

CAVITATIONAL PHENOMENA AND FEM MODELLING AT ULTRASONIC AIDED EDM. COMPARISON WITH CLASSIC EDM

Assoc. Prof. Daniel GHICULESCU, Prof. Nicolae Ion MARINESCU

“Politehnica” University of Bucharest, Romania

Abstract: The paper deals with Finite Element Method (FEM) of material removal process at ultrasonic aided EDM (EDM+US), compared to classic EDM, aiming at improving the main output parameters of EDM+US technology. The starting stage of FEM modeling is the study of cavitation phenomena from the gap, which represents additional mechanism leading to spectacular increasing of machining rate. Finally, FEM results are compared with experimental data in order to validate the model of EDM+US process.

Keywords: electrodischarge machining, ultrasonics, FEM modelling, cavitation.

1. INTRODUCTION

The paper emphasizes the necessary stages for modelling and simulation through Finite Element Method (FEM) of electrodischarge machining aided by ultrasonic longitudinal oscillations of electrode-tool (EDM+US) applied at finishing/micromachining. The well known instability of the removal process in case of classic EDM finishing/micromachining due to very working gap, less than $10\ \mu\text{m}$, can be solved by cavitation phenomena ultrasonically induced inside the gap. The process simulation in case of machining some types of microgeometry is presented, involving: modelling, meshing, boundary and loading conditions, visualization and validation. The starting point of modelling is based on study of gas bubbles development from the gap.

At the first sight, a secondary parameter relative to material removal mechanism process, the life duration of gas bubble formed around plasma channel of the discharge plays an important part, because it dictates the access of hydraulic forces of dielectric liquid within the zone adjacent to EDM spot and thus the material melted by discharge can be removed [1], [2].

2. COMPARATIVE ANALYSIS BETWEEN LIFE DURATION OF GAS BUBBLES AT CLASSIC EDM AND AIDED BY ULTRASONICS

The gas bubble of thermal nature produced by electrodischarge is the result of vapours accumulation from heating the workpiece and electrode material and mainly,

of surrounding dielectric liquid. During bubble development, there is no possibility that dielectric liquid enters within the vicinity of discharge channel base (EDM spot) and evacuates the melted material by discharge, through hydraulic forces.

The validation of many models attempting to evaluate the life duration is a difficult problem under conditions in which these phenomena occur at micrometric dimensions within working gap (the frontal one, S_F) at EDM finishing and micromachining.

A basic model of classic EDM is the Van Dijk's one, [3] which in case of 1 A discharge current and $10\ \mu\text{s}$ pulse time predicts that bubble life duration is around $180\ \mu\text{s}$. Amazing progresses concerning models validation were achieved only using video high speed camera with 10^5 and 10^6 frames/s, beginning with 1980 decade.

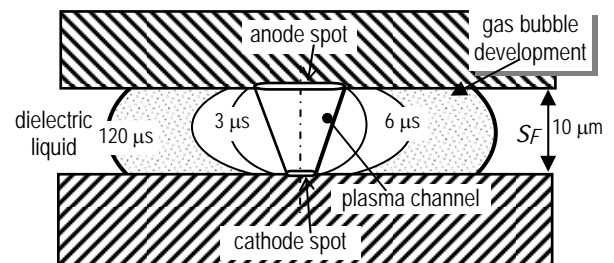


Fig. 1. Qualitative variation of gas bubble at classic EDM finishing / micromachining, pulse time $6\ \mu\text{s}$

Kremer et al. [4] and many other researchers used such camera type. A special arrangement must be made in order to visualize the bubble evolution during discharge, i.e. the electrode must be pointed,

or have reduced dimensions (μm order of frontal part).

At EDM finishing and micromachining, at around 1A discharge currents, the gas bubble is much bigger than plasma channel and EDM spots, in the order of 0.1 mm [5].

Modelling and simulation based on finite element method validated by experimental data [6], [7] confirmed that plasma channel has a conical shape with reduced dimensions next to cathode spot, approximately 4 times comparing to anode spot (fig. 1).

More recent results, confirming Van Dijck's model, were reported [5]. In case of EDM finishing or micromachining single discharge, it resulted that the gas bubble is still there, even after 120 μs from electrical break down of insulating medium at maximum working current of 25 A and pulse time of 6 μs (fig.1).

Several types of experiments with single discharges indicated that life duration of gas bubbles of thermal nature, resulted from EDM phenomena is of 10...20 times bigger than pulse time at finishing and micromachining.

