SURFACE MICRO AND NANOFINISHING USING PULSE ELECTROCHEMICAL MACHINING PROCESS ASSISTED BY ELECTRODE ULTRASONIC VIBRATIONS

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Abstract

Electrochemical machining (ECM) is an important technology in machining difficult-to-cut materials and to shape sculptured surfaces without tool wear and without inducing residual stress. Such advantages are the reason that ECM is a very good alternative for finishing machining of sculptured surfaces initially machined by other methods. In the paper experimental tests results and analysis of phenomena occurring into interelectrode gap will be presented. In order to reach surface roughness parameter Ra<100nm special attention is taken to: pulse electrochemical machining (PECM), pulse electrochemical machining assisted by electrode ultrasonic vibrations (USPECM) and machining in mixture of electrolyte and abrasive powder (APECM).

Keywords:

PECM, USPECM, AUSECM, microfinishing, nanofinishing

1 INTRODUCTION

In many cases the quality of the detail can be significantly improve by increasing its surface quality. In case of electrochemical machining the surface quality can be increased by using pulse interelectrode voltage and electrode-tool ultrasonic vibration. In order to reach micro I nano-values (*Ra* << 100 nm) surface roughness parameters, time pulse, time interval and power of electrode ultrasonic vibrations should be optimal [1-6]. Usually in industrial conditions for evaluation of surface quality usually parameters *Ra*, *Ra* are used. But in order to characterize surface geometrical structure in complex way the space surface geometrical structure parameters should be applied. Below the results of experimental tests have been presented. For measurements equipment designed and built in the Institute of Advanced Manufacturing Technology has been applied.

2 EXPERIMENTAL TESTS

The range of PECM application depends on accuracy, surface quality and metal removal rate which can be achieved during machining. Because of this fact it has been decided that experiments will be carried out with constant but as high as possible electrode tool feed rate. The same interelectrode gap is small what gives possibility to obtain high current density. In order to achieve for small interelectrode gap thickness satisfactory conditions of electrolyte flow and transportation out of interelectrode space heat and electrochemical reactions products the ultrasonic vibrations of electrode tool has been applied. On this assumption the results of the process depend mainly on time of voltage pulse, time of interval between successive voltage pulses and intensity (power) of electrode ultrasonic vibrations. Experiments have been carried out using electrochemical machine-tool EOCA 40 equipped with special pulse electrical supplier, ultrasonic head and tooling for electrode-tool and samples clamping.

Taking into account results of analysis of phenomena occurring into interelectrode gap during one voltage pulse the following factors have been taken into account.

Input factors:

- interelectrode voltage: U = 15 – 23 V,
- electrode – tool feed rate: v_f = 0.1 – 0.9 mm/min,
- pulse time: 1 – 9 ms,
- interval time: 1 – 5 ms,
- power of ultrasonic vibrations: P = 0 – 120 W.

Output factors:

- surface roughness parameter *Ra* [µm],
- interelectrode gap thickness S_k [mm],
- pulse current I_{imp} [A].

Constant factors:

- shape and dimensions of electrode-tool (ϕ = 10 mm) and machined surface F = 175 mm^2 (ϕ_1 = 8 mm, ϕ_2=2mm),
- machined material: NC6 steel,
- electrode-tool material: brass,
- electrolyte: 15% water $NaNO_3$ solution,
- electrolyte temperature: 20^{o}C,
- initial interelectrode gap thickness: S = 0.2 mm,
- electrode – tool displacement: h = 1.7 mm,

As function of investigated object the neural net which characteristic was presented in [6] has been applied.

During tests electrode-tool is displaced in direction of machined surface with velocity v_f (Figure 1). Electrolyte flows into interelectrode space through the hole in the sample. Between electrodes the voltage pulses occur with appropriate pulse and interval time duration.

