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IMPROVEMENT OF EDM CHARACTERISTICS THROUGH ULTRASONIC AIDING

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Abstract: *The paper deals with a very effective technological solution to improve characteristics of electrodischarge machining (EDM). As it is known, although EDM has attained high performances regarding accuracy and surface quality, it is room for improvement mainly concerning machining rate. Starting from the basic specific phenomena characterizing this combined nonconventional machining, aspects related to equipment, technology and obtained microgeometry parameters are presented.*

Key words: *EDM, ultrasonics, machining rate, volumetric relative wear, microgeometry.*

1. GENERAL CONSIDERATIONS

One of the relative recent applicable fields of ultrasonics, with great impact on technological performances is ultrasonic aiding of nonconventional machining, aiming spectacular improving of machining rate, accuracy and surface quality [1].

In these conditions, aiding of electrodischarge machining (EDM) with ultrasonic vibrations of tool-electrode can be framed in the preoccupation sphere of EDM technological performances improvement.

Ultrasonic aiding of EDM finishing – characterized by great instability – is justified through impressive increasing of machining rate and considerable decreasing of volumetric relative wear and machined surface roughness.

In roughing mode, the machining process has good stability, and the effect of cumulative microjets, occurring at each end of ultrasonic oscillation period (T_{US}) is apparent much lower within the great size gap. More than that, due to great pulse and pause times, there are ultrasonic oscillation periods when no discharges occur and then the effect of cumulative microjets is thus cancelled.

2. SPECIFIC PHENOMENA OF ULTRASONIC AIDING OF EDM FINISHING

Ultrasonic oscillation of tool-electrode at EDM has certain restrictions related to values of oscillation amplitude. If it is considered a reference system *tOy* attached to EDM machine (Fig. 1), then, in order to avoid short-circuit phenomena during material removal process, *condition of process stability* process is imposed – amplitudes A_y and A_t less than frontal working gap (s_F), respectively lateral working gap (s_L).

Nevertheless, if EDM aided by ultrasonics has the advantages concerning efficiency and quality of machined surface, ultrasonic cavitation must be induced within the machining gap. The cavitational phenomenon is strongly related to acoustic pressure (p_{ac}), which can be calculated using the following relation [2]:

$$p_{ac} = 2\,\pi\, f_{US}\, A\, \rho\, c_s \quad \text{[Pa]}, \tag{1}$$

where: f_{US} is frequency of ultrasonic oscillations on *Oy* direction; ρ - dielectric liquid density [kg/m^3]; A – ultrasonic oscillation amplitude [m]; c_s – sound velocity in dielectric liquid [m/s].

Experimentally, it was demonstrated that even at reduced values of amplitude A (of μm order), in case of dielectric liquids used at EDM, acoustic pressure overpasses the critical pressure (p_{cav}), necessary to produce cavitation phenomenon (cavitation threshold).

Modeling of EDM process aided by ultrasonic vibration of tool-electrode emphasizes specific phenomena corresponding to elongation values (y). Oscillation period (T_{US}) is divided in two semiperiods, in which capillary phenomena occur: liquid compression takes place in the first one, and liquid stretching, in the second one.

Decreasing of frontal gap (s_F) from the first semiperiod favors discharges between electrodes. These can be classified in two categories: the ones occurring in the first quarter 0–1 and those from the second quarter 1–2. Those from the interval 0–1 take place when gas bubbles still exist in working gap, produced by discharges and hydraulic phenomena occurred in previous period (T_{US}). These bubbles are progressively dissolved during liquid compression from first quarter of period [2]. Gas bubbles from working gap diminish inertia forces from dielectric liquid. This phenomenon has a positive effect on machined surface roughness, the discharge energy covering a greater workpiece surface due to rapid development of plasma channel, thus resulting craters with less depth (flat).

The usual frequencies are 20 kHz and 40 kHz as a result of PZT transducers using with these own frequencies (f_0). Consequently, $T_{US}/4$ values are: 6.25 and 12.5 μs.

Discharges occurring in the second quarter of period 1–2 take place in medium with maximum homogeneity, due to gas bubbles dissolution, when inertia forces of dielectric liquid have great values, which determine high current densities because of difficult development of plasma channel.

