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FINITE ELEMENT MODELLING OF HYDRAULIC MECHANICAL REMOVAL MECHANISM AT ULTRASONICALLY AIDED EDM FINISHING

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ABSTRACT: The paper deals with finite element modelling (FEM) of material removal mechanism due to ultrasonically induced cavitation in the working gap at finishing modes of electrical discharge machining. The peaks of machined microgeometry are removed, having lower shearing resistance than the other parts of microgeometry, thus the surface roughness being reduced. Experimental data are presented that indicated an optimum value of power consumed on ultrasonic chain, including the electrode-tool, at which a minimum value for surface roughness was obtained. This corresponds to a pressure developed by collective implosion of the gas bubbles from the working gap, produced by shock waves oriented along the working gap, parallel to machined surface. This ultrasonic effect is considered a cycle pulse fatigue load on the flanks of microgeometry profile.

KEY WORDS: electrical discharge machining, ultrasonics, finishing, surface roughness.

1. INTRODUCTION

The problem of surface quality at EDM is very present on different machined materials nowadays [1], extending its applications field. The solution of ultrasonic aiding of electrical discharge machining (EDM+US) proved to be very effective at finishing and micromachining, i.e. at very narrow gap. This is substantiated in terms of the main technological parameters – surface roughness, volumetric relative wear/precision and machining rate – as many researches have reported in the last three decades [2, 3]. But very few researches reported the decrease of surface roughness as effect of ultrasonic aiding. At wire micro-machining, ultrasonic assistance produce better roughness [4]. Other researches 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 problem of surface roughness (Ra/Rz) decrease together with machining rate (V_W) increase by ultrasonic assistance consists in finding an optimum value for power consumed on ultrasonic chain (P_{cUS}) since the main two parameters are in fact two contradictory conditions in terms of energy level transferred between electrode-tool and workpiece.

These current researches are focused on determination of energy/power to actuate the ultrasonic chain, which includes the electrode-tool, based on experimental data and sustained by finite element modelling, being aware that this parameter strongly depends on real working conditions.

2. EXPERIMENTAL DATA

Experimental data revealed the decrease of machined surface roughness through ultrasonic aiding at EDM finishing modes. 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 – usual EDM (fig. 1). The electrode-tool from copper with disk shape of 25 mm diameter, and 3 mm height was used. The ultrasonic (US) chain included the tool at its end.

The working parameters were: current step, I=3 A, positive (tool) polarity; injection pressure, p_{hl}=0.04 MPa (through workpieces); consumed power on ultrasonic chain, P_{cUS}=0-120W; amplitude, A=2 μm, producing ultrasonic cavitation in the gap.