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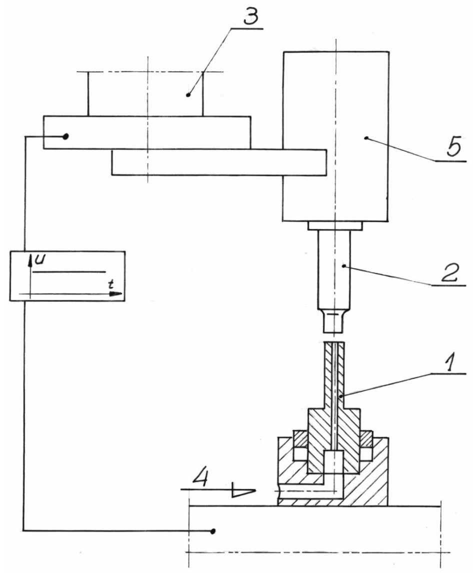

Figure 1: Scheme of test stand for investigations of PECM and USPECM process supported by electrode ultrasonic vibrations; 1 – workpiece, 2 – electrode-tool, 3 – tool plate of machine - tool EOCA 40, 4 – hole for electrolyte supplying, 5 – ultrasonic head.

3 RESULTS OF EXPERIMENTS

3.1 Pulse ECM

For constant interelectrode voltage and electrode-tool feed rate values of process technological indicators depend significantly on pulse and interval time (Figures 2, 3 and 4). For the smallest value of pulse time (1 ms) and the biggest value of interval time (5 ms) the smallest value of interelectrode gap thickness and the highest value of pulse current have been reached (Figures 2 and 3). For these conditions it had been possible to achieve the smallest value of surface roughness parameter *Ra* (Figure 4). Though the principle: the highest current density the smallest surface roughness parameter is true in analysed case.

3.2 Ultrasonically assisted PECM

Further decreasing of profile surface roughness parameter Ra can be reach by introducing electrode ultrasonic vibrations (Figs 5 - 14).

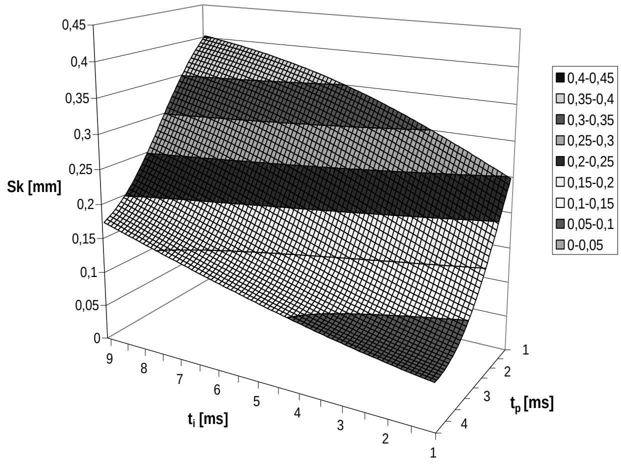

Figure 2: Relationship between interelectrode gap thickness and pulse and interval time $S_k = f(t_i, t_p)$ when electrode feed rate v_f = 0.5 mm/min, interelectrode voltage U = 19 V, ultrasonic vibrations power P = 0 W.

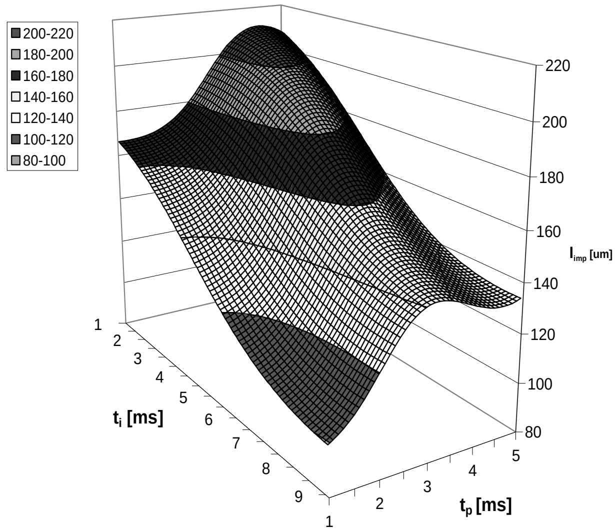

Figure 3: Relationship between pulse and interval time $I_{imp}=f(t_i, t_p)$ when electrode feed rate v_f = 0.5 mm/min, interelectrode voltage U = 19 V, ultrasonic vibrations power P = 0 W.

