The Influence of Machined Surface Microgeometry on Mechanical Hydraulic Removal Mechanism at Ultrasonically Aided EDM Finishing

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Abstract. The paper deals with Finite Element Method (FEM) of mechanical-hydraulic component of material removal mechanism at electrical discharge machining aided by ultrasonics (EDM+US) finishing. The influence of two types of crater shapes - produced by commanded and relaxation pulses - is analyzed. Based on FEM results, the ratio between depth and crater diameter is correlated with the consumed power on ultrasonic chain in order to minimize the EDMed surface roughness.

1. Introduction
The process instability at electrical discharge machining (EDM) micromachining and finishing created by narrow working gap is known [1, 2]. A very effective solution to solve this drawback is ultrasonic assistance of electrical discharge machining (EDM+US) due to cyclic acoustic pressure created in the working gap and as a result, ultrasonically induced cavitation within. Therefore a pumping effect of dielectric liquid is created which is able to significantly improve the particles evacuation from the gap [1]. Moreover, ultrasonic assistance produces a major improvement of output technological parameters in terms of machining rate, ultrasonic volumetric relative wear, and surface roughness if the working parameters are optimized [3].

The material removal mechanism at EDM+US has two components: (1) thermal one, specific to pure EDM, but deployed under cyclic variation of dielectric liquid in the gap, and (2) mechanical hydraulic one, specific to ultrasonic shock waves removal. The component (2) is strongly related to surface roughness (Ra) decrease relative to pure EDM at the same input working parameters.

Very few researches reported the decrease of surface roughness as effect of ultrasonic aiding. At wire micro-machining, ultrasonic assistance produces better roughness [4]. Other researchers observed an increase of Ra of 10\%, beside the machining rate increase since the removed volume by discharge is grown due to ultrasonic contribution to material removal mechanism [5].

The effective Ra minimization was attained through optimization of the key-parameter, the consumed power on ultrasonic chain (PcUS), which includes electrode-tool or workpiece. If PcUS is too high, Ra could be increased, although the machining rate is greater. But at finishing and micromachining, first objectives to be attained are Ra and volumetric relative wear minimization, i.e. precision increase. Establishing a correlation between machined surface microgeometry shape and optimum value of PcUS represents the main goal of this research.

2. Experimental Data
The decrease of machined surface roughness through ultrasonic aiding at EDM finishing was pointed out through experiments, using both commanded and relaxation pulses. Disk shape samples from X210Cr12 were machined comparatively on Romanian ELER 01 machine with 20 kHz longitudinal ultrasonic oscillations of the tool and without tool oscillations – pure EDM.
The electrode-tool from copper with disk shape of 25 mm diameter, and 3 mm height was used. The ultrasonic (US) chain included: PZT transducer, stepped horn and the tool at its end (figure 1). A nodal flange was used for its clamping. The perpendicularity of ultrasonic longitudinal axis on ELER 01 worktable was obtained with and orientation device based on adjustment by conjugated spherical surfaces [6].

A special generator for finishing and micro-machining, connected to ELER 01 machine was used. At commanded pulses using, the working parameters were: current step, \( I=1.5 \) A, positive (tool) polarity; pulse time, \( t_i=12 \) µs, pause time, \( t_0=6 \) µs, injection pressure, \( p_l=0.04 \) MPa (through workpiece); variation of consumed power on ultrasonic chain in the range, \( P_{cUS}=0-150\)W; amplitude, around \( A=2 \) µm. At relaxation pulses using, the specific working parameters were: negative polarity, capacitor step, \( C=68 \) nF, resistance step (mean for adjusting supply current), \( R=0.13 \) kΩ; the ultrasonic parameters were maintained.

Data concerning the machined microtopography obtained with commanded pulses are presented in figures 2-3. The images were taken with the integrated system camera-microscope Neophot 2 – Zeiss. For evaluation of craters profile, the roughness \( R_z \) was considered, measured with a Taylor-Hobson surface instrument. The average dimensions of crater diameter and depth were represented comparatively in figures 4, and 5.

**Figure 1.** Elements of technological system at ELER 01 tests of EDM+US finishing

![Elements of technological system at ELER 01 tests of EDM+US finishing](image)

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**Figure 2.** Microtopography at EDM, \( I=1.5\)A, polarity +, \( t_i=12 \) µs, \( t_0=6 \) µs

**Figure 3.** Microtopography at EDM+US, \( I=1.5\)A, polarity +, \( t_i=12 \) µs, \( t_0=6 \) µs, \( P_{cUS}=120\)W
As it can be noticed, the aspect ratio between depth and diameter of crater was 47.5% in case of EDM and 40% at EDM+US, emphasizing that ultrasonic shock waves modifies the crater profile turning it into a flatter shape. Since this a relative deep kind of crater, some material remains resolidified on crater margins against the case of relaxation pulses, pointed out at FEM modelling.