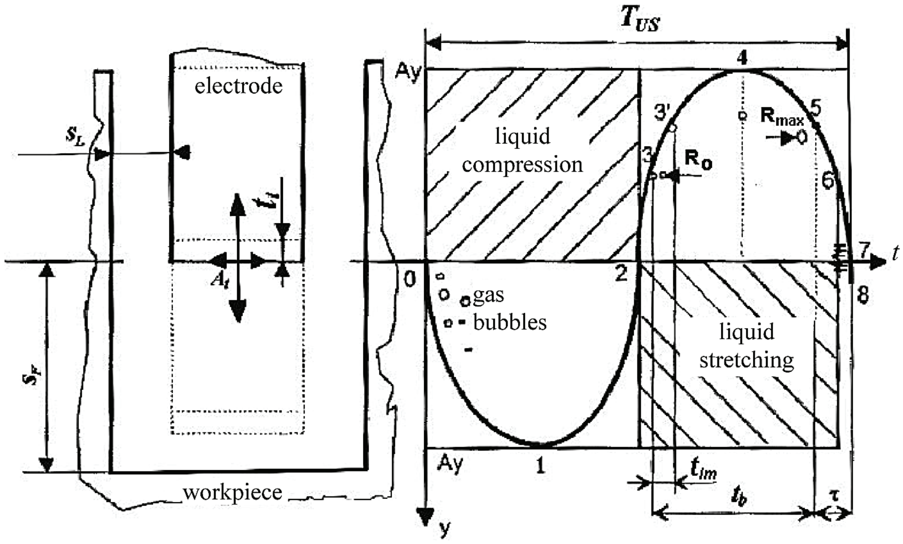


Fig. 1. Specific phenomena at ultrasonic aided EDM finishing.

The second semiperiod (liquid stretching) involves increasing of cavitational phenomena weight within ultrasonic aided EDM mechanism.

Gas bubbles surrounding cavitational nuclei, initially having R_0 radius, grow till point 3, once the pressure decreases and becoming negative due to negative elongation (y) and as a result of capillary phenomena.

Development of gas bubbles during t_b duration is a transient process with high dynamics; this phenomenon occurs as long as external pressure (p_{eb}) from environmental liquid (outer of bubble) does not overpass the pressure from the inner of the bubble (p_{ib}). In the first part of development process (t_{lm}), secondary phenomena of luminescence take place. After passing point 4 of maximum elongation y, the bubbles reach maximum radius (R_{max}), corresponding to point 5, followed by implosion due to pressure gradual rising. The interval 6–8 is called *cumulative microjets zone* because of cumulated effect produced by implosion of bubbles from working gap. In this interval, due to very high values of pressure and speed created by microjets, erosion products are completely eliminated from the gap.

It must be mentioned that during stretching semiperiod, the behavior of the types of pulses (commanded and relaxation) is different [3].

Discharges produced within the interval 2–5 take place under conditions of working gap pollution. Gas bubbles grow fast, reaching values of mm order. Consequently, there is a high probability that discharges occur within gaseous medium. Thus EDM process takes place with low current densities in plasma channel; this channel rapidly develops in pre-existing gaseous cavities because the opponent forces are lower than those from dielectric liquid. Although in this semiperiod, the gap (s_F) is greater, the delay time (t_d) can be reduced due to high conductivity of working medium composed by dielectric and removed metal vapors. This phenomenon determines low discharges energies machining in case of relaxation pulses working. The factors mentioned above have a positive effect on EDM finishing process.

As semiperiod (period) duration is of μs order, machining without flushing is possible because at the end of each oscillation cycle, the erosion products are completely eliminated from the gap by cumulative microjets. Thus, technological problems related to injection orifice (in workpiece or tool-electrode) are avoided, allowing machining in orifice zone.

Machining rate which is greater in case of ultrasonic aided EDM finishing than in case of classic EDM is the result of cavitational phenomena. Due to pressure growing in stage 5–6, the gas bubbles formed in the second semiperiod implodes at 15…20 μs (the latest) from the end of pulse, and those resulted from discharges occurred in the first semiperiod after a double time of tens of μs order. Consequently, in stage 6-8 when cumulative microjets emerge, it is possible that molted metal produced by discharge could be still in liquid state. Thus it could be removed by high pressures provided by cavitational phenomena.

