

TESTING OF A ROTARY HEAD FOR ULTRASONICALLY AIDED ELECTRICAL DISCHARGE MACHINING

Daniel Ghiculescu¹, Nicolae Marinescu², Panagiotis Kyratsis³, Ovidiu Alupei⁴ and Claudiu Pirnau⁵

¹Politehnica University of Bucharest, Romania, daniel.ghiculescu@upb.ro

²Politehnica University of Bucharest, Romania, niculae.marinescu.upb@gmail.com

³Technological Educational Institute of Western Macedonia, Greece, pkyratsis@teiwm.gr

⁴Politehnica University of Bucharest, Romania, ovidiu.alupei@gmail.com

⁵Politehnica University of Bucharest, Romania, claudiu.pyr@gmail.com

ABSTRACT: The paper deals with the testing of a rotary head for ultrasonically aided electrical discharge machining (EDM+US) that can be used at finishing and semifinishing modes and EDM with complex kinematics - "milling EDM". The rotation movement using of the electrode-tool is justified by the fact that during the EDM process, the energy is dissipated over the machined surface, and thus its roughness is decreased. But this comes also with the higher instability of EDM process, often short-circuits between the tool and the workpiece, and the idle state due to the variable gap. The tool ultrasonic vibrations oriented perpendicular on the frontal machined surface confirmed both roughness and EDM stability improving, and consequently machining rate, at all working modes tested in this research. The curves of roughness and machining rate are presented at different values of tool rotation speed and consumed power on ultrasonic chain. The obtained surface microgeometry was also studied using scanning electron microscope.

KEY WORDS: electrical discharge machining, tool rotation, ultrasonic vibration.

1. INTRODUCTION

The using of tool-electrode rotation during electrical discharge machining (EDM) process is framed in a certain approach of generating complex shapes with simple / normalized shape tools [1]. This type of EDM process, also called "milling EDM" due to its similarity with this cutting process from the kinematics point of view, is very appropriate to CNC machining.

Using this performing complex kinematics (coordination of several axes) at EDM comes also with the potential instability of the removal process. Under these working conditions, the size of the working gap is modified with very high dynamics during the removal process since the tool-electrode has a permanent relative movement against machined surface of the workpiece. The removal process is difficultly kept under control because the feed and retract movements are performed simultaneously on translation and rotation axes. This imposes appropriate evacuation of the particles from the variable gap for avoiding short-circuits between the tool and the machined surfaces, and idle state. But at microEDM drilling, the tool rotation improved technological parameters like machining rate and surface quality [2, 3].

The using of ultrasonic vibrations of the electrode-tool at EDM with tool rotary movement was also reported for improving the main output technological parameters. The increase of machining rate with up to 600% was obtained at certain

roughness [4]. The machining rate and surface roughness were improved when using rotary tool with up to 200 rpm and nanoparticles in dielectric liquid [5]. At WEDM, other solutions for ultrasonic vibrations applied at technological systems elements were reported [1].

2. PHENOMENOLOGY AT ROTARY TOOL EDM+US

The electric currents of the two types of particles, positive ions and electrons formed within plasma channel produced by a discharge, interact only partially in case of relative linear speed between anode and cathode or tool and workpiece, depending on selected polarity (fig. 1).

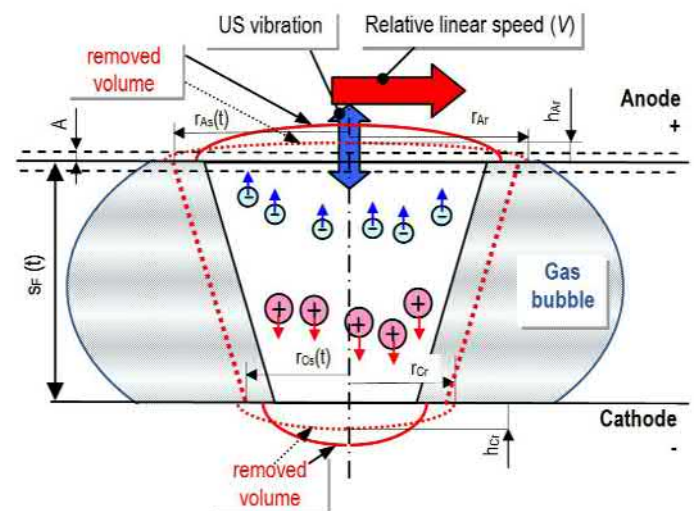


Figure 1. Phenomena modelling at rotary tool EDM+US

The frontal working gap, $s_F(t)$ is time dependent, being uneven, and changing rapidly during the

