Primary investigations on USECM–CNC process

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ABSTRACT

The primary investigations for the electrochemical machining when the universal electrode vibrating with ultrasonic frequency are presented. The influence of the amplitude of ultrasonic vibrations, interelectrode voltage, electrode feed rate, interelectrode gap thickness on final metal removal rate and surface roughness have been taken into account. The tests indicated that introduction of electrode ultrasonic vibrations can change conditions of dissolution process and cause the increase of allowance thickness a and material removed rate V_w without surface quality decreasing.

1 INTRODUCTION

Electrochemical machining (ECM) - an important technology in machining difficult for cutting materials has traditional fields of application in space, aircraft and domestic industries. It results from the fact that after electrochemical machining it is possible to receive high quality of surface layer (1), (2), (9).

One of the kinematics variants of electrochemical process is machining with using universal electrode tool (ECM - CNC). In ECM – CNC material is removed by electrode with a three dimensional movement as shown in Fig. 1. The advantages of this method are simple shape of electrode and the increase in machining accuracy and workpiece surface quality in comparison to classical sinking. This is achieved by the decrease of working area what significantly reduces the influence of heat and gas generation on the electrolyte properties in the interelectrode gap. The main disadvantage of ECM – CNC is relatively small metal removal rate in comparison to classical sinking. It is a reason that ECM – CNC should be used in finishing machining of sculptured surfaces initially machined by other methods.

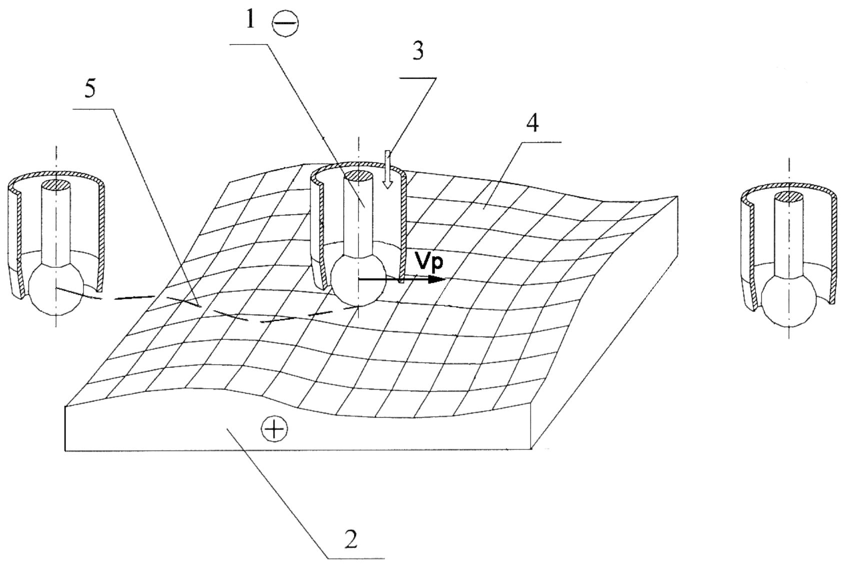


Fig. 1 Scheme of ECM – CNC machining with spherical universal electrode tool: 1 – electrode tool, 2 – workpiece, 3 – electrolyte inlet, 4 – machining surface, 5 – electrode tool path, v_p - *velocity* of electrode displacement (feed rate) (5)

2 PROBLEM FORMULATION

Taking into account results of investigation presented in (4), (6), (7), (8), (10), (11), (12) it is right to state that ultrasonic vibrations and ultrasonic field, which is creating during tool vibrations, have a significant influence on the conditions of electrode processes. The main effects of ultrasound derives from acoustic cavitation, the formation, growth and implosive collapse of bubbles in liquids irradiated with ultrasound (13). Kozak (4) suggested that ultrasonic waves gives possibility for creating the cavitation micro bubbles near the workpiece surface. Process of micro-bubbles collapsing in area adjacent to electrode gives the possibility of increasing the intensification of mass and electric charge transportation and increases the dissolution rate. Also results of investigations carried out in The Institute of Metal Cutting (10), (11), (12) showed that thanks to ultrasonic vibrations the intensification of electrochemical process by increasing the diffusion of metal ions take place. As a result the intensification of electrochemical processes can take place.