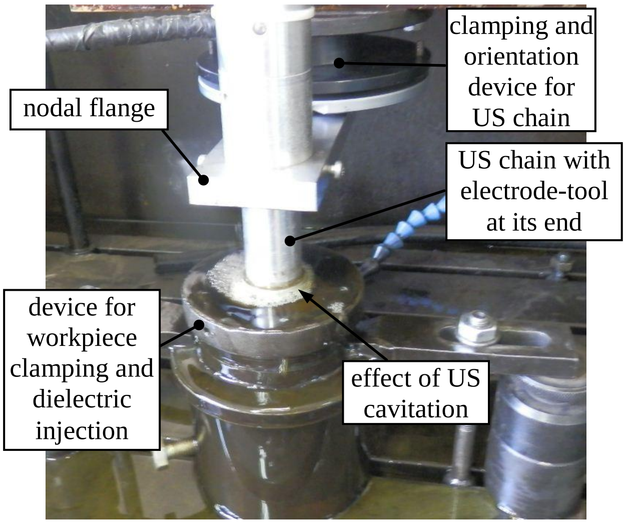


Figure 1. Technological system elements at EDM+US tests

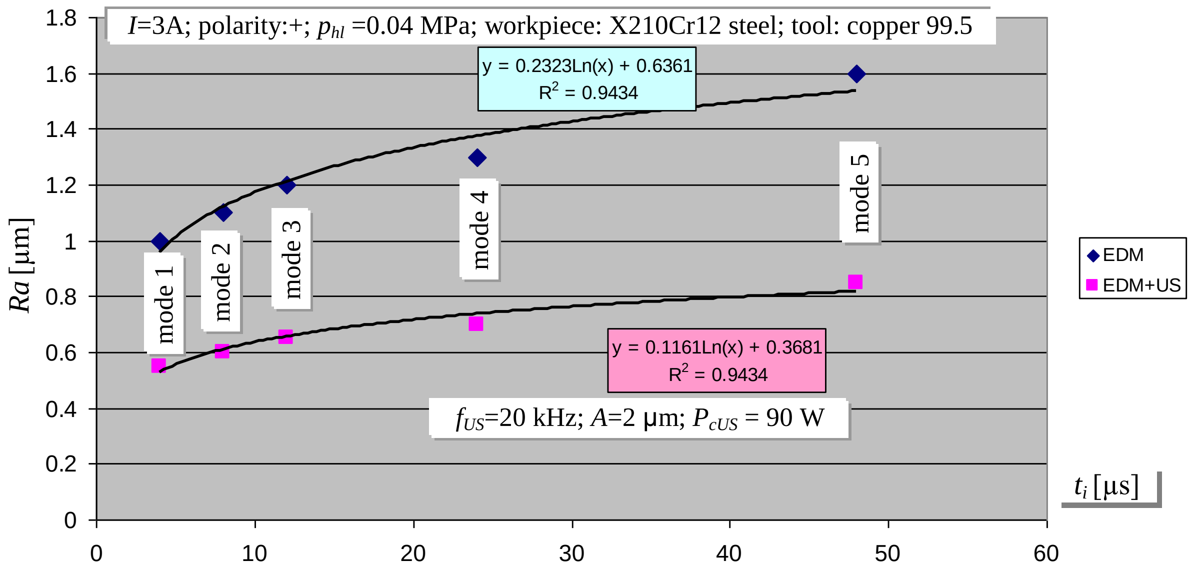


Figure 2. Machined surface roughness (*Ra*) as function of pulse time (t_i) at EDM+US and classic EDM, finishing modes

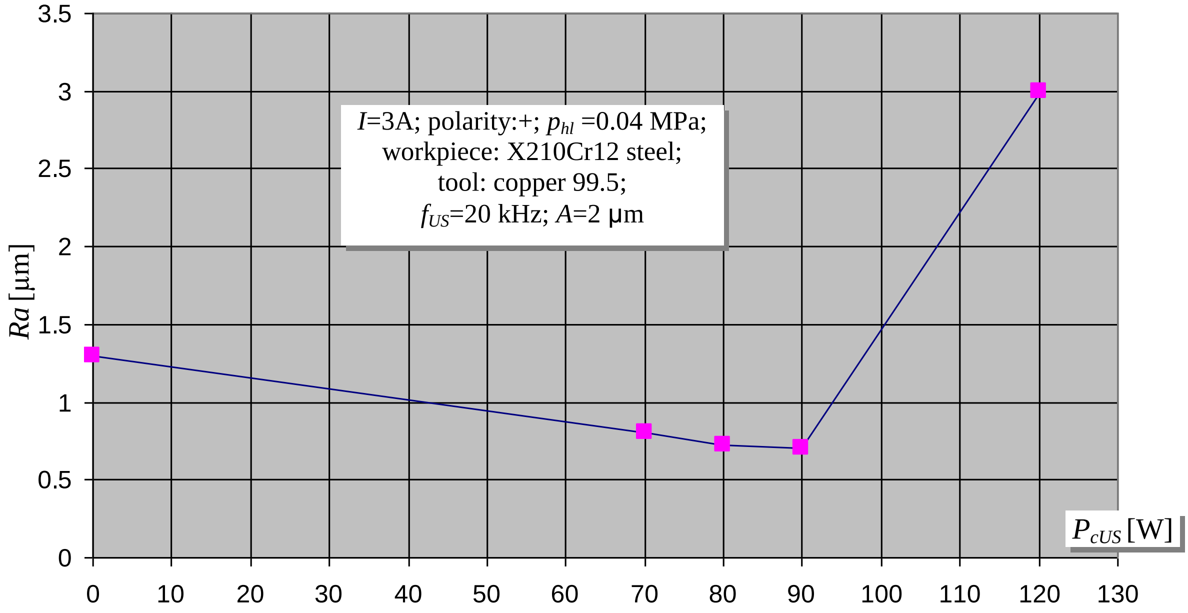


Figure 3. Machined surface roughness (*Ra*) as function of consumed power on US chain (P_{cUS}) at t_i=24 µs, t_0=12 µs

In fig. 2, machined surface roughness (*Ra*) as function of pulse time (t_i) obtained at EDM+US and classic EDM, is presented comparatively, using five finishing working modes: mode 1, t_0=2 µs (pause time), t_i=4 µs; mode 2, t_0=4 µs, t_i=6 µs; mode 3, t_0=6 µs, t_i=12 µs; mode 4, t_0=12 µs, t_i=24 µs; mode 5, t_0=24 µs, t_i=48 µs.