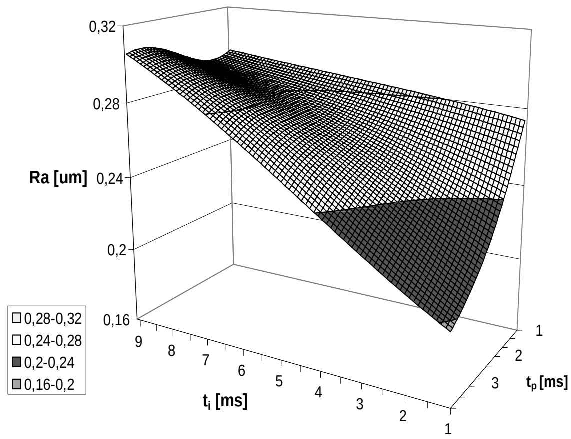

Figure 4: Relationship between surface roughness parameter *Ra* and pulse and interval time $Ra = f(t_i, t_p)$ when electrode feed rate v_f = 0.5 mm/min, interelectrode voltage U = 19 V, ultrasonic vibrations power P = 0 W.

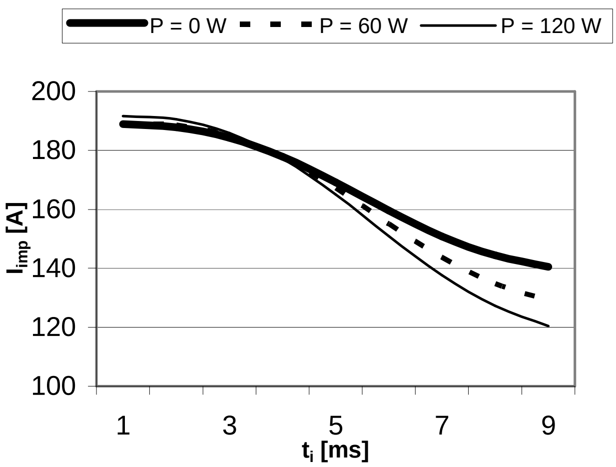

Figure 5: Relationship between pulse current and pulse time for different power of ultrasonic vibrations when time of interval t_p = 3 ms, interelectrode voltage U = 19 V, electrode – tool feed rate v_f = 0.5 mm/min.

At the same time the pulse current slightly decreases and interelectrode gap increases. It results from the fact that introduction of electrode ultrasonic vibrations decreases electrodes polarization.

Surface roughness parameters in presented above PECM have been measured from one surface profile. Below the space surface geometrical structure parameters were used. It has been taken into account for comparison three cases. The first surface (No 1) has been machined without electrode ultrasonic vibrations. The second (No 2) has been machined with maximal power of electrode ultrasonic vibrations (P = 120 W). Comparison of these surfaces presents influence of electrode ultrasonic vibrations on surface geometrical structure. The third surface (No 3) has been machined for optimal process parameters (pulse time, interval time and power of electrode ultrasonic vibrations P = 60W). The measurement has been done for two areas of the machined surface. The direction of measurements in the first area (A) was perpendicular to direction of electrolyte flow and in the second area (B) parallel to direction of electrolyte flow. Length of measurement distance was 1.25 mm, distance between successive profiles was 0.025 mm, and profile height had been measured each 0.0002 mm.

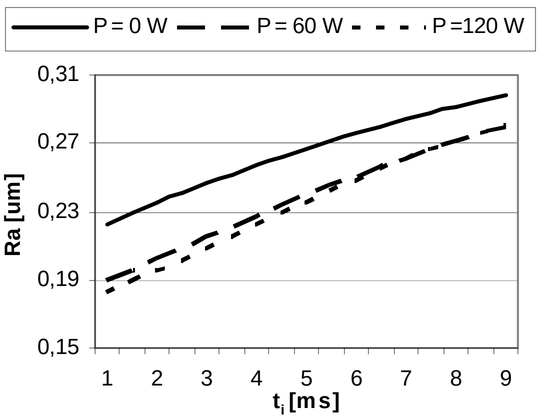

Figure 6: Relationship between surface roughness parameter *Ra* and pulse time t_i for different power of ultrasonic vibrations when interelectrode voltage U = 19 V, time of interval t_p = 3 ms, electrode – tool feed rate v_f = 0.5 mm/min.