The main disadvantages of ECM – CNC machining is small material removal rate and problems with creating appropriate hydrodynamic conditions in order to remove machining products from interelectrode gap. Taking into account facts presented above it can be assumed that one of the ways for solving this problem can be introduction of electrode ultrasonic vibrations into interelectrode gap. Below the results of primary investigations on ECM – CNC process assisted by universal electrode ultrasonic vibrations (USECM - CNC) are presented.

3 MATHEMATICAL MODELLING

Mathematical modelling of electrochemical machining with universal ball-ended electrode was presented in (5). This model was developed for given conditions of dissolution, initial shape of workpiece and tool trajectory. Equations describing surface shaping process was solved for displacement of machined surface according to the normal to machined surface. In this case of modeling it is possible to determine the successive distances Δa_n with which machined surface is displaced in time Δt (Fig. 2):

$$\Delta a_{nA} = \eta k_{vA} i_A \Delta t = \eta k_{vA} \kappa \frac{U-E}{D} \Delta t = V_n \Delta t \qquad (1)$$

where: ηk_{vA} – coefficient of electrochemical machinability in point A, κ - electrolyte conductivity, V_n – velocity of metal removal rate in direction perpendicular to machined surface, i_A – current density in point A, D – distance between electrode and workpiece, U – interelectrode voltage, E – potential drops in the electrolyte films adjacent to the electrode and workpiece.

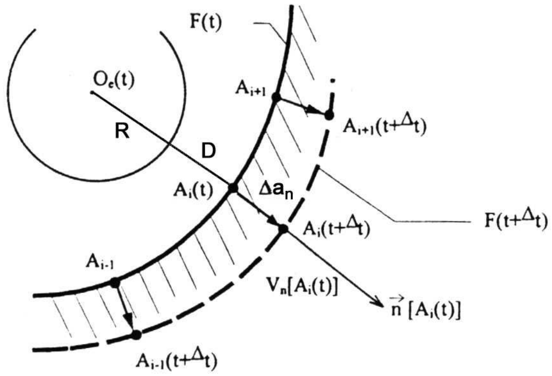
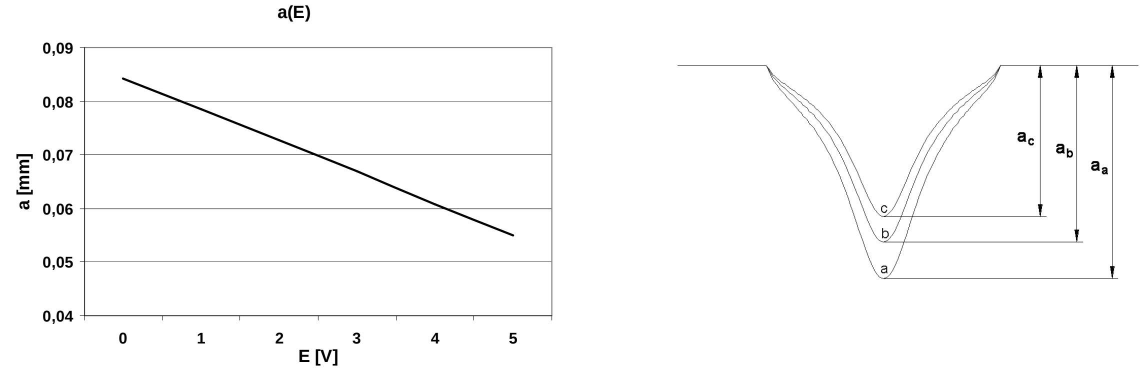


Fig. 2 Scheme used for describing machined shape changes in time Δt; Δa_n – anode surface displacement in Δt time (5)

Based on this model the special software was worked out at The Institute of Metal Cutting. This software was used for predicting the changes of allowance thickness *a* with the voltage drop in the electrolyte films adjacent to the electrode and workpiece during one electrode path. Results of these simulations were presented in Fig. 3a from which it is clear that *a* decrease with *E* increase.


a)

b)