The decrease of *Ra* due to ultrasonic assistance is maintained in the range of 45-47%, using a consumed power on ultrasonic chain of 90 W.

This value was found to be optimum under these working conditions, as it is presented in fig. 3 - the variation of machined surface (Ra) as function of consumed power on ultrasonic chain (P_{cUS}) at t_i=24 µs, t_0=12 µs (mode 4).

As it can be noticed, an increase of P_{cUS} power over 90 W could grow the machined surface roughness, but also the machining rate. Since the main objective at finishing is Ra minimization, the solution of working with high value of P_{cUS} is not suitable.

Examples of machined surfaces microtopography obtained by classic EDM and EDM+US finishing, mode 4 are presented comparatively in fig. 4, 5. These were taken by Reichert Univar microscope and Buehler OmniMet Enterprise software.

Their corresponding profiles of microcraters produced by discharges under the same finishing mode at classic EDM and EDM+US are presented in fig. 6, 7. The craters depth was determined using a Taylor-Hobson surface instrument.

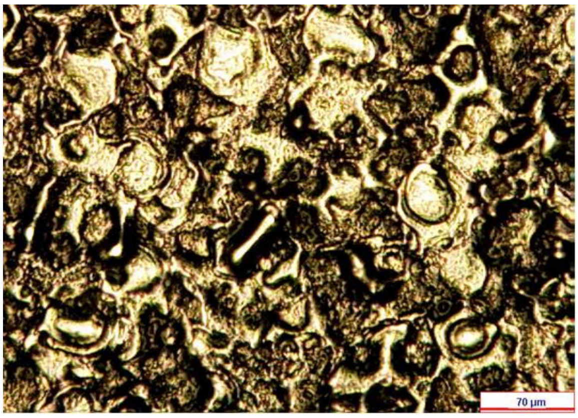


Figure 4. EDM microtopography with Ra=1.3 μm at I=3 A, t_i=24μs, t_o=12μs, positive (tool) polarity

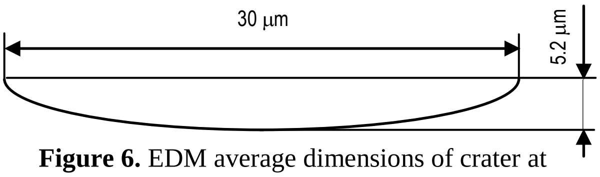


Figure 6. EDM average dimensions of crater at I=3 A, t_i=24μs, t_o=12μs, polarity +

As it results from consumed ultrasonic power (P_{cUS}) optimization, the average crater dimensions are lower at EDM+US than those from classic EDM. Naturally, the volume of material removed by discharge is greater at EDM+US, but the crater dimensions could be reduced, and implicitly the surface roughness Ra / Rz, due to the *cumulative microjets stage* (CMS), i.e. collective implosion of the gas bubbles from the working gap. Therefore shock waves are developed by CMS and oriented along the working gap, parallel to machined surface, shearing the margins of the craters. These are more sensitive to such type of high loads, 100 MPa order of magnitude, considered as fatigue pulse cycles, and occurring at each final of ultrasonic period [6]. These assumptions will be supported below by modelling the EDM+US removal mechanism described above by finite element method (FEM).

3. FEM MODELLING OF HYDRAULIC MECHANICAL REMOVAL MECHANISM

The material removal mechanism at EDM+US comprises two components: (1) a thermal one, which is specific to pure EDM, detailed in our previous papers as [6]; (2) a hydraulic mechanical one, which is the consequence of ultrasonic vibration of the electrode-tool perpendicular on machined surface. This vibration direction is more effective than the parallel to machined surface one [7].