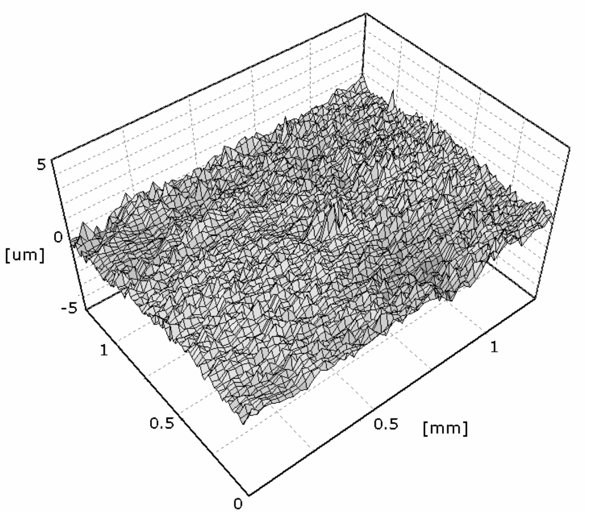

Figure 7: Primary (without filtration) space surface (No 1 -A) geometrical structure after machining without electrode ultrasonic vibrations (*P* = 0 W) when: v_f = 0.5 mm/min, *U* = 19 V, t_i = 5 ms, t_p = 3 ms; space surface parameters: see Table 1.

Taking into account the same surface but when measuring in direction perpendicular to electrolyte flow its geometrical structure can be quite different (Figure 8). When machining with electrode ultrasonic vibrations (*P* = 120 W) the geometrical structure of the surface is changed significantly (Figure 9). From comparison surfaces in Figures 8 and 9 results that surface structure parameters generally increase for machining with maximal power (*P* = 120 W) of electrode ultrasonic vibrations. Probably the power of electrode ultrasonic vibrations was too high and conditions of electrochemical dissolution process changed significantly in direction perpendicular to electrolyte flow and in direction along electrolyte flow. From Figures 7, 8, 9 and 10 results that by decreasing pulse time and using optimal power of electrode ultrasonic vibrations surface geometrical structure has been significantly improved. However surface is not quite flat. The machined surface changed from almost flat (Figures 7 and 8) to convex (Figure 9) and then to concave (Figure 10). It indicates that it is possible to find process parameters for which the surface will be flat.

In the next stage of surface geometrical structure analysis the profile (mean of 50) parameters have been taken into account.

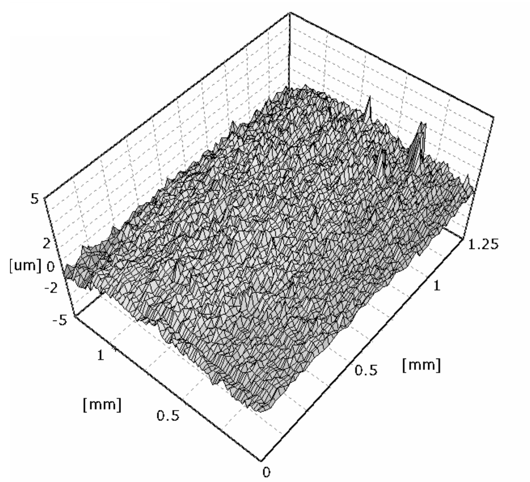

Figure 8: Primary (without filtration) space surface (No 1 - B) geometrical structure after machining without electrode ultrasonic vibrations (*P* = 0 W) when: v_f = 0.5 mm/min, U = 19 V, t_i = 5 ms, t_p = 3 ms; space surface parameters: see Table 1.

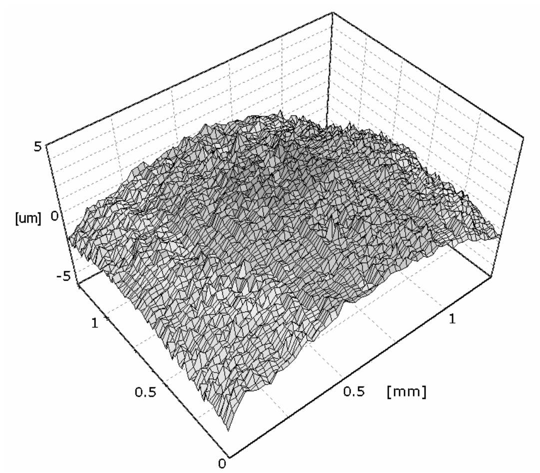

Figure 9: Primary (without filtration) space surface (No 2 - B) geometrical structure after machining with electrode ultrasonic vibrations (*P* = 120 W) when: v_f = 0.5 mm/min, *U* = 19 V, t_i = 5 ms, t_p = 3 ms; space surface parameters: see Table 1.