Data concerning the machined microtopography obtained with relaxation pulses with pure EDM and EDM+US are presented in figures 6, 7, together with their corresponding crater average profile in figures 8, 9.

In case of used relaxation pulses, the aspect ratio was 20%. At ultrasonic aiding, the aspect ratio became 16%, which highlights again the trend of reducing this parameter by removing the crater margins. This is a result of shear load produced by ultrasonic cavitation, when PcUS was optimized based on FEM results. This will be finally emphasized in case of both types of pulses.
The total hydraulic pressure ($p_{ht}$) variation in the gap is determined by elongation ($z$) – figure 10, according to relation:

$$p_{ht} = 2\pi \cdot c \cdot \rho \cdot f_{US} \cdot A \sin \omega t + p_{hl} \ [\text{Pa}],$$

(1)

where: $c$ is sound velocity in dielectric liquid [m/s]; $\rho$ - dielectric liquid density [kg/m³]; $f_{US}$ - ultrasonic frequency [Hz]; $A$ - amplitude of elongation $z$, [m]; $\omega = 2\pi f_{US} \ [\text{s}^{-1}]$; $p_{hl}$ - local hydraulic pressure [Pa]. In this case, the parameters values were: $p_{hl}=0.04\text{MPa}$, $\rho=840 \text{kg/m}^3$, $K=1.35 \times 10^9 \text{Pa}$ (K - bulk modulus), $c=(K/\rho)^{1/2}=1267.7 \text{ m/s}$, $A=2\mu\text{m}$, $f_{US}=20\text{kHz}$. At each final of ultrasonic period $T_{US}$, the cumulative microjets stage (CMS) occurs, collective implosion of gas bubbles, generating shock waves with pressure of 100 MPa order of magnitude, oriented along the frontal gap (horizontally) in case of EDM+US finishing tests.

3. Finite Element Modelling

Comsol Multiphysics, Structural Mechanics with Time Dependent variant was used for modelling the mechanical hydraulic component of EDM+US removal mechanism. A 2D parametric model was created for each type of pulse used (figure 11), taking into account the symmetry of machined geometry properties and cavitation phenomena.

![Figure 11. Example of assigned parameters for the model of hydraulic mechanical removal at EDM+US finishing tests with commanded pulses](image)

The load duration ($t_{US}$), produced by CMS is assimilated to time of bubbles shutdown, calculated with Rayleigh relation [7]:

$$t_{US} = \frac{2}{\omega} \ln \left(1 + \frac{1}{\alpha}ight)$$
\[ t_{US} = 0.915 R_m \sqrt{\frac{\rho}{P_{ia}}} \ [s], \]  

(2)

where \( R_m \) is maximal radius before contraction, limited by maximum frontal gap, 0.01 mm for these EDM+US finishing tests. The bubbles implosion time was determined around, \( t_{US} = 0.8 \mu s. \)

The material removal due to ultrasonic contribution is achieved mainly in solid state, by shearing the most sensitive parts of the microgeometry to this load type, the margins of craters, controlled by parameters \( a_{cr}, b_{cr} \) (e.g., 12.5 \( \mu m \), and 5 \( \mu m \) at relaxation pulses), and \( r_{ms} \). In case of commanded pulses producing deeper craters, the resolidified material amount is greater on crater margins, and therefore \( r_{ms} = 0.5 \mu m \) against the crater resulted from relaxation pulses using, where \( r_{ms} = 0.1 \mu m. \)

The boundary conditions were (figure 12): (a) pressure cyclic load (\( p_{US} \)) produced by CMS, applied on one flank of microcrater profile, resulted from previous discharges; (b) fixed constraint on the workpiece inferior surface due to vertical forces applied for clamping - workpiece orientation was on its bottom plane and lateral cylindrical surface through a bushing with inherent clearance.

The workpiece material was D3 (UNS T30403), corresponding to X210Cr12, with properties taken from Comsol library, completed by critical time dependent ones.

The meshing was achieved by 1862 triangular elements with an average quality of 0.967 on 0-1 scale provided by Comsol meshing module, and increasing finesse in the interest zone, where a higher precision is necessary (figure 12. b).