Cavitational phenomena ultrasonically induced

In our experimental researches, cavitation was obtained using ultrasonic longitudinal oscillations of tool-electrode with 20 kHz frequency, amplitude of 1…2 μm in P3 oil (frequently used in Romania as dielectric liquid) with density $\rho = 840$ kg/m^3 and hydrostatic pressure 0.1 MPa.

Maximum acoustic pressure (p_{ac}) created in these conditions was 0.15…0.3 MPa, calculated with relation (1).

Forming and development of gas bubbles take place in the second semiperiod (Fig. 2) in which acoustic pressure has negative value as total hydrostatic pressure (p_{ht}).

The pressure p_{ht} is equal with pressure from exterior of bubble (p_{eb}), and is determined through relation:

$$p_{eb} = p_{ac} \sin \omega t + p_h \quad \text{[MPa]}, \tag{2}$$

where:

$$\omega = 2\pi f_{US} \quad [\text{s}^{-1}] \tag{3}$$

and p_h is hydrostatic pressure in machining gap [MPa].

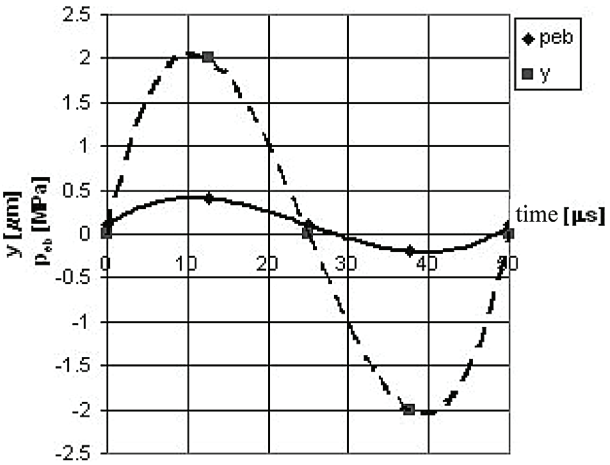


Fig. 2. Variation of elongation and pressure in working gap at ultrasonics aided EDM.

In experimental conditions mentioned above, variations of elongation (y) and pressure p_{eb}, calculated with relation (2), during an oscillation period T_{US} = 50 µs are presented in Fig. 2.

The own frequency (f_0) of cavitation bubble can be established in respect of its radius (R_0) with Minnaet relation:

$$f_0 = \frac{1}{2\pi R_0}\sqrt{\frac{\psi}{R_0}\left(p_h + \frac{2\sigma}{R_0}\right)} \quad [\text{Hz}]\,, \tag{3}$$

where: ψ is ratio of specific heats at constant pressure and volume (adiabatic exponent) of gas from inside the bubble; ρ – density of dielectric liquid [kg/m^3]; p_h – hydrostatic pressure [Pa]; σ – superficial tension of liquid [N/m].

Frequencies f_{US} situated below own frequency (f_0) of bubble with radius R_0 lead to cavitation. Frequencies greater than f_0 determine a trend of bubble volume increasing coupled with an oscillatory movement. Nuclei with radii lower than 10^{-2} mm (case of EDM gap) have own frequencies greater than the most used ultrasonic frequencies of 20 kHz and 40 kHz, consequently they can be cavitation nuclei [4].

Implosion time (τ) is much lower than of bubble development and depends on radii ratio before and after implosion (β), dielectric liquid density (ρ), superficial tension (σ) and hydrostatic pressure (p_h), according to relation:

$$\tau = R_m\sqrt{\frac{3\rho}{2p_h}}\int_{\beta}^{1}\frac{\beta^{\frac{3}{2}}}{(1-\beta)\left[\beta^2+(\beta+1)\dfrac{1+3\sigma}{p_h R_m}\right]}\,d\beta \quad [\text{s}] \quad ,(4)$$

where:

$$\beta = R_f / R_m\,, \tag{5}$$

and R_m is maximum radius [m]; R_f – final radius after contraction [m].

In case of P3 oil, with maximum frontal working gap, s_F = 0.01 mm and pressure of 0.1 MPa, τ = 0.84 µs is obtained.

In addition to material removal in liquid state, at cumulative microjets occurrence 6–8 (Fig. 1), material in solid state is also removed.