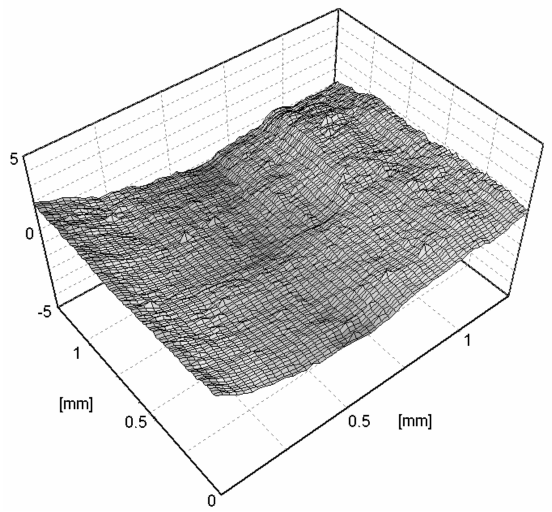

Figure 10: Primary (without filtration) space surface (No 3 - B) geometrical structure after machining without electrode ultrasonic vibrations (P = 60 W) when: v_f = 0.5 mm/min, U = 19 V, t_i = 1 ms, t_p = 3 ms; space surface parameters: See Table I.

	No1/ A	No 1/B	No 2/A	No 2/B	No 3/A	No 3/B
SPp [µm]	2,577	4,332	2,837	3,06	1,686	1,937
SPv [µm]	1,56	1,293	1,54	5,454	1,263	1,252
SPz [µm]	4,137	5,625	4,376	8,514	2,949	3,189
SPa [µm]	0,337	0,329	0,493	0,921	0,602	0,508
SPq [µm]	0,428	0,422	0,609	1,147	0,691	0,611
SPsk	1,683	1,871	1,567	1,636	1,323	1,503
SPku	3,565	5,651	2,922	3,383	1,93	2,684
SRp [µm]	2,235	4,107	2,387	1,613	0,468	0,73
SRv [µm]	0,93	1,12	0,679	0,623	0,491	0,214
SRz [µm]	1,365	1,371	0,922	1,4	0,374	0,381
SRa [µm]	0,234	0,246	0,242	0,225	0,067	0,084
SRq [µm]	0,3	0,317	0,316	0,287	0,085	0,108
SRsk	1,811	2,039	2,002	1,698	1,632	1,731
SRku	4,593	8,641	6,299	3,611	3,232	3,835

Table I : Space surface geometrical structure parameters with and without filtration according: Polish Standard PN-EN ISO 4287.

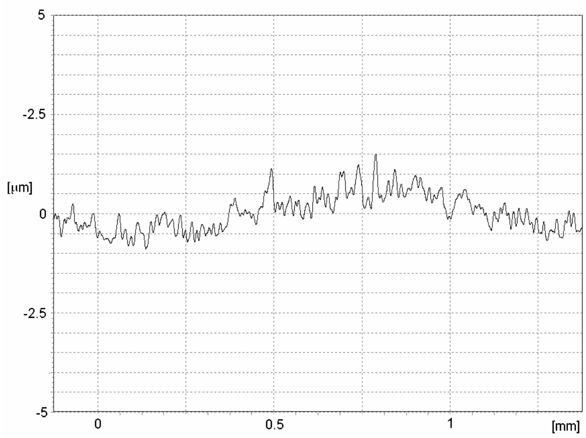

Figure 11: Primary surface profile (No 1 – A) after machining without electrode ultrasonic vibrations (P = 0 W) when: v_f = 0.5 mm/min, U = 19 V, t_i = 5 ms, t_p = 3 ms; space surface parameters: see Table II.