In fig. 1, a qualitative variation of gas bubbles dimensions variation is presented. The gas bubble development comprises the following stages: (a) pre-ignition; (b) dielectric breakdown (discharge); (c) evolution during discharge (3 μs); (d) evolution at pulse end (6 μs); (f) evolution long time after pulse end (120 μs).

After bubble collapse, no material removal is achieved because it is already solidified, but only a clearing up of the working gap is completed.

The real relative dimensions of gas bubble could be evaluated, using high speed camera at different values of discharge current $I = 5 \dots 45 \text{ A}$ [5]. At finishing and micromachining, the values of interest regarding the maximum current are 5 and 10 A. The gas bubble increases after the pulse end and reaches a radius of around 0.6 mm.

In real processes comprising successive discharges, the life duration of the gas bubble formed around the plasma channel could be much shortened by the following electrical discharge due to the pressure created by new plasma channel development.

This is related to the phenomenon of successive discharges placement in relative close spaces as it was reported by several researches, using specialized equipments to

locate the discharges at classic EDM [8], [9], [10].

The discharges succession due to decreased dielectric capacity of working medium has the capacity to remove a great amount of material from the same zone, and stops only after the corresponding frontal gap increases to such a value that determines growing of electrical resistance due to higher value of s_F . The following discharges move to another zone, under the criterion of minimum frontal gap (s_F), the cycle of successive discharges being resumed.

This phenomenon is also explained by the proximity where the next discharge occurs, which is determined by high conductivity of working medium, the result of ionization state generated by previous discharge. The dielectric liquid capacity can not be restored if pause time is not sufficient. Experimental data pointed out that after pause time ranged between 2 and 5 μs , the gas bubble formed when working with parameters corresponding to micromachining still exists in the gap even after 750 μs [5].

Due to gas bubble high volume compared to less than 10 μm gap (fig. 1), next discharge could be produced in gaseous medium.

The life shortening of gas bubble is strongly dependent on ignition delay time (t_d); its dependence from other process parameters can be described as:

$$t_d \sim \frac{s_F^3}{\kappa \cdot u_0^2} \quad (1)$$

where: κ is electrical conductivity of working liquid; u_0 - ignition voltage, generally, a constant of EDM generator.

Analyzing relation (1), it can be noticed that delay time is very sensitive to κ . In case of finishing, this could be expressed in relative long t_d - more than 100 μs as our experimental data pointed out [1], [2] - due to low electrical conductivity. This is the result of low energy discharge, specific to finishing and micromachining. So, in this case, at classic EDM, life time of gas bubble could last long time after pulse end, and consequently a great amount of material could be already solidified by the time that hydraulic forces could access the EDM spot.

When the electrode-tool longitudinally vibrates with ultrasonic frequency, usually 20 kHz, during EDM+US, cavitation phenomena are induced in the frontal gap.

An acoustic pressure (p_{ac}) is created inside dielectric liquid, which can be calculated with the relation:

$$p_{ac} = 2\pi \cdot f_{US} \cdot c \cdot \rho \cdot z \quad (2)$$

where: f_{US} is ultrasonic frequency [Hz]; c - sound velocity in dielectric liquid [m/s]; ρ - dielectric liquid density [kg/m³]; z - electrode elongation [m], determined with:

$$z = A \sin \omega t \quad (3)$$

where: A is oscillation amplitude [m]; $\omega = 2\pi f_{US}$ [s⁻¹].

Total hydrostatic pressure (p_{ht}) also takes into account the local pressure from the gap (p_h):

$$P_{ht} = P_{ac} + P_h \quad (4)$$

Total hydrostatic pressure (p_{ht}) variation along the elongation is represented in fig. 2, based on relations (2-4). We used amplitudes of 2 μm that were enough to produce cavitation – thus p_{ac} was over cavitation threshold (p_{cav}) under our working conditions in dielectric liquid that has a density of 840 kg/m³ (P3 oil) ; p_h was considered 0.1 MPa.