removal process with the rotary tool. It strongly depends on the time of interaction anode - cathode, evaluated through the number of discharges between them. At the tool rotation around its axis, the $s_F(t)$ value is larger in the middle than at the periphery where the relative speed (V) is higher (see dot lines), in comparison with simple EDM (continuous lines). Thus, the electronic bombardment from the cathode is dissipated on larger surface of the anode, $r_{As}(t)$ and the ionic current decreases. So, the density of discharge energy is lower because the radius of cathode spot, $r_{Cs}(t)$ is larger. Thus, the craters produced at cathode by discharges have large radii (r_{Cr}), low depths (h_{Cr}) and so, machined surface roughness (Rz) is reduced – see dot lines. Similarly, at anode, the spot radius $r_{As}(t)$ is increased and the crater radius (r_{Ar}) is larger, and its depth (h_{Ar}) lower, and consequently, the roughness Rz is decreased.

Although, the increase of relative linear speed between electrodes has a positive effect on finishing EDM, there is a limit for the relative speed, in which the quality surface is improved. A material transfer from the tool to the workpiece was observed beginning at higher relative linear speed than 47.5 m/min reported by V. N. Haldeev. At low energy and pulse durations, i.e. $W_e = 10^{-3}-10^{-4}$ J, pulse time $t_i = 3 \mu s$, pulse frequency $f_p = 66$ KHz, this material transfer was more intense [6].

This agrees to Williams and Zolotych, who stated that at low pulse durations or at first stages of the discharges, the material removal process is based on the electrostatic forces, i.e. electronic and ionic currents. Only at longer pulse duration, the material removal becomes weightily thermal [1].

At ultrasonically aided EDM, the amplitude (A) of the vibratory movement of the tool (see dashed lines, fig. 1) or the workpiece changes the value of frontal gap, $s_F(t)$, but with only few micrometers. The values of A are enough to produce cavitation in the working gap, contributing to produce ultrasonic pressure, according to relation [1]:

$$p_{us} = 2 \pi A f c \rho \quad [\text{Pa}] \quad (1)$$

where: f is ultrasonic frequency [Hz]; c – the sound speed within the dielectric liquid [m/s]; ρ – the dielectric liquid density [kg/m^3].

The value of p_{us} must exceed a certain threshold to produce cavitation, depending on the composition and characteristics of the dielectric liquid [7].

The ultrasonically induced cavitation within the working gap acts like a pumping effect, improving the evacuation of the removed particles. Furthermore, due to the collective implosion of the

gas bubbles from the gap (cumulative microjets stage - CMS) at the end of every stretching semiperiod of the dielectric liquid, the gas bubble formed around plasma channel implodes, having much shorter life time that at usual EDM. If the discharge is overlapped on CMS , the dielectric liquid could find the workpiece material in liquid state and remove it in larger amount than at classic EDM, and hence machining rate is increased. Moreover, the material could be removed also in solid state by shock pressure exerted by cumulative microjets on micropeaks of machined microgeometry, which are more sensitive at shearing efforts, being prominent. Thus, the machined roughness (Rz) is decreased [1].

3. EXPERIMENTAL SETUP

A variant of a rotary head for EDM+US with transmission belt, derived from a patent request [8], was tested on the Romanian ELER 01 machine in our specialized laboratory at Polytechnic University of Bucharest (fig. 2).