Shock waves contribute to erosion of workpiece surface when developed pressure, at contact with solid wall, overpasses flowing limit of individual grains. Microjets having an orientation parallel with machined surface – the only one possible in EDM working gap [5] – assure besides evacuation of removed particles from the gap, generation of tangential forces, which can remove superficial micropeaks; some of them are already in plastic state as a result of previous discharges, others, in solid state.

3. EQUIPMENT AND TECHNOLOGY OF EDM FINISHING AIDED BY ULTRASONICS

The structure of equipment necessary to achieve ultrasonically aided EDM is presented in Fig. 3 where: 1 is reflecting bush; 2 – PZT transducer; 3 – nodal flange; 4 – radiant bush; 5 – acoustic horn; 6 – tool-electrode; 7 – working tank; 8 – workpiece fixing cassette device; 9 – PZT cooler fan; 10 – plate-support of acoustic chain; 11 – workpiece.

In Fig. 4, the achievement of ultrasonic aided EDM equipment is presented, implemented on a Charmilles machine, where position numbers represent: assembly (1) composed by PZT transducer (sandwich type), reflecting and radiant bushes, stepped or catenoidal acoustic horn (2) in half wavelength and tool-electrode (3). Keeping low temperature of PZT during working is essential in direct connection with resonance condition achieving. For that reason, we used a flexible cooling system with two fans (7) mounted on magnetic supports, creating air currents disposed at 90-degree angle.

Dielectric injection was accomplished through a hose (6) coupled at device (5) of worpiece fixing and also at dielectric aggregate of machine. Equal fixing forces of workpiece are achieved by two clamps (8).

Longitudinal (perpendicular on machined surface) ultrasonic vibrations of electrode-tool are provided by an ultrasonic generator (G_{US}) with consumed power (P_{cUS}) up to 400 W and frequency (f_{US}) in the range of 19…21 kHz.

On the basis of experimental results, main output technological parameters functions were established – machining rate (V_W), volumetric relative wear (ϑ) and roughness (R_a) – for the two types of EDM pulses, by means of a regression data analysis, computer aided, using the lowest squared values method:

- for finishing modes with commanded pulses,

$$R_a = R_a\,(t_i);\quad \vartheta = \vartheta\,(t_i);\quad V_W = V_W\,(t_i)\,, \tag{6}$$

where t_i is pulse time;

- for finishing modes with relaxation pulses,

$$R_a = R_a\,(C),\quad \vartheta = \vartheta\,(C),\quad V_W = V_W\,(C)\,, \tag{7}$$

where C is condensers battery capacity of relaxation generator.

For illustration, in Figs. 5, 6 and 7, variation of functions from relations (6) is presented (in figures, P_{aUS} – active ultrasonic power on acoustic chain).

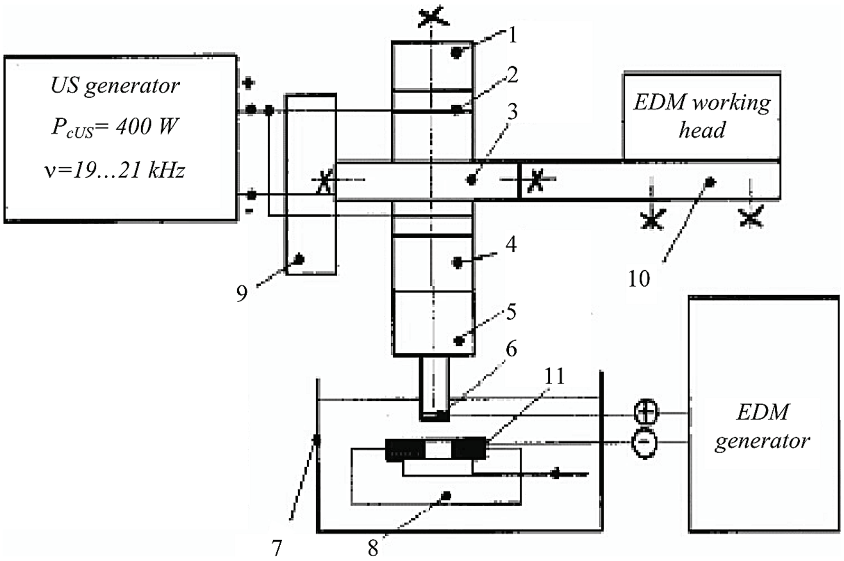


Fig. 3. Structure of equipment for ultrasonics aided EDM finishing.