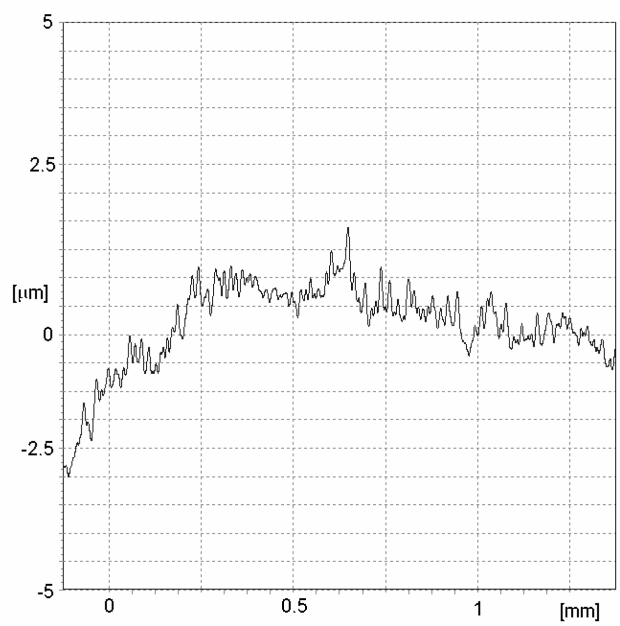

Figure 12: Primary surface profile (No 2 – A) after machining with electrode ultrasonic vibrations (P = 120) when: v_f = 0.5 mm/min, U = 19 V, t_i = 1 ms, t_p = 3 ms; v_f = 0.5 mm/min; space surface parameters: see Table II.

From Figures 10 and 11 results that application of electrode - tool ultrasonic vibrations change course of phenomena occurring into interelectrode space. When power of ultrasonic vibrations is increased the intensity of cavitation phenomena also can increase. As a result the significant disturbances in electrolyte flow can take place. It is possible that into interelectrode gap the is mixture of cavitation bubbles and spaces without electrolyte (after bubble collapse) are created what can be a reason of mean conductivity of interelectrode gap increase and then pulse current decreasing (Figure 6). However the smallest values of surface roughness parameter Ra is obtained for machining with electrode tool ultrasonic vibrations for the smallest pulse time (Figure 6).

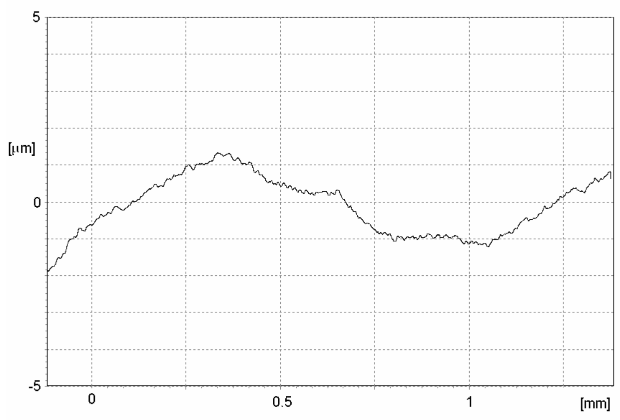

Figure 13: Primary surface profile (No 3 – A) after machining with electrode ultrasonic vibrations (P = 60 W) when: v_f = 0.5 mm/min, U = 19 V, t_i = 1 ms, t_p = 3 ms; Space surface parameters: Table II

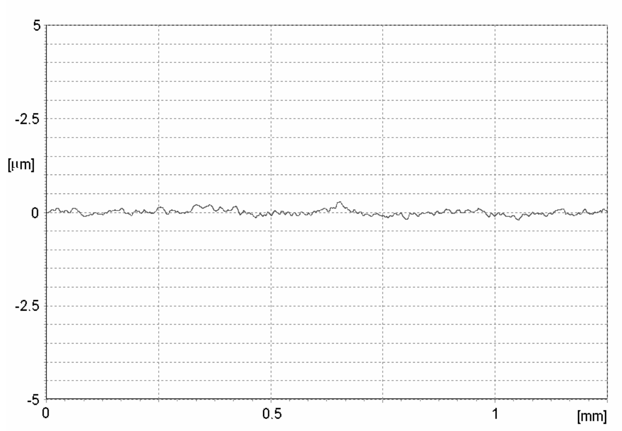

Figure 14: Filtrated surface profile (No 3 – A) after machining with electrode ultrasonic vibrations (P = 60 W) when: v_f = 0.5 mm/min, U = 19 V, t_i = 1 ms, t_p = 3 ms; Other surface geometrical structure parameters: see Table II.