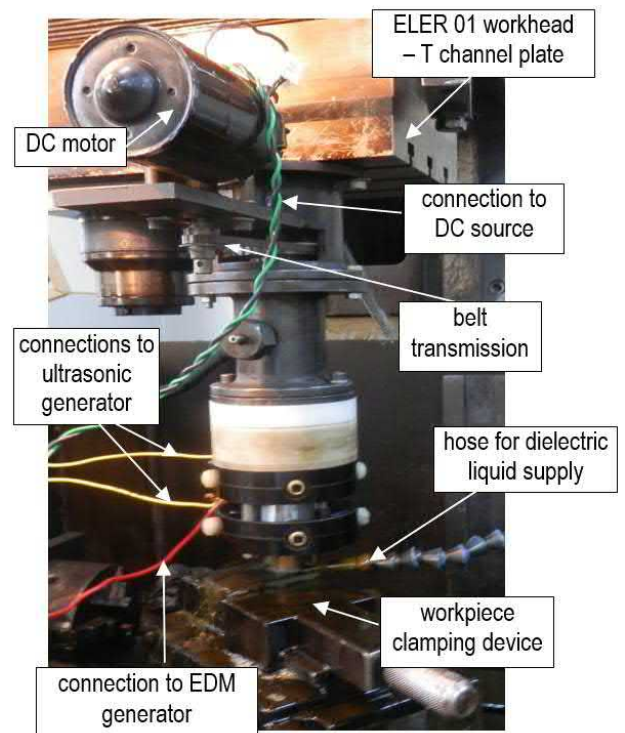


Figure 2. The rotary head for EDM+US on ELER 01 machine

Samples from C 45 steel, thermally hardened were machined by classic and ultrasonically aided EDM in the same working conditions. The tool electrode integrated in the ultrasonic chain was from Cu 99. The following machining parameters kept constant during the tests were: current step $I = 6$ A; pulse time $t_i = 24 \mu s$, pause time $t_o = 12 \mu s$, positive tool polarity, lateral flushing with $p_f = 0.02$ MPa of dielectric pressure. The other selected parameters, specified in table 1 were varied. The machined samples and the related statistic results are presented chronologically.

Table 1. Machining parameters and experimental results at EDM and EDM+US

Selected parameters						Obtained parameters			
No. of sample	Motor supply voltage, U [V]	Tool rotation, n [rot/min]	Tool linear speed, V[m/min]	Ultra-sonic aiding (US)	Machining time, t_m [min]	Machining depth, t [mm]	Machining rate, V_w [mm ³ /min]	Roughness, Ra [μm]	Notices
1	10	12	0.75	US	5	0.18	11.30	3.2	low instability*
1'	10	12	0.75	-	5	0.07	4.40	4.3	high instability**
2	12	18.4	1.16	US	5	0.16	10.05	2.8	low instability*
2'	12	18.4	1.16	-	5	0.05	3.14	3.8	high instability**
3	9	6.4	0.40	US	5	0.2	12.56	3.3	low instability*
3'	9	6.4	0.40	-	5	0.08	5.02	4.4	high instability**
4	5	2.8	0.18	US	5	0.27	16.96	3.4	low instability*
4'	5	2.8	0.18	-	5	0.15	9.42	4.6	high instability**
5	11	12.8	0.80	US	5	0.17	10.68	2.9	low instability*
5'	11	12.8	0.80	-	5	0,06	3.77	3.9	high instability**

* very rare phenomena of short-circuit between the tool and the workpiece

** frequent phenomena of short-circuit between the tool and the workpiece

The current density on the frontal surface (S_f) of the tool-electrode with 10 mm radius was calculated:

$$J = I / S_f = 6 / \pi 1^2 = 1.91 \text{ A/cm}^2. \quad (2)$$

This is low enough, due to the chosen current step I , for avoiding the instability of the removal process, very sensitive at EDM with rotary tool. For materials couple, Cu – steel, this is $J_{max} = 15-20 \text{ A/cm}^2$ [1].

For ultrasonic aiding EDM, the power of 90 W of an adaptive ultrasonic generator built in-house was used in the first stage of testing.

Periphery linear speed of the tool-electrode was determined, considered as reference parameter. The rotation speed of the motor was measured at different supply voltages, provided by a DC variable source, specified in table 1. Taking into account, the wheels radii ratio R_1/R_2 (1:2.5) of belt transmission and tool-electrode diameter, the periphery linear speed (V) was calculated with the following relation:

$$V = 2\pi R_s n_s / 1000 \quad [\text{m/min}] \quad (3)$$

where: R_s is the tool radius [mm]; n_s – the tool rotation [rot/ min],

$$n_s = n_m (R_1 / R_2) \quad [\text{rot/min}] \quad (4)$$

where n_m is a measured rotation speed of the motor.

The machining rate (V_w) was determined with the following relation:

$$V_w = t S_f / t_m \quad [\text{mm}^3/\text{min}] \quad (4)$$

where t is machining depth [mm]; t_m – machining time [min].

For determination of the machined surface roughness, the Charmilles standard ruler was used.