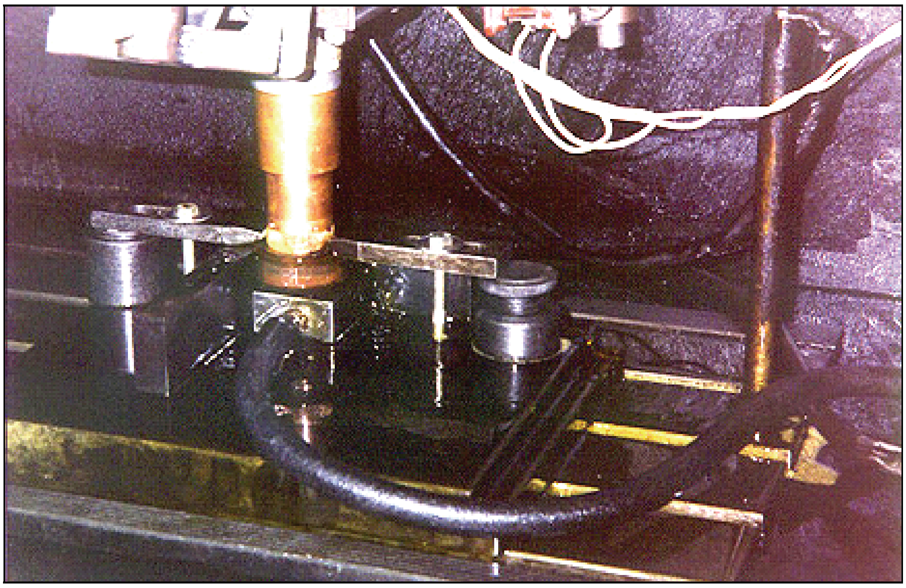


Fig. 4. Achievement of equipment for ultrasonics aided EDM finishing.

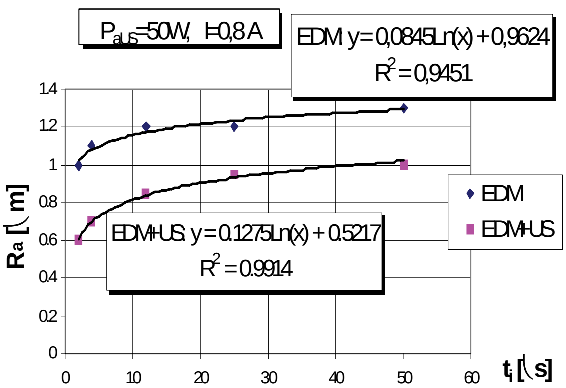


Fig. 5. Variation of machined surface roughness.

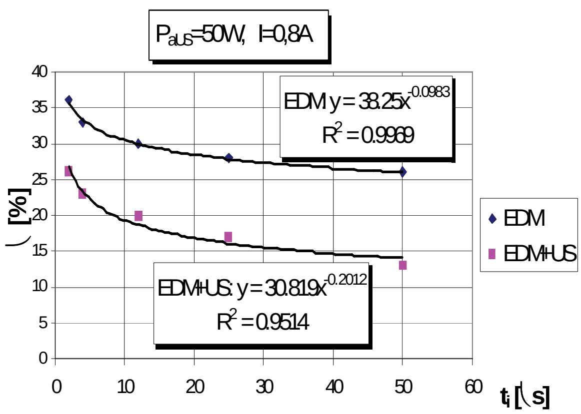


Fig. 6. Variation of volumetric relative wear.

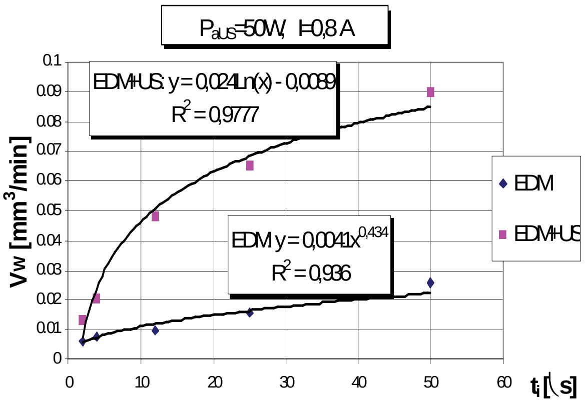


Fig. 7. Variation of machining rate.