![Figure 12](image)

**Figure 12.** Boundary conditions and meshing: (a) pressure cyclic load on one flank of microcrater profile; (b) fixed constraint at the workpiece bottom with vertical clamping force

In order to underline the volume of material removed by hydraulic mechanical effect of ultrasonic cavitation, the ultimate tensile strength at fatigue pulsing cycle (\( \sigma_0 \)) was calculated [8]:

\[ \sigma_0 = 1.12(40 + 0.16 \sigma_r), \ [MPa] \]  

(3)

where: \( \sigma_r \) is the usual ultimate tensile strength. In case of X210Cr12, \( \sigma_r = 1500 \) MPa, and the parameter of interest is \( \sigma_0 = 313.6 \) MPa.
4. Results and Discussion

Some significant distributions of Von Mises stress resulted from FEM modelling are presented, affecting the machined surface roughness at EDM+US, using both types of EDM pulses: commanded (figure 13), and relaxation ones (figure 14). The ultrasonic pressure exerted by CMS shock waves (pUS) was varied in the range of 100-125 MPa. Von Mises stress above fatigue ultimate tensile strength (σ0), i.e. the coloured zone, indicated the volume of removed material.

Two zones of machined microgeometry are highlighted from the point of view of material removal: (1) the micropeak zone – when the material is removed from this area, the surface roughness (Ra) is reduced; (2) the microvalley zone – in this case, Ra is increased.

Two distinct behaviours are observed at pUS growing, corresponding to commanded and relaxation pulses, respectively: in figure 13, the material is removed gradually, starting from micropeak to microvalley; in figure 14, the zone of removed material is moved suddenly from micropeak to microvalley. Both threshold pUS values, at which the material removal begins in microvalley, are determined based on FEM results, and presented in figure 15.

![Figure 13. Von Mises stress [MPa] on microgeometry obtained with commanded pulses, higher than ultimate tensile strength of fatigue pulsing cycle, σ₀=313.6 MPa at different ultrasonic pressures, pUS](image-url)
The thresholds for ultrasonic pressure (pUS) are: 111 MPa at relaxation pulses, and 122 MPa at commanded pulses microgeometry (figure 15). Beyond these values, machined surface roughness increases. These values are in correspondence with the values of consumed power on ultrasonic chain PcUS, which determine the oscillation amplitude (A), affecting first term from relation (1). The experimental data confirmed these assumptions: optimum value of PcUS in terms of Ra minimization is 90 W for relaxation pulses, and 120 W for commanded pulses microgeometry (figure 16).
5. Conclusions
Ultrasonic assistance of EDM finishing is able to reduce a technological key-parameter, the machined surface roughness (Ra) if a critical optimization condition, related to the consumed power on ultrasonic chain (PcUS), which includes the tool, is achieved.

FEM modelling of material removal mechanism at EDM+US finishing reveals that at microgeometry obtained with commanded pulses (deeper craters, high aspect ratio), higher values of ultrasonic pressure cyclic load (pUS) are required to remove the margins of the craters against the case of relaxation pulses microgeometry (flatter clatters, low aspect ratio), where lower values pUS are needed.

This is in agreement with experimental data confirming that the power PcUS is higher at commanded pulses using, in order to reduce the machined surface roughness, i.e. remove the crater borders. In case of relaxation pulses microgeometry, the required power PcUS is lower, the margins to be removed being less robust, and therefore more sensitive to ultrasonic fatigue shear loads.

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References
[1] B. C. Khatri, P. Rathod, J. B. Valaki, Ultrasonic vibration–assisted electric discharge machining: A research review, Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture, March (2015) 1-12.
[2] S. Z. Chavoshi, X. Luo, Hybrid micro-machining processes: A review, Precision Engineering, 41 (2015) 1-23.
[3] D. Ghiculescu, Ultrasonically Aided Electrical Discharge Machining, in: M.P. Jahan (Ed.), Electrical Discharge Machining (EDM), Types, Technologies and Applications, Nova Publishers, 2015, pp. 151-208.
[4] Z.N. Guo, T.C. Lee, T.M. Yue, W.S. Lau, A study of ultrasonic - aided wire electrical discharge machining, Journal of Materials Processing Technology, 63 (1997) 823–828.
[5] A. Abdullah, M.R. Shabgard, Effect of ultrasonic vibration of tool on electrical discharge machining of cemented tungsten carbide (WC-Co), International Journal of Advanced Manufacturing Technology, October, 38, 11 (2008) 1137-1147.
[6] D. Ghiculescu, N.I. Marinescu, S. Nanu, Equipment for ultrasonic aiding of electrical discharge machining of microslots, Romanian Granted Patent, RO-126191/ 30.05.2012.
[7] I. Anton, Cavitation (in Romanian), Romanian Academy, Bucharest, 1984.
[8] V. Drobota, Resistance of Materials (in Romanian), Didactic and Pedagogical, Bucharest, 1982.