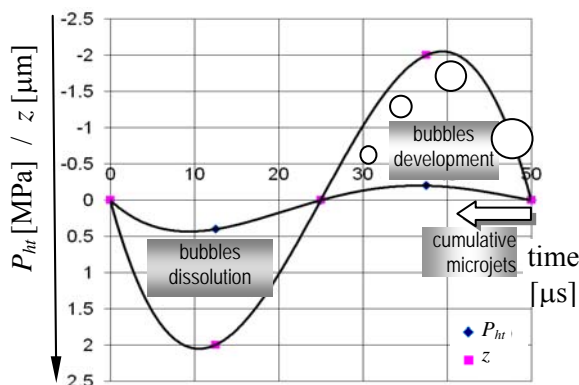


Fig. 2. Variation of tool elongation and hydrostatic pressure within the frontal gap at EDM+US finishing/micromachining

As one can see from fig. 2, the ultrasonic oscillation period, (T_{US}), which, in this case, has 50 μs , comprises two semiperiods, characterized by capillary phenomena due to micrometric gap between electrode and workpiece:

(1) liquid compression when p_{ht} is positive and all the bubbles from the gap are dissolved;

(2) liquid stretching when p_{ht} becomes negative and the gas bubbles are developed

till the final of oscillation period when the pressure from the gap increases again. This is the moment of cumulative microjets stage when all the bubbles from the gap implode, producing pressure of 100 MPa order [11].

Using P3 oil, at maximum frontal finishing gap, $s_F=10 \mu\text{m}$ and $p_h = 0.1 \text{ MPa}$, according to Rayleigh [11], it results a bubble shutting down time, $\tau=0.8 \mu\text{s}$. This cavitation phenomenon is equivalent to a single discharge effect, but multiplied by millions times, as the number of bubbles imploding in the same time within the working gap. This collective implosion acts like a decisive additional mechanism in the frame of material removal process as it will be emphasized at FEM modelling.

Comparing to classic EDM, at US aiding, the bubble surrounding plasma channel has short life, the cumulative microjets removing almost all material melted by discharge; thus V_W is much increased. These cavitation phenomena from the gap can be related to the polarity effect which takes advantage of energy distribution on anode/cathode couple [1], [2].

The liquid compression from the first semiperiod stops the plasma channel development. Consequently, current density J and anode power, P_a / cathode power, P_c , ratio are increased. Taking account of polarity effect, negative polarity together with small time pulses are recommended in order to increase machining rate (anode power) and decrease electrode wear (cathode power).

The stretching semiperiod is favourable to plasma channel development, inertia forces of dielectric liquid being low. According to polarity effect, when current density J lowers, then P_a/P_c ratio also decreases. Hence, it is useful to work with positive polarity, in order to maximize the power to workpiece, which is the cathode in this case. Thus, the polarity effect helps to increase machining rate and decrease electrode wear.

Based on these considerations, commanded pulses are recommended to be used because they can be controlled and delivered within the stretching semiperiod – synchronized with tool oscillations.

This is an objective of our further researches to produce a specialized EDM generator dedicated to EDM+US finishing/micromachining, which aims at growing of EDM efficiency.

3. FEM MODELLING OF ULTRASONIC AIDED EDM

As input data for EDM+US modelling by FEM, the thermo physical characteristics of main constituents of materials to be machined are considered.

In case of steels micromachining, thermo-physics characteristics, specific heat, density, thermal conductivity, melting point of ferrite and cementite were inserted as it is presented in table 1, because Fe α and Fe₃C have dimensions of μm order, the same as EDM spots produced on machined surface.

Table 1. Thermo physical characteristics of steel main constituents

Consti- tuents	Specific Heat [J/kgC]	Density [kg/m ³]	Conduc- tivity [J/ m s C]	Melting Point [°C]
Fe α	449,3	7870	75,24	1538
Fe ₃ C	501,6	7200	50,16	1227

The types of boundary conditions were: (a) constant surface temperature; (b) constant output thermal flux.

These were based on Utsumi's measurements concerning the spot temperature and Conn's hypothesis related to narrowing of the plasma channel in the cathode zone, previously experimentally confirmed [3], also in high agreement with our experimental data [6], [7]. Consequently, the following boundary conditions related to (a) are inserted: at EDM micromachining with relaxation pulses, negative polarity (electrode-tool is cathode), the temperature on anodic spot, was $t_{aspot}=2500$ °C and its radius, $R_{aspot}=10$ μm ; at EDM micromachining with commanded pulses, with positive polarity (electrode-tool is anode), cathode spot temperature is $t_{cspot}=2550$ °C and its dimension, $R_{cs}=2.5$ μm . For condition (b), a constant output thermal flux of $\Phi = 0.1$ W/mm² was taken into account.

Concerning meshing, in the first stage, 2D meshing, on frontal surface of workpiece to be machined was achieved. In order to rationalize the use of calculation resources, a progressively finer discretization in interest zone, adjacent to cathodic/anodic spot, was accomplished. The elements dimensions were: 1; 2.5 μm ; 5 μm ; 10 μm ; 15 μm ; 20 μm ; 25 μm ; 50 μm etc. At the peripheral areas of workpiece, the finesse of discretization was

very much diminished to element dimensions up to mm order.