4. EXPERIMENTAL RESULTS

The variation of machining rate in respect to the tool-electrode linear speed was represented in fig 3:

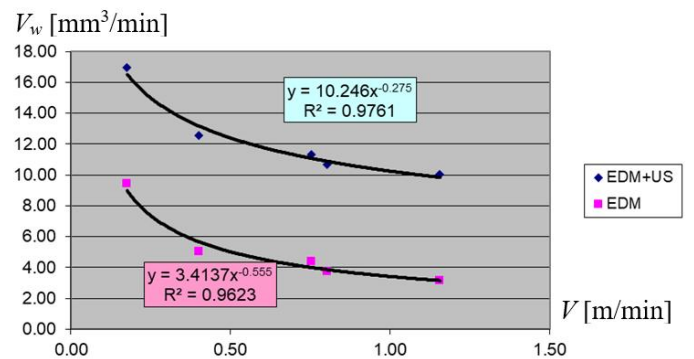


Figure 3. The machining rate variation at EDM and EDM+US with tool-electrode rotation as function of its linear speed

This variation points out that machining rate decreases at tool speed growing in both variants with and without ultrasonic aiding. This is explained by the discharges energy dissipation on larger surface at increase of the relative speed between the tool-electrode surface and the machined surface.

Table 2. Machining parameters and experimental results at EDM+US

Selected parameters						Obtained parameters			
No. of sample	Motor supply voltage, U [V]	Tool rotation, n [rot/min]	Tool linear speed, V[m/min]	Ultrasonic power, P _{cUS} [W]	Machining time, t _m [min]	Machining depth, t [mm]	Machining rate, V _w [mm ³ /min]	Roughness, Ra [μm]	Notices
1	12	18.4	1.16	90	5	0.18	11.30	2.8	reduced instability*
2	12	18.4	1.16	100	5	0.2	12.56	3.1	reduced instability*
3	12	18.4	1.16	80	5	0.16	10.05	3.2	reduced instability*
4	12	18.4	1.16	70	5	0.14	8.79	3.6	medium instability**
5	12	18.4	1.16	60	5	0.11	6.91	3.8	medium instability**

* very rare phenomena of short-circuit between the tool and the workpiece

** phenomena of short-circuit between the tool and the workpiece with medium frequency

At limit, when the tool linear speed is null on the horizontal plane, machining rate is highest with the tool moving only on the vertical direction.

Comparatively, at rotary tool EDM, high instability of machining process was observed – frequent phenomena of short-circuit between the tool surface and machined workpiece.

Ultrasonically aiding rotary tool EDM determines a rising of machining rate of over three times mostly at higher rotation speed of tool-electrode, where instability of machining was greater at classic rotary tool EDM (without ultrasonic assistance).

The obtained values of machined surface roughness were specified in the table 1. A decrease of Ra roughness is noticed at all working modes of ultrasonically aided (EDM+US) in comparison with those without ultrasonic assistance (EDM) with rotary tool-electrode – fig. 4.

EDM+US, and respectively of approximately 17% at classic EDM with rotary tool.

A decrease of up to 25% of Ra roughness was also obtained by ultrasonic assistance of rotary tool EDM in the specified working conditions.

In order to study the influence of oscillation amplitude (A), respectively of consumed power on the ultrasonic chain (P_{cUS}) on machining rate, and on machined surface roughness, a series of machining was conducted, keeping constant the rotation speed at V=1.16m/min. The experimental results obtained were specified in the table 2.

The variation of machining rate (V_w) and surface roughness (Ra) in respect with the power P_{cUS} are presented in fig. 5.

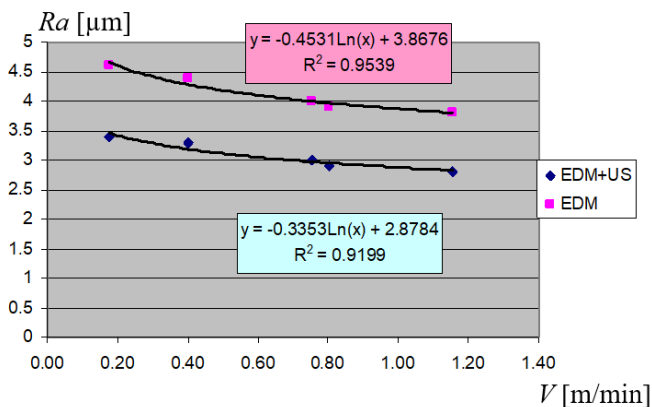


Figure 4. The roughness variation at EDM and EDM+US with tool-electrode rotation as function of its linear speed