	No 1A	No /B	No 2/A	No 2/B	No 3/A	No 3/B
Pp [µm]	0,789	0,796	0,811	0,663	0,553	0,232
Pv [µm]	0,572	0,575	0,679	0,623	0,491	0,214
Pz [µm]	1,361	1,371	1,490	1,286	1,044	0,445
Pc [µm]	0,579	0,648	0,534	0,351	0,012	0,130
Pt [µm]	2,030	1,992	2,953	2,461	2,216	0,800
Pa [µm]	0,295	0,279	0,416	0,452	0,510	0,110
Pq [µm]	0,362	0,346	0,502	0,519	0,552	0,133
Psk	0,166	0,305	0,009	0,097	0,057	0,014
Pku	2,704	2,840	2,393	2,082	1,552	2,704
PSm [µm]	39,910	44,327	34,063	26,898	2,116	40,887
PS [µm]	14,849	15,640	14,657	14,978	11,283	10,268
Pmr [mm]	0,600	0,591	0,619	0,619	0,623	0,665
Rp [µm]	0,750	0,788	0,716	0,579	0,189	0,209
Rv [µm]	0,531	0,560	0,551	0,516	0,164	0,171
Rz [µm]	1,281	1,347	1,267	1,095	0,353	0,380
Rc [µm]	0,563	0,612	0,572	0,496	0,137	0,143
Rt [µm]	1,742	1,819	1,747	1,579	0,506	0,601
Ra [µm]	0,232	0,244	0,232	0,223	0,065	0,081
Rq [µm]	0,291	0,306	0,289	0,275	0,081	0,098
Rsk	0,370	0,372	0,260	0,062	0,162	0,349
Rku	3,036	2,972	2,826	2,686	2,895	2,836
Rz10p [µm]	1,354	1,416	1,365	1,219	0,375	0,397
RSm [µm]	36,735	37,996	32,393	42,088	37,452	43,184
RS [µm]	14,812	15,623	14,645	14,996	10,402	10,216
Rmr [mm]	0,576	0,578	0,586	0,611	0,616	0,620

Table 2: The surface geometrical parameters with and without filtration according: Polish Standard PN-EN ISO 4287 - profile method.

Some differences from above mentioned principle occur for smaller values of interval time (Fig.13) and the highest values of electrode-tool feed rate. When interval time is in the range 1 – 2 ms heat and electrochemical reaction products are not satisfactory removed from interelectrode space before successive voltage pulse occurs, what can be a reason that surface roughness is bigger for bigger power of ultrasonic vibrations. The smallest value Ra = 90 nm has been obtained for pulse time 1ms and interval time 3 ms when electrode-tool feed rate was 0.5 mm/min and interelectrode voltage 19 V. It indicate that investigations aiming to obtain lower surface roughness should be in the future carry out for time of pulse smaller than 1 ms. However, in mean time the other investigations when using mixture of electrolyte and abrasive powder have been carried out.

3.1 Ultrasonically assisted abrasive ECM

In experiments the following changeable parameters have been taken into account: *w* – number of rotation per minute, v_p - velocity of electrode – tool displacement, *P* – ultrasonic generator power, *Z* – abrasive powder dimensions. The constant parameters were: electrolyte concentration: 15% $NaNO_3$ water solution; abrasive powder concentration: 42.5 g/dm^3; workpiece diameter: ϕ = 60 mm, interelectrode voltage: U = 15 V, electrode – tool radius: R = 5 mm; initial interelectrode gap S_o = 0.1 mm; material of workpiece: NC6 or 4H13 steel – according Polish Standards. As abrasive powder SiC has been applied. The relation between grain number and its dimensions is presented below:

- 1000 $\Rightarrow$ 5 $\div$10 µm,
- 360 $\Rightarrow$ 23 $\div$ 40 µm,
- 240 $\Rightarrow$ 45 $\div$ 100 µm.

As basic technological indicator of investigated process Ra parameter has been taken into account. Allowance removed during tests was very small and it was possible to assume that workpiece dimensions were not changed significantly during USECM smoothing.

From experimental tests results that:

- the smallest value of *Ra* for 4H13 steel was obtained for: *w* = 4500 rot/min, v_p = 5 mm/min, *Z* = 360 (23 – 40 µm), *P* = 90 W;
- the smallest value of *Ra* (Figure 7) for NC6 steel was obtained for: *w* = 3500 rot/min, v_p = 40 mm/min, Z = 360 (23 – 40 µm), *P* = 90 W.