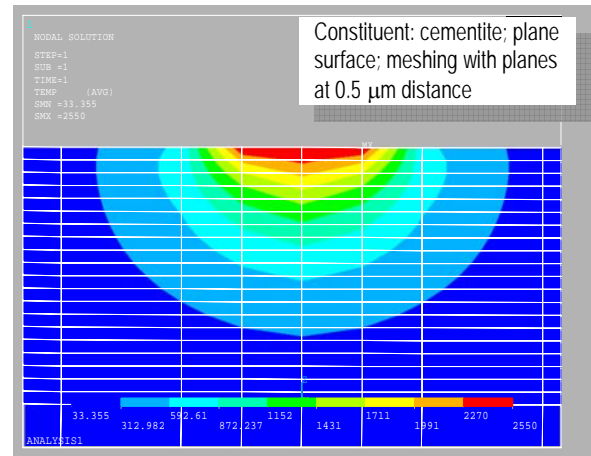


Fig. 3. Temperature distribution after 4 μs commanded pulse on plane microgeometry

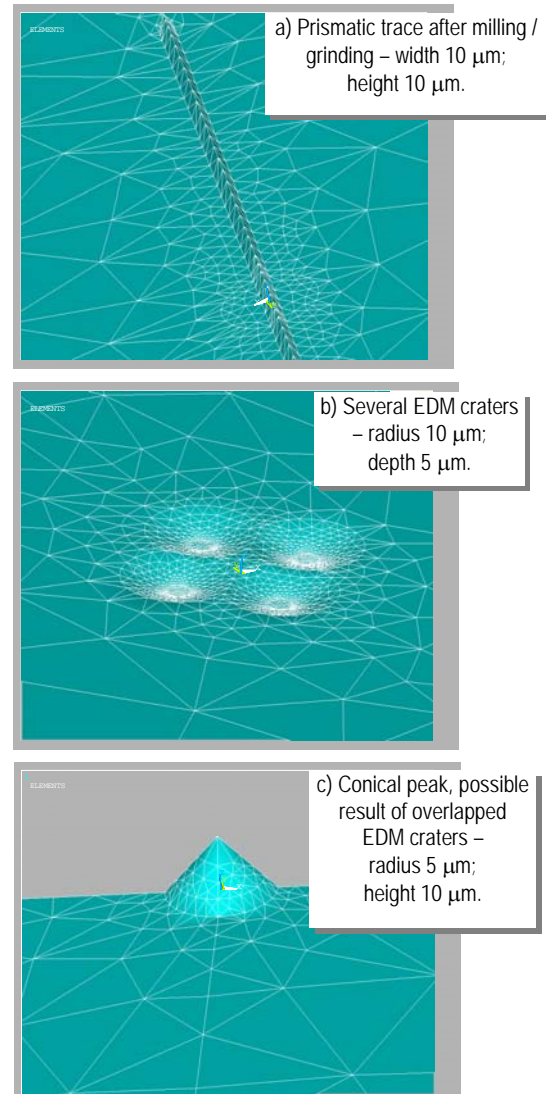


Fig. 4. Meshing on different microgeometries

In the second stage, the meshing was extended in 3D by generating elements, identical to those from frontal surface, on parallel horizontal planes, distanced to 0.5 μm one of each other (fig. 3).

The calculation model was parameterized, using 3D ANSYS thermal models (SOLID 70 type), which provides options for state changing. This element type can also take into account mass transport and allows standard thermal solutions to be interpreted as output parameters from fluids flow.

This multistage meshing was applied on different microgeometry shapes that can be assimilated as previous surface machinings, e.g. plane milling or grinding, rough EDM etc., as it is shown in figure 4. a, b, c.

All temperature distributions on frontal view and transversal section (fig. 3, 5-9) pointed out that volume removed in case of US aiding is 4-5 times greater than in classic EDM finishing.

The volume removed by a single discharge at EDM+US is bordered by melting isothermal, 1538 $^{\circ}\text{C}$ in case of ferrite, and 1227 $^{\circ}\text{C}$ in case of cementite. At steels classic EDM, the volume removed is framed by boiling isothermal 2500-2550 $^{\circ}\text{C}$. This is explained in terms of gas bubble duration formed around plasma channel during discharge [1].

We also emphasize that better understanding of removal mechanism is not possible without taking into account the specific shape of machined surface microgeometry. For comparison, the temperature distribution on transversal section in case of rigorous plane surface is presented in fig. 3.