It is also observed a decrease of machined surface roughness at growing of the tool-electrode linear rotation speed both at classic EDM and EDM+US. On the studied interval of linear speed, V [0.18-1.16] m/min, it is obtained a Ra decrease of around 18% at

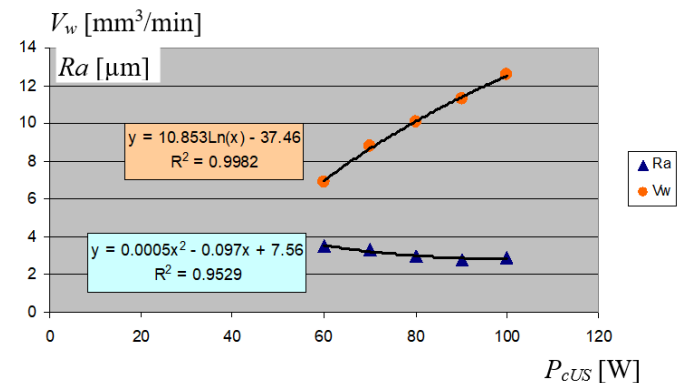


Figure 5. The variation of machining rate and Ra roughness at EDM+US with rotary tool-electrode as function of consumed power on ultrasonic chain

It is observed a growing of machining rate (V_w) at increase of consumed power P_{cUS}. It was also determined an optimal value of power, P_{cUS} = 90 W, at which the Ra roughness is minimal.

The space (s) covered on circular path by EDM spot due to rotational movement on the machined surface during pulse time (t_i) can be calculated with:

$$s = V t_i \approx 2 R_s \sin (\alpha/2) =$$

$$= 2 R_s \sin \{(\pi/180) n t_i/2\} \quad [\text{m}] \quad (5)$$

where α is the rotation angle at tool section centre covered during pulse time t_i .

Thus, it was noticed that even in case of used highest linear speed (V), the parameter s is very low, in the range of μm , influencing somehow the craters diameters. The images taken by SEM of machined micro-topography at different values of linear speed of the tool (V), comparatively at EDM and EDM+US are presented in fig. 6-11.

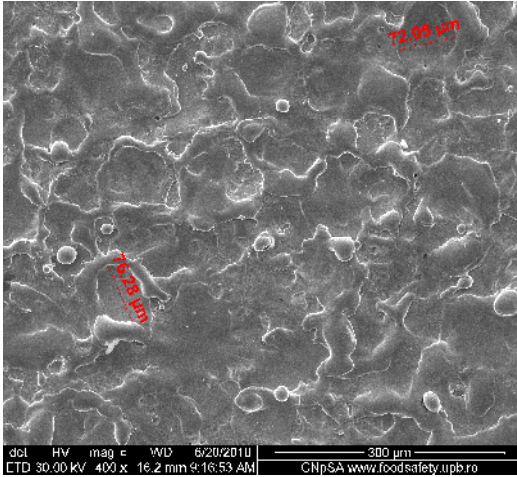


Figure 6. Microtopography obtained at EDM with $I=6\text{ A}$; $t_i=24\ \mu\text{s}$; $t_o=12\ \mu\text{s}$; polarity +; $V=0.18\ \text{m/min}$.

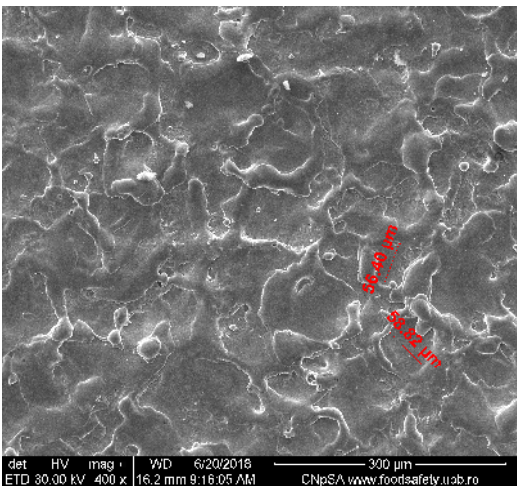


Figure 7. Microtopography obtained at EDM+US with $I=6\text{ A}$; $t_i=24\ \mu\text{s}$; $t_o=12\ \mu\text{s}$; polarity +; $V=0.18\ \text{m/min}$; $P_{CUS}=90\text{ W}$

As it can be noticed, the lowering of craters diameters is consistent at all EDM+US working modes against the EDM ones, which is explained by the removal of craters borders in solid state, due to shearing load produced by ultrasonic cavitation related to roughness decrease. Many craters are covered by melted material produced by discharges. So, there are some difficulties to estimate the real dimensions of generated craters.