Comsol Multiphysics, Structural Mechanics with Time Dependent variant was used for modelling the second component of EDM+US removal mechanism. A 2D parametric model was created taking account of machined geometry properties and cavitational phenomena as it is presented in fig. 8.

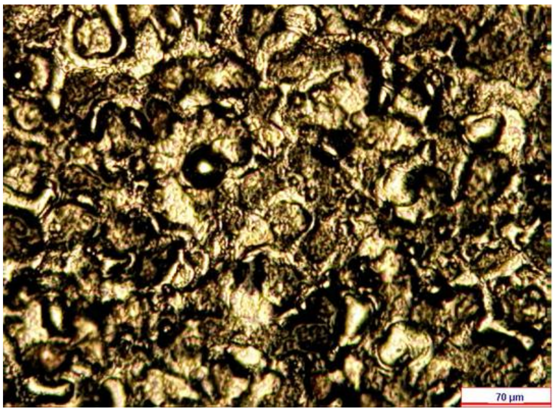


Figure 5. EDM+US microtopography with Ra=0.7 μm at I=3 A, t_i=24μs, t_o=12μs, positive polarity, P_{cUS}=90 W

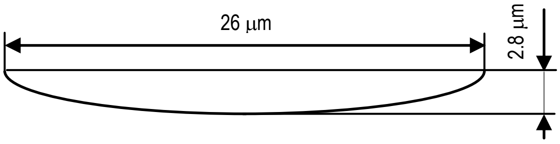
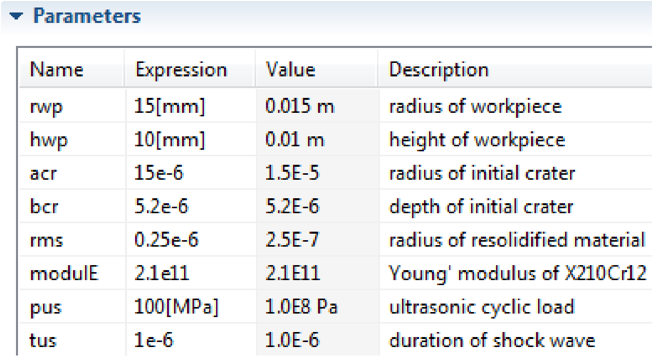


Figure 7. EDM+US average dimensions of crater at I=3 A, t_i=24μs, t_o=12μs, polarity +, P_{cUS}=90 W



▾ Parameters

Name	Expression	Value	Description
rwp	15[mm]	0.015 m	radius of workpiece
hwp	10[mm]	0.01 m	height of workpiece
acr	15e-6	1.5E-5	radius of initial crater
bcr	5.2e-6	5.2E-6	depth of initial crater
rms	0.25e-6	2.5E-7	radius of resolidified material
modulE	2.1e11	2.1E11	Young' modulus of X210Cr12
pus	100[MPa]	1.0E8 Pa	ultrasonic cyclic load
tus	1e-6	1.0E-6	duration of shock wave

Figure 8. Parameters assigned for the model of hydraulic mechanical removal mechanism at EDM+US finishing

On one flank of craters profile produced by EDM was applied a variable cyclic load as pressure (p_{US}) with gradually increased value in order to estimate the volume removed through shock waves produced by CMS. This occurs cyclically at each final of dielectric liquid stretching semiperiod (fig. 9).

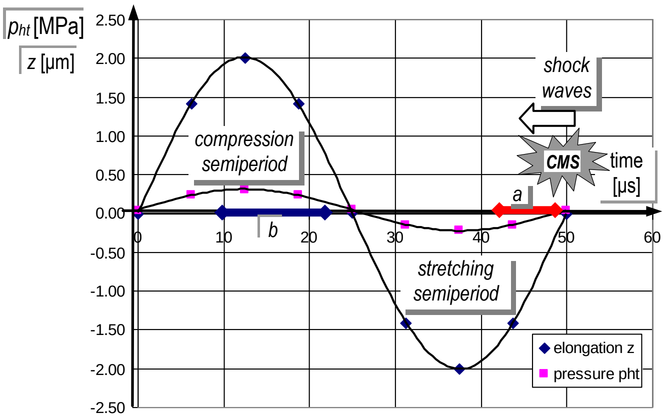


Figure 9. Elongation (z) and total pressure (p_{ht}) in the gap within an ultrasonic period of T_{US}=50 μs (f_{US}=20kHz)