As it can be observed the depth of the crater bordered by melting isothermal is roughly 2.5 μm which is in disagreement with experimental data presented in fig. 10 that statistically illustrates deeper craters produced by commanded pulses.

At EDM+US, if the discharge is produced during stretching semiperiod all bubbles implode at final of this semiperiod when liquid compression recommences, in cumulative microjets stage.

At classic EDM, the bubble life lasts much longer after pulse end - ms order, according to Van Dijck's model [3] later confirmed [5]. The consequence is that by this time, material melted by discharge is

already solidified compared to EDM+US, when it is still in liquid state when the bubble collapses. At classic EDM, material is mainly removed at the end of pulse when overheated material with 200-300 $^{\circ}\text{C}$ over boiling temperature during discharge suddenly boils due to pressure decrease [3].

Data provided by FEM confirm that at finishing or micromachining, high homogenous structure is preferred with as much as possible ferrite content. In fig. 5, the temperature distribution after the same single commanded pulse is presented on ferrite and cementite. Due to different thermo-physical characteristics of these constituents, the crater depth produced by EDM+US is 7.2 μm respectively, 11.2 μm .

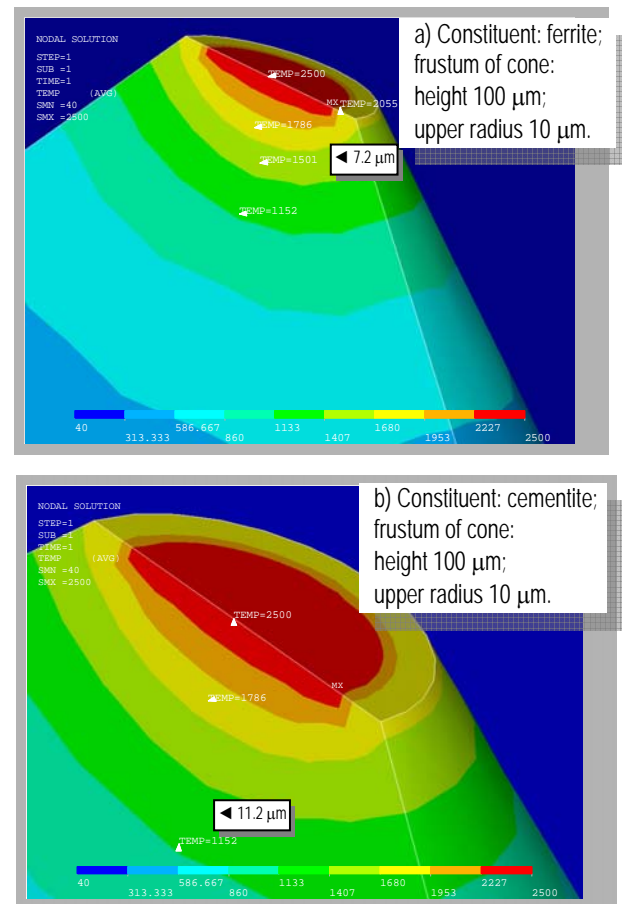


Fig. 5. Temperature distribution after 4 μs commanded pulse on conical microgeometry

If discharges occur in the first semiperiod of compression within the ultrasonic oscillation period, the advantage of shortening the bubble life formed around the plasma channel could be lost.

The cumulative microjets stage would take place after roughly double time than in

case of discharges located during the stretching semiperiod. In this case, much more material melted by discharge could be solidified by the end of ultrasonic period.

In order to take advantage of lowering the bubble life time generated by ultrasonic aiding, commanded pulses must be used, because they can be controlled to occur within stretching semiperiod.

Although commanded pulses have the advantage of correlation with ultrasonic longitudinal oscillation of the tool, at classic EDM, relaxation pulses are more effective as it is presented in fig. 6.

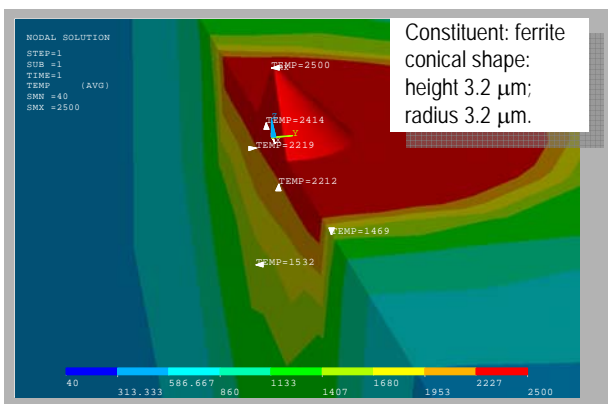


Fig. 6. Temperature distribution produced by 0.5 μs relaxation pulse on conical microgeometry

Thus, the entire protrusion can be removed by discharge (the volume bordered by boiling isothermal, 2500 °C) even in case of ferrite with low thermal absorption capacity. In comparison, when analyzing the temperature distribution produced by commanded pulse, it can be noticed (fig. 7), that at classic EDM, the same conical shape is not entirely removed by a single discharge (the volume bordered by 2550 °C isothermal).