4. MICROGEOMETRY OF MACHINED SURFACE

The shape of microgeometry obtained through ultrasonically aided EDM was compared to the one resulted with classic EDM finishing, in identical working conditions. It is also analyzed the influence of main input working parameters upon the microtopography of machined surface.

After machining, the surface roughness (R_a) was determined using a surface measurement instrument, “Surtronic” Rank Taylor Hobson.

Using the relation of correlation between roughness parameters:

$$R_z \cong 4.5 R_a^{0.97} \tag{8}$$

and knowing the R_a value for each machined surface, the average depth (approximately R_z) of the microcraters was determined.

The machined surface microgeometry was photographed with an integrated system camera-microscope, Neophot 2-Zeiss, obtaining pictures magnified at 500:1 (Fig. 9). On the basis of the mean diameters from the figures mentioned above and R_z values, we determined the correspondent cross sectional views of the microcraters shapes in case of different working parameters (Fig. 8 – EDM+US is ultrasonic aided EDM).

The analysis of microcraters shapes resulted when working with relaxation pulses and negative polarity – with/without ultrasonics - emphasizes the following aspects comparatively with commanded pulses with positive polarity:

- more roundness of the crater circumference;
- margins not overrisen;
- craters more flat in cross section;
- greater dimensional variation of craters diameters;
- greater overlapping of the craters.

The mean ratio between the average depth and crater diameters ranges from 10 to 37% at relaxation pulses unlike the one obtained with commanded pulses that varied from 22 to 53%. This means that at relaxation pulses the isothermal depth of melting (boiling) is smaller due to the effect produced by electrons bombardment, whose weight in material removal mechanism is more important than ionic current one. This is the specific case of machining with negative polarity and short pulse time (t_i).

On this basis, the removal process of the material from the flat craters is easier and the metal is not resolidified on the crater border like at commanded pulses.

Concerning craters dimensions, one can notice that at relaxation pulses crater diameters belonged to a range of 13…30 µm as against the one from commanded pulses which is 6…10 µm. Consequently, greater crater diameters at relaxation pulses than those produced with commanded pulses cause overlapping of craters.

The influence of ultrasonics action on surface microtopography is essential and apparent in the removal mechanism. When machining with increased consumed power, i. e. P_{cUS} = 300 W, the surface roughness (R_a) was greater than the one obtained without ultrasonics and proportionally the crater dimensions were also greater (Fig. 9). This is the reason for we reduced P_{cUS} parameter and thus the surface quality was improved – the main objective at EDM finishing.

It is also observed that crater borders became more regular with decreasing of P_{cUS}. As it can be noticed from Fig. 9, when working with relaxation pulses at P_{cUS} = 300 W, the shape was very fuzzy and then when machining with P_{cUS} = 100 W, the margins became oval (with its main axis positioned toward different directions), and finally, when lowering at P_{cUS} = 70 W, the crater borders were almost round.

The crater flatness obtained with relaxation pulses produces a slight lessening of the pressure waves in the cumulative microjets stage, as against the one occurred with commanded pulses, where the craters were deeper [5]. Hence ultrasonic action at EDM finishing with relaxation pulses is more powerful at the microheights level and this is the reason of decreasing ultrasonic power down to the limit of cavitation occurrence, mentioned above in order to improve the surface quality.

More than that, crater borders at relaxation pulses are more sensitive to the ultrasonics action (pressure waves) as well as the surface roughness than at commanded pulses. The crater margins obtained with commanded pulses are overrisen as a result of the gathering of the material on the borders due to the difficult removal of the molten metal from a relative deep crater. This phenomenon gives to these micropeaks a greater shear resistance in comparison with the ones resulted from relaxation pulses.

5. CONCLUSIONS

Ultrasonic aided EDM finishing has the capacity to improve technological performances of material removal process as it is emphasized in the following conclusions:

1. Material removal in liquid and solid state contribute not only to machining rate increasing at ultrasonic aided EDM finishing comparatively to classic EDM through addition of EDM and cavitational specific effects, but also to improvement of machined surface quality through micropeaks removal, which have lower shearing resistance.