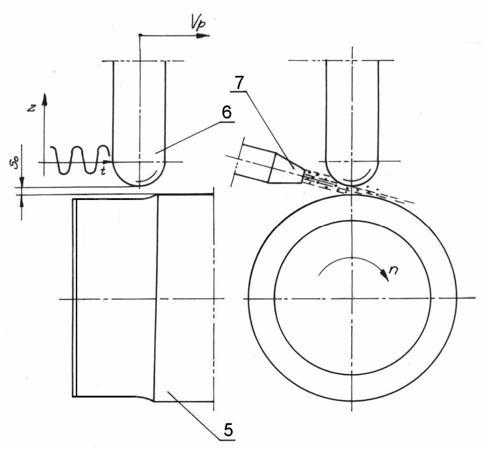

Figure 15: Scheme of machining area in case of ultrasonically assisted electrochemical turning in mixture of electrolyte and abrasive powder, 5 – workpiece, 6 – electrode tool, 7 – electrolyte nozzle

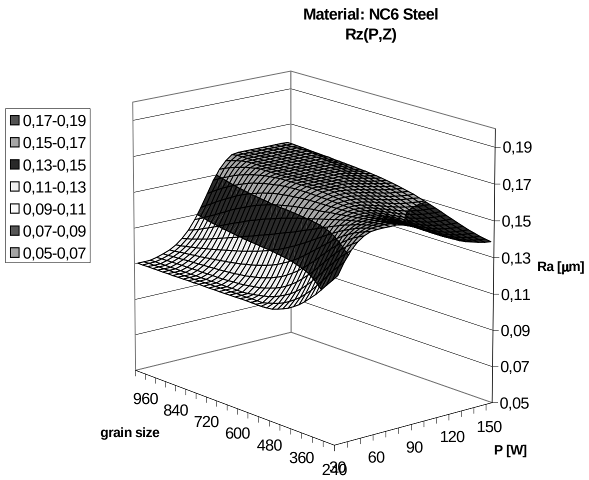

Figure 16 : Relationship $R_a(P, Z)$ for NC6 steel, U = 15 V, w = 3500 turn/min, v_p = 22.5 mm/min.

Material removal during smoothing process is very small: in range 0,01 to 0,12 g. So, investigated process is typical smoothing process for decreasing surface roughness parameters. Decrease of surface roughness results here from electrochemical dissolution process assistance by ultrasonic vibration, cavitations phenomena and mechanical impact abrasive grains at machined surface.

Abrasive grains impact at machined surface and support material removal process as a result of: microcutting, plastic microdeformation, depasivation and depolarisation. The share of these phenomena in smoothing process depends on process parameters: v_p, w, Z, P. More detailed explanation of phenomena occurring in machining area needs further investigations. Summarizing it is possible to state that ultrasonically assisted ECM process in mixture of electrolyte and abrasive grains make it possible (in presented experimental condition) to obtain surface roughness parameter *Ra* in the range of 0,1 – 0,05 µm, what is significantly smaller than in USECM process without abrasive powder.

4. SUMARISING

From above presented experimental tests and considerations it results that electrode ultrasonic vibrations change the course of the dissolution process and values of technological indicators of the USPECM process by changing the conditions of electrochemical dissolution process.

Introduction of electrode ultrasonic vibrations can be a reason of:

- creating shock wave and cavitation phenomena which are accompanied by micro jets and pulse pressure in boundary layer, what is a reason of changing hydrodynamic conditions in machining area,
- generating some amount of heat what can increase temperature in machining area,
- changing the course of chemical reactions in aqueous solutions.

As a result of above mentioned phenomena it is possible for optimal process parameters to:

- improve the heat and reactions products removal out of machining area,
- support diffusion and decrease the rate of passivation processes,
- decrease the potential drops in the layers adjacent to electrodes ,
- increase coefficient of machinability,
- create the optimal hydrodynamic conditions from surface roughness parameter Ra point of view,
- decrease the surface roughness parameter Ra in comparison to classical and pulse electrochemical machining without electrode-tool ultrasonic vibrations, however surface waviness can be created

The electrode ultrasonic vibrations complicate the course of phenomena occurring into interelectrode gap by creating the occurrence of the new phenomena (cavitation). On this stage of investigations the best quality of machined surface can be reached when mixture of electrolyte and abrasive powder is applied. For more precise description of the USPECM and USAECM processes the further investigations are necessary.

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