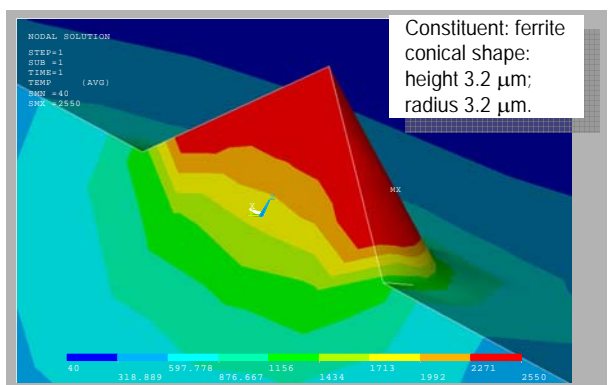


Fig. 7. Temperature distribution produced by 4 μs commanded pulse on conical microgeometry

When the discharge produced by commanded pulse is aided by ultrasonics, the melted volume is bordered by 1538 °C isothermal, the entire conical shape being removed.

The efficiency of relaxation pulse is also visible on prismatic shapes generated by milling or grinding as it is presented in fig. 8. The entire protuberance in transversal section can be removed by single discharge at classic EDM (2500 °C isothermal) even in case of ferrite.

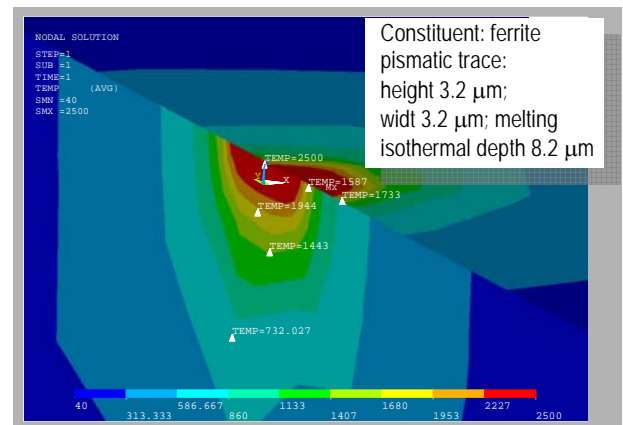


Fig. 8. Temperature distribution produced by 4 μs commanded pulse on prismatic microgeometry

The longitudinal traces produced by plane grinding (see fig. 4.a) determine lower depth of EDM craters than in case of accidental microtopography with isolated peaks (fig.5-7). This phenomenon can be explained by increasing the adjacent volume to EDM spot on which thermal energy produced by discharge is dissipated.

Finally, we focused on analysis of temperature distribution after a discharge located on surface entirely covered by craters produced by previous rough EDM (fig. 4.b).

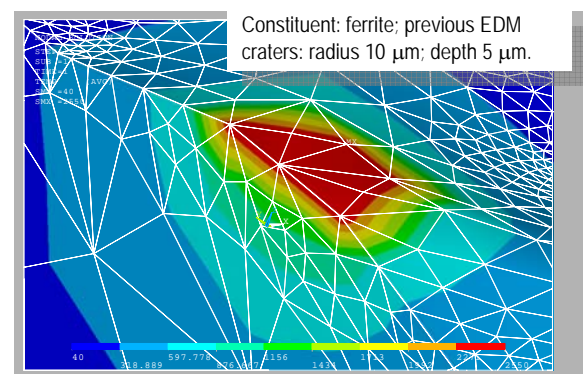


Fig. 9. Temperature distribution produced by 4 μs commanded pulse on previous rough EDM

When the discharge produced by commanded pulse of 4 μs is located in geometrical centre of the microtopography, comprising four such EDM craters, one can notice that the zone of thermal influence does not cover the entire surface of craters (fig. 9). Thus, the most part of craters margins have the ambient temperature of dielectric liquid, 40°C.

In whole modelling of microgeometries presented above, the overall dimensions of technological systems had not a significant influence upon the temperature distribution produced by discharge. It can be observed that the surfaces of workpiece are still at ambient temperature 40 °C (dielectric liquid temperature) after the discharge produced by any type of pulse.