Fig. 3 Results of ECM – CNC computer simulation: a) relation between maximal thickness of removed allowance *a* and voltage drop *E* for: $U=14\ V$, $v_p=30\ mm/min$, $S_o=0.5\ mm$, $R=5\ mm$, $\kappa=0.0136\ 1/\Omega mm$, $k_v=0.0213\ mm^3/As$; b) machining surface crossections in direction perpendicular to electrode displacement for $E=0, 3, 5\ V$

This relation is evident and well known, however can be very helpful for analysis results from USECM – CNC investigations. Also changes of the machined surface intersection shape with potential drop E (Fig. 3b) should be taking into account in analysis of ultrasonic vibrations influence. In case of electrochemical machining with universal ball-ended electrode assisted by ultrasonic vibrations the vibrations impact on workpiece surface depends on angle α (Fig 4a) in following way:

$$\frac{A_n}{A} = \cos\alpha \Rightarrow A_n = A\cos\alpha \tag{2}$$

where: α range is $(0, \alpha_{max})$ and α_{max} results from condition of minimal current density, which is necessary for dissolution process to proceed. In similar way can change potential drops E. Therefore increasing of removed allowance $\Delta a(x)$ causing by ultrasonic vibrations influence is not constant for all points but decreasing with α increase (Fig. 4b). This fact and above presented results of ECM – CNC simulation were useful for preliminary explanation of the differences in machined surfaces shaped after ECM – CNC and USECM – CNC machining.

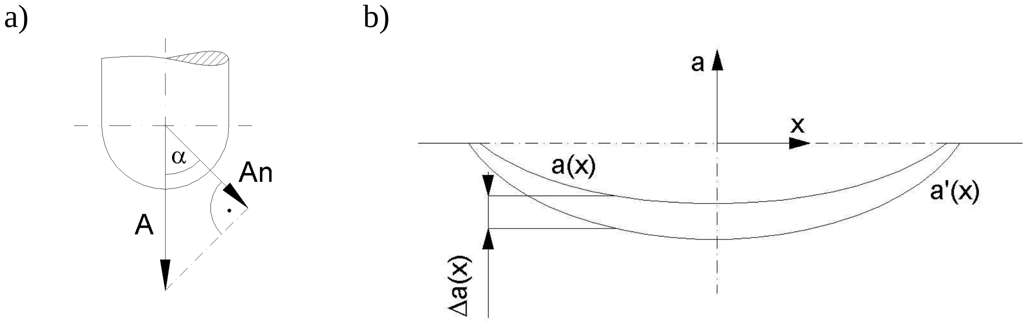


Fig 4 Ultrasound impact on workpiece surface: a) relation $A_n(\alpha)$; b) distribution $a(x)$ and $a'(x)$; $a(x)$ – thickness of machined allowance in ECM – CNC, $a'(x)$ – thickness of machined allowance in USECM - CNC

4 DESCRIPTION OF EXPERIMENTS

The ultrasonic head and equipment for workpiece clamping have been mounted in the working chamber of the electrochemical machine type EOCA 40 produced by The Institute of Metal Cutting. Ultrasonic head and generator have been also worked out at The Institute of Metal Cutting. The technical specification of head is presented in Table 1.

Table 1 Technical specification of ultrasonic generator

Working frequency	*f=22±1.5 kHz*
Maximal power of transducer vibration	*P=160 W*
Maximal amplitude of electrode vibration	*A=16 μm*
Maximal current	*100 A*
Supply	*220 V, 50 Hz*

The tests have been carried out for two ways of machining for ball ended electrode tool ($R=5$ *mm*). The first one was for the case with electrode ultrasonic vibration (USECM - CNC). The second was the classical ECM – CNC machining. The following parameters have been taken into account: interelectrode voltage $U=8 \div 20\ V$, electrode feed rate: $v_p=1 \div 59\ mm/min$, starting electrode distance from workpiece $S_o=0.1 \div 0.9\ mm$, electrolyte – water solution of $NaNO_3$, $C_e=10\div25\%$, power of ultrasonic vibrations $P=30 \div 150\ W$ (it corresponds to amplitude range: $2.73 \div 9.75\ \mu m$). The resulting factors were: thickness of removed allowance a, material removal rate V_w and surface roughness parameters R_a, R_z. As the machined material NC6 tool steel has been applied, electrode has been made of copper. The machined material is a martensitic steel and consists of Fe 1.4 % C, 0.6 % of Mn and 1.4 % of Cr. The scheme of test stand is presented in Fig 5a. In this primary part of experiments only one electrode path over machined surface has been carried out (Fig 5b).