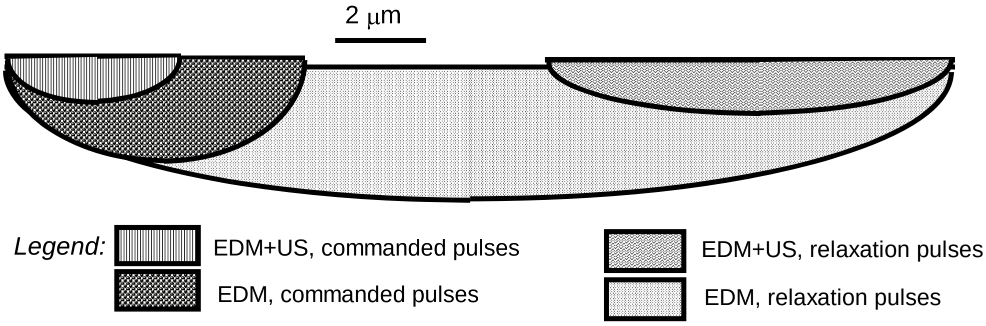
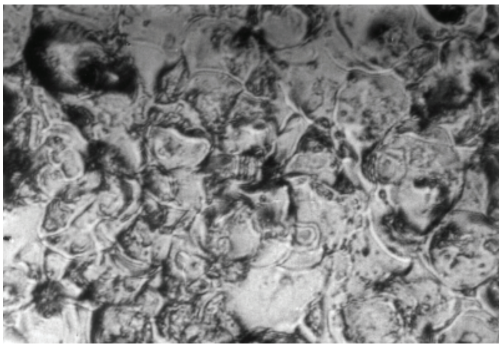
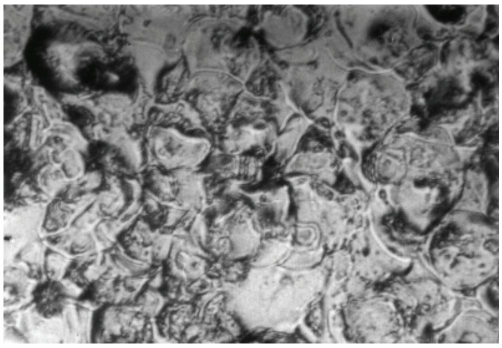


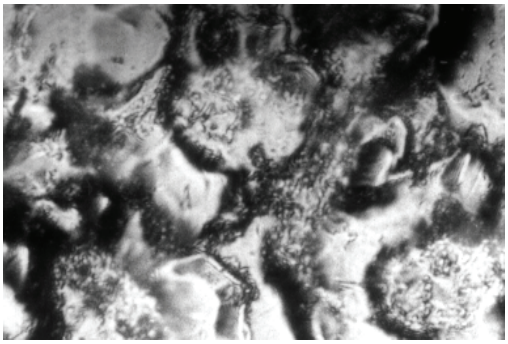
Fig. 8. Crater dimensions in transversal section.



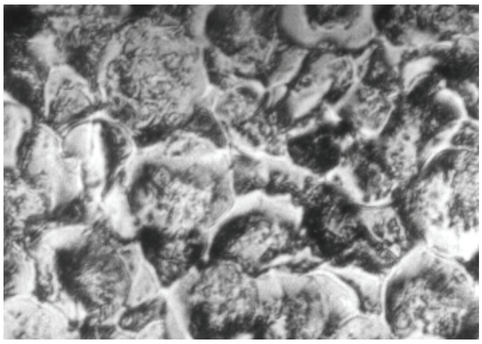
Microtopography EDM; I=1; C=1 (×500)



Microtopography EDM +US; I=1; C=1;P_{cUS}*=300 W (×500)*



Microtopography EDM +US; I=3; C=5; P_{cUS}*=100 W (×500)*



Microtopography EDM +US; I=1; C=1; P_{cUS}*=70 W (×500)*

Legend: I = step of condenser supply current; C = step of condenser capacity; P_{cUS}*=consumed ultrasonic power*

Fig. 9. Microtopography obtained at EDM finishing with/without ultrasonics aiding.

2. Technology of EDM aided by ultrasonics allows increasing of machining rate up to 500%, decreasing of volumetric relative wear and machined surface roughness up to 50% comparatively to values obtained at classic EDM, under the same conditions of machining.

3. Studying of microtopography elucidates some characteristics of very intricate mechanism of material removal at ultrasonic aided EDM finishing.

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