Although melting isothermal highlights that at EDM+US craters are deeper (fig. 3, 5-9), experimental data pointed out that are not deeper than those from classic EDM, as it is presented in fig. 10 if some optimization conditions are fulfilled [1]. This proves that cumulative microjets remove material also in solid states. This is the effect of levelling machined surface (decreasing R_a), by removing the margins of craters, which are more sensitive to shear loads produced by orientation of ultrasonic shock waves parallel to machined surface developing pressure in order of 100 MPa.

Aiming at levelling machined surface, the power for actuating the acoustic chain was decreased close to corresponding value producing cavitation. In case of relaxation pulses, which generate flatter craters, with margins having lower shear resistance to ultrasonic shock waves, the actuating power must be diminished by 30% in order to not damage machined surface. We used values of around 100 W to actuate the acoustic chain, for commanded pulses, and surface roughness was decreased with up to 50%.

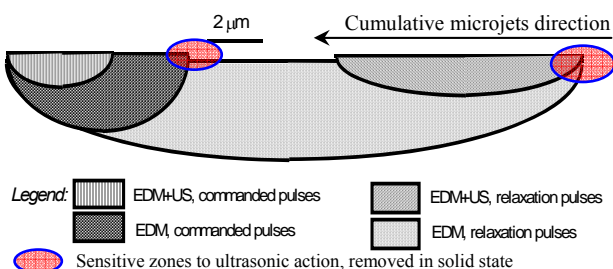
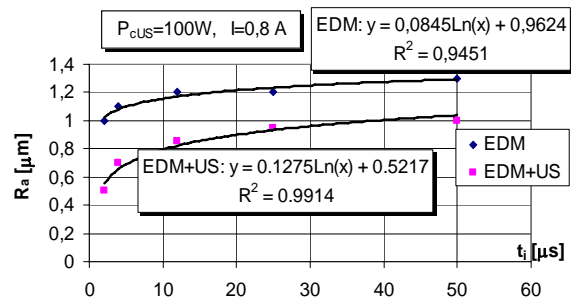


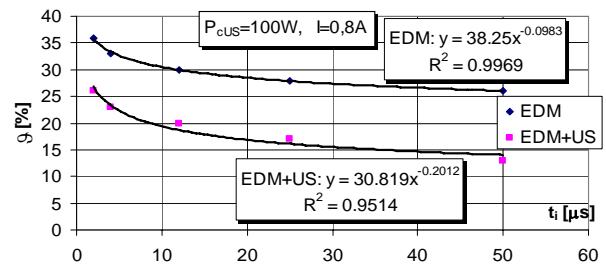
Fig. 10. Crater dimensions in transversal section experimentally determined

4. TECHNOLOGICAL PERFORMANCES OF EDM+US

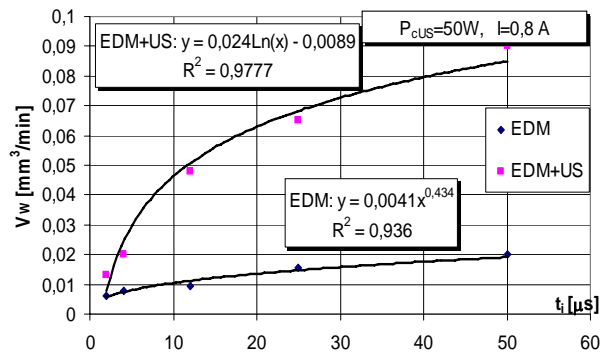
Based on optimization conditions of input working parameters [1], some experimental curves of main technological parameters obtained by method of least squares, are presented in figure 11 in order to point out the technological performances of EDM+US finishing/micromachining:



a) Surface roughness (R_a) versus pulse time



b) Relative volumetric wear (ϑ) versus pulse time



c) Machining rate (V_w) versus pulse time

workpiece - C120 steel (2%C, 12%Cr); 30 flat electrode - Cu 99.5; dielectric liquid - 22% aromatic hydrocarbons (P3 oil)

Fig. 11. Technological parameters of EDM+US

These actual results could be improved based on polarity effect, if the ultrasonic electrode-tool oscillations are synchronized with EDM commanded pulses delivered

during ultrasonic stretching semiperiod. This is the next step that we intend to approach by achieving CIM of EDM+US technological system as it is presented in figure 12:

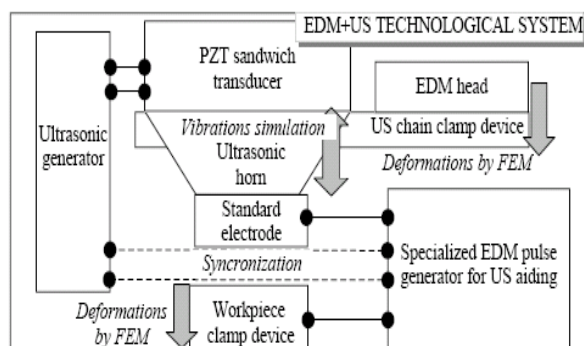


Fig. 12. CIM of technological system for EDM+US

These further researches could solve the lack of flexibility of this high potential technology, very much restricted by condition of resonance, leading to many adjustments of horns length and implicitly, time consuming in the preparation stage of fabrication cycle.

5. CONCLUSIONS

Comparing temperature distribution provided by FEM on different shapes of surface microgeometry after different type of pulses to experimental data obtained with same working parameters, we have confirmation that modelling of EDM+US taking account of microgeometry type and also characteristics of material constituents is essential in order to understand the complex mechanism of material removal.

Cutting the life time of gas bubble formed around the plasma channel by cavitation phenomena at ultrasonic aided EDM finishing/micromachining could explain machining rate increasing, up to 500%. In case of EDM+US, with usual frequency of 20 kHz, bubble life time could be in the order of 10 μ s. In classic EDM, this could be 10 times greater, mainly due to long delay time of ignition under finishing/micromachining conditions. Thus, at EDM+US, the hydraulic forces of dielectric can faster access the EDM spot removing more material in liquid state.

Acknowledgment: These paper results are obtained within the framework of Romanian Research project, 72-194, financed by National Centre of Programs Management.

REFERENCES

- [1] GHICULESCU, D. MARINESCU, N. I. JITIANU, G., SERITAN, G. On precision improvement by ultrasonics-aided electrodischarge machining, *Estonian Journal of Engineering*, p. 24-33, ISSN 1736-7522 (electronic), ISSN 1736-6038 (print), 2009.
- [2] GHICULESCU, D. MARINESCU, N. I. JITIANU, G., SERITAN, G. Precision Increasing at Ultrasonics Aided Electrodischarge Machining, *Proceedings of 6th International DAAAM Baltic Conference "INDUSTRIAL ENGINEERING"*, Vol.1, p. 233-238, Tallinn, Estonia, 2008.
- [3] VAN DIJCK, F., SNOEYS, R. Theoretical and Experimental Study of the Main Parameters Governing the Electrodischarge Machining Process, *Mecanique*, p. 105-110, 1975.
- [4] KREMER, D.; LHIAUBET, C., MOISAN, A.. A study of the effect of synchronizing ultrasonic vibrations with pulses in EDM, available at: <http://http://www.cirp.net/> Accessed: 2009-05-25, 1991.
- [5] SCHULZE, H.-P., WOLLENBERG, G., HERMS, R., MECKE, K., Gas bubble morphology in small working gaps at spark erosion, 2004 Annual report Conference on Electrical Insulation and Dielectric Phenomena, Boulder, Colorado, USA, 16-20, October, 2004.
- [6] GHICULESCU, D., MARINESCU, N. I., NANU, S. Influence of macro and microgeometry machined surface on ultrasonic aided electrodischarge machining, *Proceedings of 11th International ESAFORM Conference on Material Forming*, Lyon, France, *International Journal of Material Forming*, Springer Paris, ISSN, 1960-6206 (Print) 1960-6214 (Online), 2008.
- [7] GHICULESCU, D., MARINESCU, N. I. FEM Simulation of Material Removal Mechanism at Ultrasonic Aided Electrodischarge Machining Finishing, *Proceedings of The 19th International DAAAM Symposium*, p. 547-548, 2008.
- [8] Kojima, H., Kunieda, M., Nishiwaki, N. (1992). *Understanding Discharge Location Movements During EDM*, ISEM X, pp. 144-149, Magdeburg, Germany.
- [9] Ydreskog, L., Novak, A. (1989). *A Method for EDM Spark Location Detection*, *Proceedings of ISEM IX* pp. 297-300, Nagoya, Japan.
- [10] Fuzhu, H, Grangure, P., Kunieda, M. (2008). *Improvement in accuracy in potential method for detecting EDM spark locations*, *Journal of Materials Processing Technology*, available at: <http://www.sciencedirect.com/science/> Accessed: 2009-07-13.
- [11] ANTON, I. Cavitation, vol I, II, Academy Publishing House, 1984.