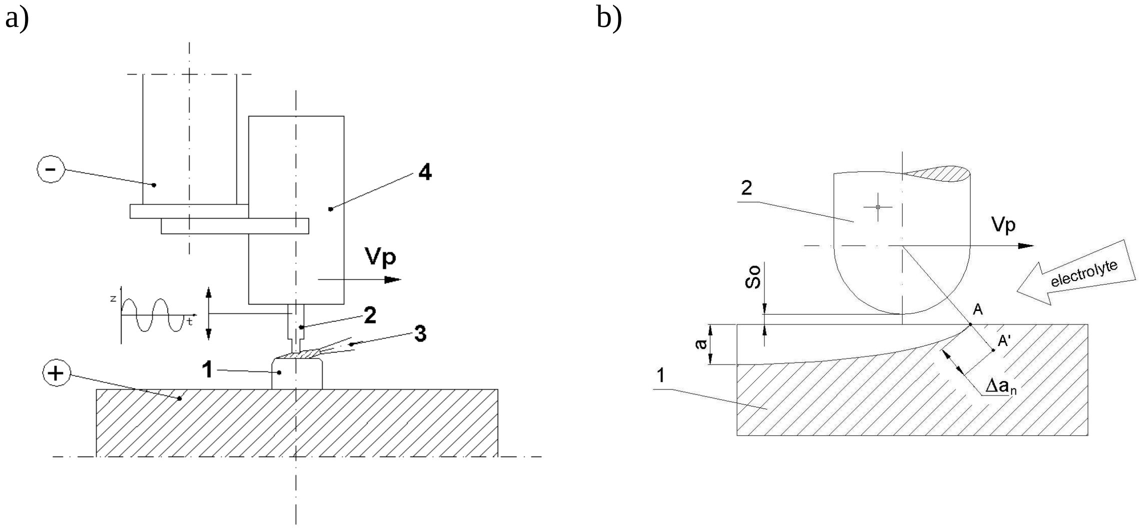


Fig. 5 Scheme of test stand for experiments (a) and machining in experiment (b); 1 – workpiece, 2 – electrode tool, 3 – electrolyte inlet, 4 – ultrasonic head, v_p –direction of machining, a - removed allowance thickness

It has been assumed that function of investigated object can be the equation in form of polynomial. As function of investigated object also neural nets have been taken (3). The results of analysis show that polynomials were adequate for all investigated factors, but errors of approximation when using neural nets were lesser than errors obtained from classical polynomials approximation. Below the results and analysis of investigations are presented.

5 ANALYSIS OF EXPERIMENTAL RESULTS

From Fig. 6 it results that it is possible to choose such USECM – CNC process parameters that increase of material allowance thickness removed take place. When electrode ultrasonic vibrations are introduced the allowance thickness for values of S_o between $0.1 \div 0.7\ mm$ considerable increases.

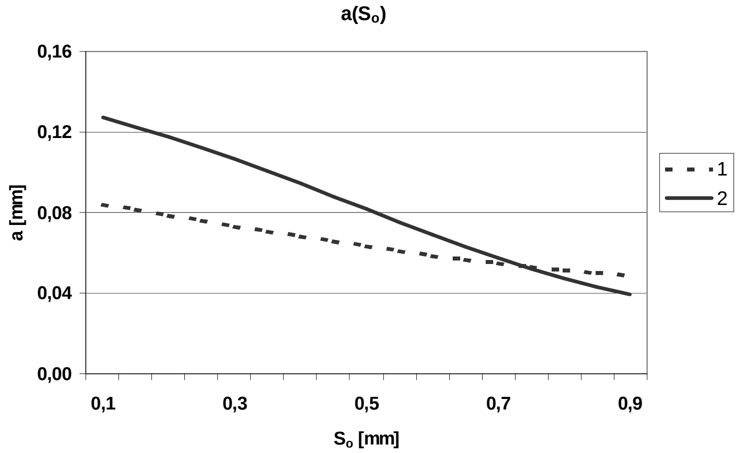


Fig. 6 Relationship $a(S_o,)$ when $U=14$ V; curve 1 – ECM – CNC machining, curve 2 – USECM – CNC machining, amplitude of electrode vibrations $A=5.70$ *μm*