This is governed by total hydraulic pressure (p_{ht}) variation in the gap, calculated with the relation:

$$p_{ht} = 2\pi \cdot c \cdot \rho \cdot f_{US} \cdot A \sin \omega t + p_{hl} \quad \text{[Pa]}, \qquad (1)$$

where: c is sound velocity in dielectric liquid [m/s]; ρ - dielectric liquid density [kg/m^3]; f_{US}-ultrasonic frequency [Hz]; A-amplitude of elongation z, [m]; $\omega=2\pi\, f_{US}$ [s^{-1}]; p_{hl} - local hydraulic pressure [Pa]. The parameters values were: p_{hl}=0.04MPa, ρ=840 kg/m^3, K=1.35x10^9 Pa (K - bulk modulus), $c=(K/\rho)^{1/2}$=1267.7 m/s, A=2µm, f_{US}=20kHz.

Within an ultrasonic period T_{US}=50 µs, the pulses could be delivered close to CMS with a low probability (case (a) in fig. 9), and then the shock waves are able to stop the discharge as the experiments pointed out. So, the dielectric liquid enters the EDM spot since the gas bubble formed around the plasma channel of discharge is collapsed. At this moment, the material is removed in liquid state through thermal component of removal mechanism (1), this being the main source of machining rate increase through ultrasonic aiding.

In case of delivering the pulses outside CMS time interval with a much larger probability of delivering, (case (b) in fig. 8), t_{US} lasting only around 1 µs, the material melted by discharge is already solidified at CMS occurring. The process of resolidification is completed roughly within 1 µs after pulse end [8].

Therefore in this case, the material removal due to ultrasonic contribution is achieved mainly in solid state, by shearing the most sensitive parts of the microgeometry to this kind of load. These are the margins of the EDM craters (controlled by parameters a_{cr}, b_{cr}, r_{ms}, see fig. 8). The component (2) is responsible of machined surface roughness decrease if the ultrasonic load (p_{US}, see fig. 8) is optimized or roughness increase if not, as FEM results will emphasize below.

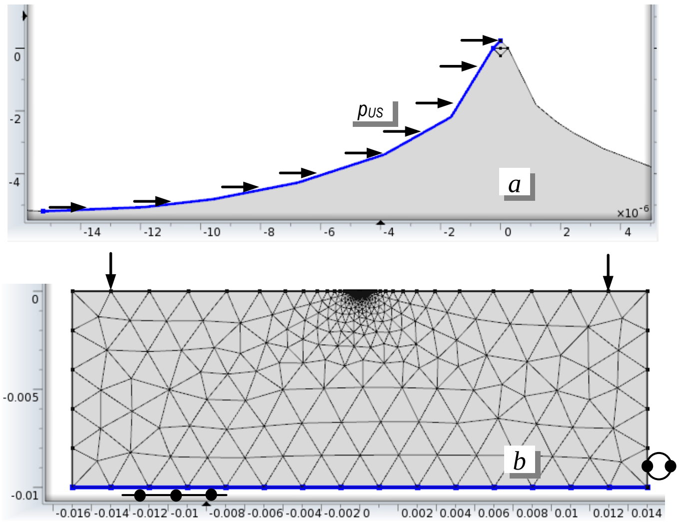


Figure 10. Boundary conditions and meshing: (a) pressure cyclic load on one flank of microcrater profile; (b) fixed constraint at the workpiece bottom with vertical clamping force

The boundary conditions were (fig. 10): (a) pressure cyclic load (p_{US}) applied on one flank of microcraters profile, obtained by previous discharges; (b) fixed constraint on the workpiece inferior surface since forces were vertically applied for clamping - workpiece orientation was on its bottom plane and lateral cylindrical surface, using a bushing with inbuilt clearance.

The worpkpiece material was D3 (UNS T30403), corresponding to X210Cr12, whose properties were taken from Comsol library and completed with required time dependent ones.

The meshing was achieved by 2307 triangular elements with an average quality of 0.97 on 0-1 scale, and increasing finesse in the interest zone, where a higher precision is necessary (fig.10. b).