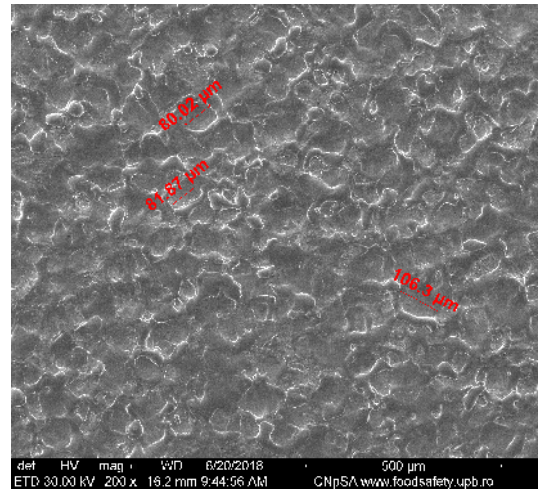


Figure 8. Microtopography obtained at EDM with $I=6\text{ A}$; $t_i=24\ \mu\text{s}$; $t_o=12\ \mu\text{s}$; polarity +; $V=0.4\ \text{m/min}$

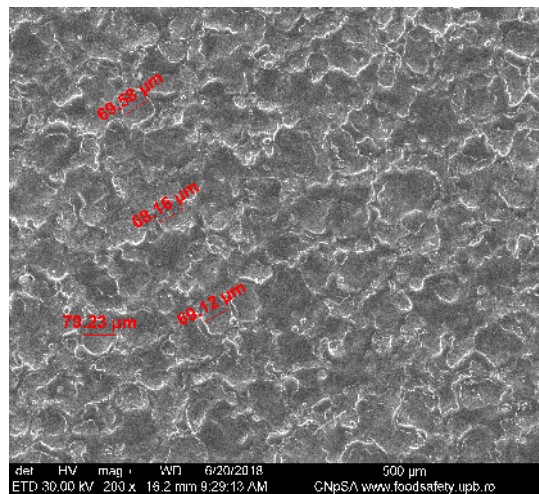


Figure 9. Microtopography obtained at EDM+US with $I=6\text{ A}$; $t_i=24\ \mu\text{s}$; $t_o=12\ \mu\text{s}$; polarity +; $V=0.4\ \text{m/min}$; $P_{CUS}=90\text{ W}$

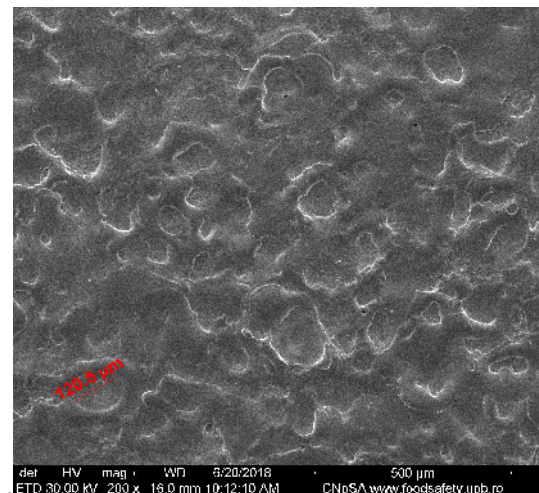


Figure 10. Microtopography obtained at EDM with $I=6\text{ A}$; $t_i=24\ \mu\text{s}$; $t_o=12\ \mu\text{s}$; polarity +; $V=0.8\ \text{m/min}$

It can be also observed that at increase of tool linear speed, the crater diameters grow gradually due to discharges energy dissipation on larger machined surface.

