-electrical discharge grinding (µ-EDG), and micro-wire electrical discharge grinding (µ-WEDG) [6], [7].

This paper is focused on some of the most widely used variants, µ-die sinking and µ-ED drilling. At present, µ-die sinking is mostly used in single or small series production, mainly in fabrication of tools for
micro-embossing or micro-injection moulding. Minimal structure widths that can be achieved by μ-die sinking ranges between 20 μm and 40 μm [12], [13]. Channels of around 20 μm and corner radii of 10 μm at aspect ratios of up to 25 can be produced. Deviations of contouring accuracies are ±1 μm [12].

At μ-ED drilling, the rotating or stationary pin electrode is moved axially into the workpiece. Conventional electrodes for μ-ED drilling made from cemented carbide are available with diameters down to 45 μm [1]. Smaller dimensions for electrodes down to 2.5 μm are also available [7]. Special clamping systems also made from cemented carbide or ceramics are needed for the exact guiding and positioning of the electrode [6].

Compared to classic EDM, μEDM is focused on the following items [6], synthesized in fig 1:

**Fig. 1. Specific issues addressed at microEDM**

A. **Strict control of discharge parameters: frequency of discharge (pulse and pause time), level of the energy input, (current, voltage and pulse time)** - the minimum discharge energy of 0.1 μJ is obtainable, which determines a very small material removal at one single discharge and an extremely small gap width ranging from 1 to 5 μm [8].

B. **High precision control of the motion of the electrodes** - in case of actual installations, the feed is achieved through a servo system with highest sensitivity and positional accuracy of 0.5 μm on the X, Y and Z axes movement [3]. The present preliminary experiments of authors are made on Z axis with 0.5 μm resolution;

C. **Requirement concerning the wear of the electrodes and compensation for the wear** - since μEDM operates at very short discharge durations from \( t_i = 10 \text{ ns} \) to \( t_i = 2.5 \text{ μs} \) [7], the tool electrode is usually charged as the cathode to reduce tool electrode wear [9]. This is explained by the polarity effect, which is also included in Van Dijck’s model [10], the basis of FEM modelling in the present paper; even graphite, cemented carbides or tungsten-copper (very thermally and mechanically resilient) are used for tool electrodes, the relative wear can be over 30%; this is extremely visible at machined surfaces with edges and corners due to increased electric field intensity [6].

D. **Improved understanding of μEDM process removal and the factors that affect it like material properties, thermal conduction of the workpiece, melting and recasting processes, and their effect on the surface finish/integrity** - this is our goal for present and further researches by undertaking FEM studies at micrometer scale, validated by experimental data concerning material removal mechanism;

E. **Improved flushing of the gap, evacuation of the removed particles from the process** - this is in strong correlation with gap size and working of dielectric unit. Taking into account the gap width of several μm, a filtering capacity under 1 μm is recommended.

The issue of dielectric liquid has to be considered too. Dielectric oil with lower viscosity, \( v ≤ 1.8 \times 10^{-6} \text{ m}^2/\text{s} \) (appropriate for μm gap width), is used in the micro-die sinking process [6]. In comparison to dielectric oil, deionized water contributes to a higher surface quality [11] and material removal rate [9]. These could be explained by the following phenomena: density of the water is lower, allowing the development of the plasma channel and consequently, a lower energy density on EDM spot; the water has higher conductivity determining a greater gap size and therefore an improved evacuation of the removed particles from the gap. In order to avoid the secondary effect of electrolysis, negative polarity is recommended aiming at achievement of additional anodic dissolution to the workpiece.
In respect with requirement (E), several improved flushing modes have to be analyzed yet. The following modes of direct flushing strategies could be used: lateral flushing (a), injection flushing (b) and suction flushing (c); b and c variants are more expensive when using the tubular electrodes (very high costs under 0.1 mm diameter). Injection or suction through workpiece is difficult to apply at very small dimensions of μm level. Flushing through the electrode is in the most cases impossible because of the small electrode dimensions.

Indirect flushing strategies have to be approached, which consist in relative motion between the tool electrode and the workpiece, simultaneously with the tool feed. The relative motion can be a periodic high frequency vibration or a rotary motion of the tool electrode. Thus, at μ-ED drilling, the electrodes have rotations up to n = 2000 rot/min [13], [14], [15] in order to obtain higher accuracies in roundness, higher aspect ratios and higher material removal rates. These results are similar to those of planetary motion at EDM. Additionally, the effectiveness of the flushing is increased by a translatory vibration with an amplitude between 4 μm and 20 μm and a frequency of 50 - 300 Hz [6]. Nevertheless experimentally, it was demonstrated that low frequency vibrations is inferior to ultrasonic ones in terms of machining rate [16]. Ultrasonic aiding μEDM can be considered also an indirect flushing strategy.

3. ULTRASONIC AIDED MICROEDM

Ultrasonic vibrations of electrode-tool and workpiece was applied successfully to increase performances at microEDM as several researchers reported. The vibration of tool electrode or workpiece improves dielectric circulation and the pumping action, by pushing removed particles from the gap and sucking cleaned dielectric, which provides ideal condition for discharges, i.e. efficient discharges and higher removal rate [17].