In order to put in evidence the volume of material removed by hydraulic mechanical effect of ultrasonic cavitation, the ultimate tensile strength at fatigue pulsing cycle (σ_0) was calculated, using the relation [9]:

$$\sigma_0 = 1.12(40+0.16\, \sigma_r), \quad \text{[MPa]} \qquad (2)$$

where: σ_r is the usual ultimate tensile strength. In case of X210Cr12, σ_r=1500 MPa, and the necessary parameter is σ_o =313.6 MPa.

4. FEM RESULTS

The most significant examples of distribution of Von Mises stress are presented below, resulted from FEM modelling, showing the volume of material removed by CMS shock wave, affecting the machined surface roughness at EDM+US.

The ultrasonic pressure exerted by CMS shock waves (p_{US}) was varied in the range of 100-200 MPa, and Von Mises stress above ultimate tensile strength at fatigue pulsing cycle (σ_0), i.e. the coloured zone, indicated the removed material – fig.11. a-e.

As it can be noticed, two zones of machined microgeometry are emphasized 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. At lower values of ultrasonic pressure p_{US}, the material is removed exclusively from the micropeak zone. When p_{US} is progressively increased, the volume removed is also increased, but Ra is still improved (fig. 11. a, b). At higher p_{US} values, the material begins to be removed gradually from the microvalley, the surface roughness being affected negatively (fig. 11.c-e).