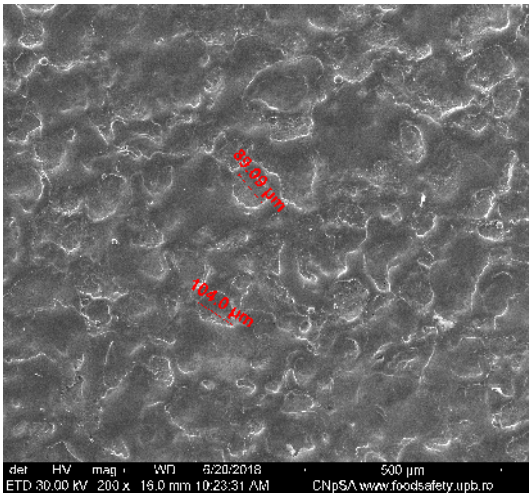


Figure 11. Microtopography obtained at EDM+US with $I=6$ A; $t_i=24$ μ s; $t_o=12$ μ s; polarity +; $V=0.8$ m/min; $P_{cUS}=90$ W

7. CONCLUSIONS

The machining rate decreases at growing of the tool rotation speed. At EDM, an increase of the machining instability (frequent short-circuit between the tool and the machined surface) occurs against EDM+US. For this reason, in this experimental stage, the researches were focused on the interval of lower values of rotation speed, 0.75 – 1.16 m/min. Ultrasonic assistance of rotary tool EDM contributes substantially at growing of machining stability (rare short-circuits) by ultrasonic cavitation - cyclic variation of pressure in the gap, which helps at better evacuation of removed particles. Thus, EDM+US with rotary tool justifies this technological solution at CNC machining with complex kinematics (“milling” EDM), where relative movement tool-workpiece influences removal process instability.

Ultrasonic assistance of rotary tool EDM assures a growing of machining rate of around three times against EDM without ultrasonic aiding, in the same working conditions. The increase is more obvious at higher rotation speed of the tool-electrode, when the instability of EDM process was greater.

At growing of the tool-electrode rotation speed (V) within the studied interval of V , the machined surface roughness (R_a) is reduced with up to 20% at both variants, EDM and EDM+US with rotary tool. Through ultrasonic assistance of EDM with tool rotation, a decrease of roughness with around 25% occurs against EDM without ultrasonic aiding, in the same working conditions. In this context, SEM images emphasized that crater diameters are larger at growing of tool-electrode rotational speed, based on discharges energy dissipation on machined surface, and hence levelling effect. Moreover, at EDM+US, craters diameters are smaller than at EDM, which

pointed out that their margins are removed by ultrasonic pressure.

At EDM+US with tool rotation, the machining rate grows when the power consumed on ultrasonic chain (P_{cUS}), integrating the tool increases. The machined surface roughness (R_a) is minimal at P_{cUS} of around 90 W under these working conditions.

Further researches will be carried on using higher linear speed of the tool, up to the limit of material transfer from the tool-electrode to the workpiece.

8. ACKNOWLEDGEMENT

The SEM images obtained on the samples were possible due to EU-funding project POSCCE-A2-O2.2.1-2013-1, SMIS-code 48652.

9. REFERENCES

1. Jahan, M.P., et al. *Electrical Discharge Machining (EDM), Types, Technologies and Applications*, Nova Publishers, New York, USA, (2015).
2. Billa, S., Sundaram, M., Rajurkar K., A study on the high aspect ratio micro hole drilling using ultrasonic assisted micro-electro discharge machining, *Journal of Materials Engineering and Performance* 17 (2), pp. 210-215, (2008).
3. Yu, Z.Y., Zhang, Y., Li, J., Luan, J., Zhao, F., Guo, D., High aspect ratio micro-hole drilling aided with ultrasonic vibration and planetary movement of electrode by micro-EDM, *CIRP Annals*, Volume 58, Issue 1, pp. 213-216, (2009).
4. Ghoreishi, M., Atkinson, J., A comparative experimental study of machining characteristics in vibratory, rotary and vibro-rotary electro-discharge machining, *Journal of Materials Processing Technology*, 120, pp. 374-384 (2002).
5. Baseri, H., Sadeghian, S., Effects of nanopowder TiO₂-mixed dielectric and rotary tool on EDM, *Int. J. Adv. Manuf. Technol*, 83, pp. 519–528, (2016).
6. Haldev, V.N., The features of material transfer from the tool-electrode to the workpiece in dimensional EDM process at the relative movement of electrodes, *Electronnaia Obrabotka Materialov*, vol. 26, 4, 1990.
7. Anton, I., *Cavitation*, Vol. I and II, Romanian Academy Publishing House, Bucharest, 1984.
8. Ghiculescu, D., Marinescu, N.I, Alupei – Cojocariu, O.D. Carutasu, L., *Rotary head for ultrasonically aided electrical discharge machining*, OSIM Patent request: A / 00528 / 23.07.2015.