Ogawa et al. reported out that the depth of microholes by the combined effect of EDM with ultrasonic vibration becomes almost two times greater than without ultrasonic vibration and machining rate was increased [18].

Wansheng et al. demonstrated that holes with diameter less than 0.2 mm and the aspect ratio more than 15 can be produced without difficulty by ultrasonic vibration using micro-EDM [19].

Yan et al. reported that with combined effect of μ-EDM and ultrasonic μ-vibration, the diameter variation of micro holes between the entrance and exit was about 2 μm at diameters of about 150 μm and depth of 500 μm [20].

Gao and Liu found that efficiency of ultrasonic aided microEDM is 8 times greater than simple microEDM at workpiece ultrasonic vibration of 0.5 mm thickness from steel and 45 μm electrode from tungsten [21]. These increased performances (of only few examples of ultrasonic aiding μEDM) were not entirely explained because of intricate removal mechanism based on ultrasonically induced cavitation, which is the subject of our researches.

4. EXPERIMENTAL DATA

Reference experimental data considered for FEM modelling validation were synthesized in table 1 and 2:

<table>
<thead>
<tr>
<th>Machining</th>
<th>EDM</th>
<th>EDM+US</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.6</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Flat workpiece material: X210Cr12; tool material: Cu 99.5; static pulse duration with pulse time \( t_i = 25 \mu s \), pause time \( t_0 = 12 \mu s \), positive polarity, current step \( I = 0.9A \)

<table>
<thead>
<tr>
<th>Machining</th>
<th>EDM</th>
<th>EDM+US</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Flat workpiece material: X210Cr12; tool material: Cu 99.5; static pulse duration with pulse time \( t_i = 2μs \), pause time \( t_0 = 2μs \), positive polarity, current step \( I = 0.9A \)

A special equipment consisting in a new EDM generator for low discharge energies and a feed system with 0.5 μm resolution was used, assembled on Romanian ELER 01 machine. For actuating the acoustic chain, comprising at its end the electrode tool, an
ultrasonic generator was used with 20 kHz frequency and 100 W consumed power on acoustic chain. The crater diameters mean values were determined by Neophot – Zeiss photo-microscole with 500:1 magnifier. The crater depths were established by surface roughness measurement apparatus, “Surtronic” Rank Taylor Hobson.

5. FINITE ELEMENT MODELLING

In order to better understand the process of μEDM with and without ultrasonic aiding, the machining of a microhole and a micro convexity was simulated. Parameters of μEDM and classic finishing EDM were used comparatively. The volume removed by a single discharge provided by Finite Element Method (FEM) was compared with reference experimental data presented above obtained at flat surface machining.

The new 4.2 version of Comsol Multiphysics with the time dependent heat transfer module was used for modelling. The model of over heating with 200-300K, above the normal boiling temperature, due to increased pressure on EDM spot during pulse time was used to determine the volume removed by discharge. The sudden drop of the pressure just at the end of pulse produces the material removal at classic EDM [10]. The crater volume is bordered by 3273 K boiling isothermal in case of steel.

The overheating model was the subject of many discussions in scientific community during the time. Switching off the discharge current causes a collapse of the plasma channel. 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 [22–25]. Lazarenko and Zolotich, parents of EDM, agreed superheating model, which is in accord with Van Dijck’s model [10]. This is more complex, including the calculation of plasma channel radius development, the life duration the gas bubble around the plasma channel, the temperature distribution inside the electrode-tool and workpiece, and the material removal mechanism.

A 2D geometry was created based on the symmetry of simulated phenomena. A parameterized model was built, which included a workpiece square profile, two initial craters on superior surface produced by previous discharges, the EDM spot placed on symmetry axis and two points that border the gas bubble that surrounds the EDM spot. The used parameters, mentioned above, from global definitions page are presented in fig. 2:

![Fig. 2. Example of assignations for modelling parameters](image)

An example of 2D geometry created for microhole machining is presented in fig. 3:

![Fig. 3. Example of 2D geometry for microhole machining modelling](image)

Several FEM studies were undertaken in order to establish an optimal dimension of the workpiece, not affecting the temperature distribution produced by a single discharge, taking account of the calculation resources. The workpiece profile was a square of 10, 1, 0.5 and 0.25 mm side length. An example of temperature distribution on flat surface workpiece is presented in fig. 4 on the whole volume and in detail around EDM spot:
Generally, the global temperature in workpiece material is little affected by a single discharge effect (fig. 4-a). The volume of crater bordered by boiling isothermal [10] has some variations which have to be analyzed case of high precision microEDM (fig. 4-b). For comparison, the results obtained were synthesized in table 3:

<table>
<thead>
<tr>
<th>Workpiece length size [mm]</th>
<th>Crater depth (y) [µm]</th>
<th>Crater radius (x) [µm]</th>
<th>Δ (dimensional variations)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Y [µm]</td>
</tr>
<tr>
<td>10</td>
<td>1.998</td>
<td>3.791</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2.002</td>
<td>3.806</td>
<td>0.004</td>
</tr>
<tr>
<td>0.5</td>
<td>2.001</td>
<td>3.792</td>
<td>0.003</td>
</tr>
<tr>
<td>0.25</td>
<td>1.998</td>
<td>3.786</td>
<td>0</td>
</tr>
</tbody>
</table>

As it can be noticed commonly, crater dimensions grow if the workpiece dimensions decrease, which can be explained by the fact that thermal shock is greater on a smaller volume. At the smallest dimensions, the crater dimensions decrease as a result of closer position of workpiece margins which are cooled by a dielectric constant working temperature of 313K. At micrometer level the dimensional variations (Δ) are very low reported to the ones of 10 mm square length, FEM machining precision being not affected. Regarding this modelling issue, FEM results are in good agreement with preliminary experimental data.