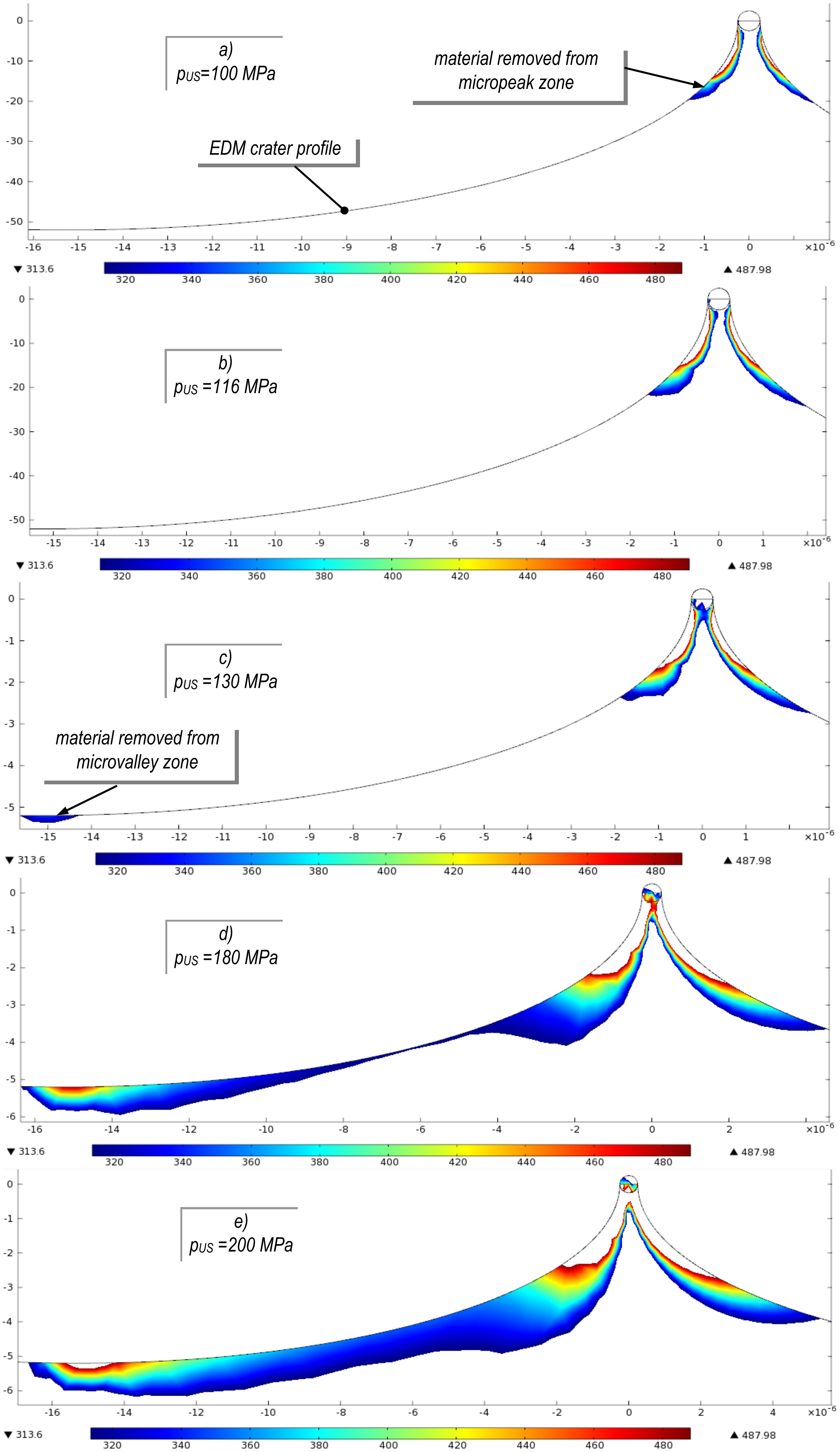


Figure 11. Von Mises stress [MPa] on sample microgeometry from X210Cr12, higher than ultimate tensile strength of fatigue pulsing cycle, σ_o=313.6 MPa at different ultrasonic pressures exerted by shock waves

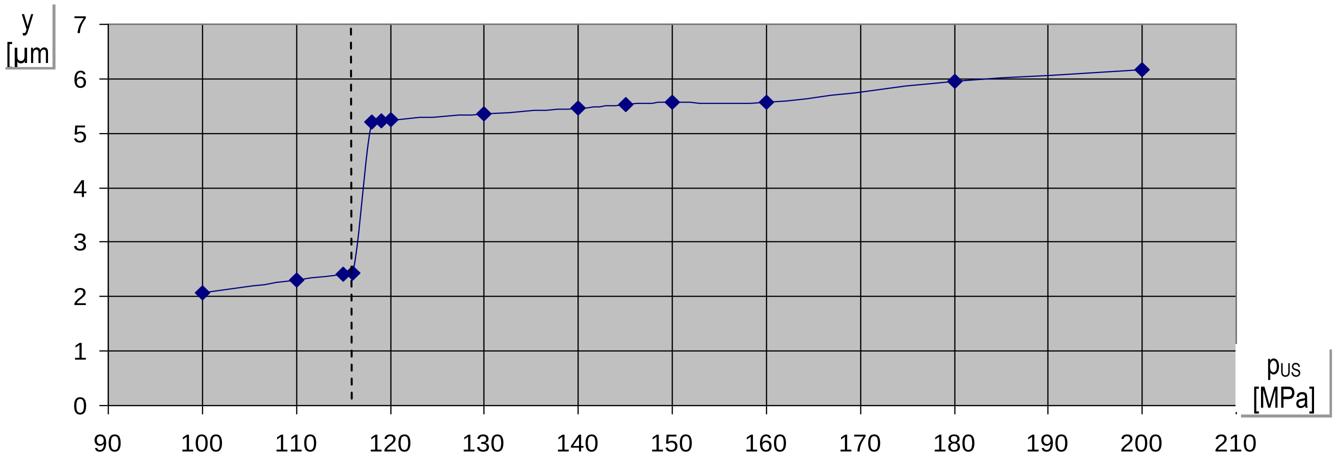


Figure 12. Depth variation (y) of layer removed as function of ultrasonic pressure of shock wave (p_{US})

The variation of layer depth ultrasonically removed as function of ultrasonic pressure p_{US} is presented in fig. 12. It can be noticed that a threshold of 116 MPa in terms of ultrasonic pressure is emphasized, when the layer depth is increased suddenly because the material begins to be eroded also from the microvalley. This determines the dramatic increase of the surface roughness.

5. CONCLUSIONS

The volume removed by ultrasonic aiding of electrical discharge machining finishing can be increased normally by both constituents of material removal mechanism of EDM+US: thermal and hydraulic mechanical component. The ultrasonic assistance naturally increases the machined surface roughness. Nevertheless, the surface roughness can be decreased by optimization of consumed power on ultrasonic chain (P_{cUS}), corresponding to ultrasonic pressure exerted by shock waves (p_{US}) produced by induced cavitation in the working gap. The working key-parameter P_{cUS} strongly depends on real machining conditions and has to be determined experimentally.

6. ACKNOWLEDGEMENT

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