The FEM modelling was achieved on X210Cr12 workpiece material, which corresponds to D3 (UNS T30403) thermo-physical properties from Comsol library, completed also with other needed temperature dependent characteristics.

Border conditions (fig. 5) are represented by thermal isolation in gas bubble zone, temperature 1, 313 K, on workpiece margins and temperature 2, 3473 K, on EDM spot, according to van Dijck’s model [10].
At FEM modelling of microhole machining by $\mu$EDM, temperature distribution after a single discharge shows that globally, the workpiece volume is insignificantly affected (fig. 6-a). At micrometer level (fig. 6-b), the temperature distribution in the zone adjacent to EDM spot emphasizes a crater volume removed by a single discharge with lower depth than in case of flat surface machining (see previous FEM results and preliminary experimental data).

Comparing to classic finishing EDM mode, the volume removed by a single discharge is with 320% greater than in previous case as it is presented in fig. 7:

The temperature distribution after a single discharge at conjugated surface $\mu$EDM is presented in fig. 8, in comparison with the temperature distribution at machining same surface by classic EDM finishing (fig. 9).
FEM results emphasize that at micro-convexity $\mu$EDM (fig. 7), the volume removed by discharge is 30% greater than that removed at micro-concavity (microhole) with the same dimensions. This is explained by the fact that thermal energy in case of micro-convexity is dissipated on larger volume, adjacent to EDM spot. Comparing to classic EDM finishing (fig. 8), the crater volume removed by single discharge at $\mu$EDM is almost 13 times lower.

In case of classic EDM finishing, the similar comparison shows that volume removed by single discharge on micro-convexity reported to micro-concavity is with 300% greater. Starting from these results, a $\mu$EDM strategy can be set up. When machining micro-convexity, the level of input discharge energy has to be minimized in order to increase the machining precision.

At $\mu$EDM+US, the life duration of gas bubble is reduced to half semiperiod of ultrasonic oscillation. At final of stretching semiperiod of dielectric liquid from the gap, a collective implosion of bubbles from the gap occurs (cumulative microjets stage - CMS). If the pulse duration is overlapped on CMS, the hydraulic forces of dielectric can remove the material melted by discharge [26]. In fig. 9, the melting isothermal position indicates the volume that can be removed by ultrasonic aiding at a single discharge, which is around 12 times greater than in case of classic EDM. Similarly, in fig 10, the removed volume is significantly increased, but this can affect the machining precision; in this case, relative long pulses are not recommended. At $\mu$EDM+US, ultrasonic removal consists in craters margins trimming, which have lower shear resistance [26], thus surface roughness being improved (see table 1, 2). It is very difficult to overlap short pulses on CMS.

4. CONCLUSIONS

The state of the art in microEDM provides information concerning the enhancement of the products range and continously dimensionial decreasing of machined surfaces. At micro-die sinking the minimum surface dimensions are down to 20 $\mu$m and at micro-drilling, down to 2 $\mu$m. The technological measures to be considered are the decreasing of input discharge energy level at $10^{-3}$ $\mu$J, the feed system precision below 1 $\mu$m, tooling precision, flushing improvement in a gap of 1…5 $\mu$m, better understanding of material removal process. Ultrasonic aiding and FEM simulation of $\mu$EDM are solutions to address some issues mentioned above.

FEM simulation of $\mu$EDM led to different strategies concerning micro-cavities and micro-convexity machining.

In case of micro-cavities, the level of discharge energy can be greater because it is dissipated on a larger volume adjacent to EDM spot. The ultrasonic aiding can also be applied leading to machining rate increase. If the power for actuating the acoustic chain is minimized but sufficient to ultrasonically induce cavitation in the gap, the precision is not affected. Thus, the flushing could be improved especially when the aspect ratio is high and consequently, the surface quality.

In case of micro-convexities, the volume removed by single discharge is greater than in case of micro-concavities. So the level of discharge energy must be minimized. The use of negative polarity which produces flatter craters is recommended. In case of ultrasonic aiding the power needed to actuate the acoustic chain must be lower than in case of micro-cavities or when working with positive...
polarity. Due to narrowing the plasma channel in the vicinity of cathodic zone (workpiece), the energy density on EDM spot is greater than in case of negative polarity.

Further researches will be dedicated to μEDM-US process of micromachining different surface shapes, including both experiments and FEM modelling aiming at optimization of working parameters.

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REFERENCES