From equation (1) results that differences in values of a in case of machining with and without electrode ultrasonic vibrations can be explained by differences in dissolution process conditions. For the same parameters (v_p, U) of both processes these differences can result from the fact that ultrasonic vibrations change the course of electrode reactions and change the values of E, $\eta k_v, \kappa$ and V_n. During the tests the increase of current density for USECM – CNC machining was observed what can indicate that ultrasonic cause decreasing of E. The differences in shape of electrode path crossections for the investigated ways of machining (Fig. 7) are similar to differences between shapes obtained from simulation for various E (Fig 3b). It confirms, that the assumption about decreasing E was correct.

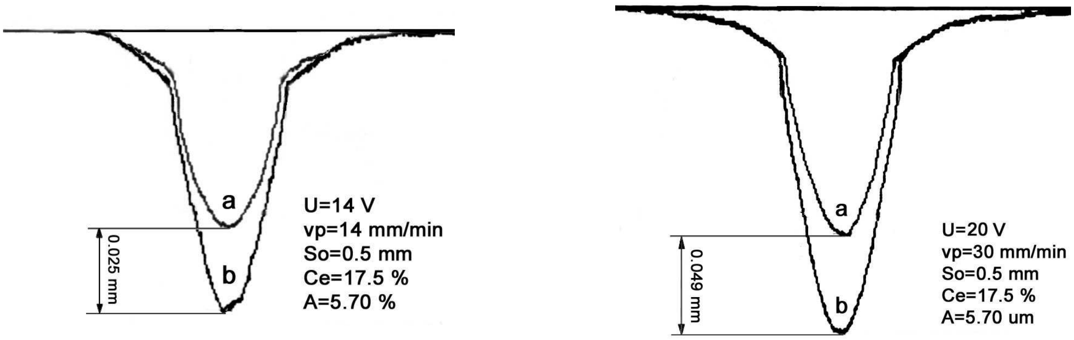


Fig. 7 Comparison of crossections from experiments for ECM – CNC (a) and USECM – CNC (b)

The decreasing of E can be explained by cavitation bubble collapse in liquid, which results in an enormous concentration of energy from the conversion of the kinetic of liquid motion into heating of the bubble. This collapse in multi-bubble cavitation field produces hot spots with effective temperatures of ≈5000 K, pressures of ≈1000 atmospheres, and heating and cooling rates above 10^{10} K/s (13). Thus, cavitation can create extraordinary physical and chemical conditions in liquids. Cavity collapse near an extended solid surface becomes non-spherical, drives high-speed jets of liquid into the surface, and creates shockwave damage to the surface. Thus, micro-jets and shock wave impact on surface have a substantial effects on the chemical composition and physical morphology of solid that can enhance chemical reactivity (13). Above presented phenomena cause changing value of potential drops in the layers adjacent to electrodes (electrode polarization *E*).

In general, properties of specific energy source determine the course of chemical reactions. Ultrasonic energy differs from traditional energy sources (such as heat, light or ionizing radiation) in duration, pressure, and energy per molecule (13). A huge local temperatures and pressures together with extraordinary heating and cooling rates generated by cavitation bubble collapse mean that ultrasound provides a unique conditions in electrolyte. Therefore, as a result of ultrasonic vibrations in machining area, the sonolisys of aqueous solutions may occur, according to which H atoms and OH radicals are formed in the course of ionization and excitation events in solvent:

$$H_2O \rightarrow H+OH$$

These radicals either combine to form H_2 or H_2O_2 or attack soluted molecules, which in this way are reduced or oxidized. These particles mainly take part in the redox reactions of dissolved metal ions. Above mentioned phenomena can also cause changes of values of dissolution process indicators ($E, \eta k_v$)

The comparison of relations $V_w(S_o)$ showed in Fig. 8 also confirm that introduction of ultrasonic vibrations change the course of dissolution process and, in the consequence of it, improve material removal rate. The relation $V_w(S_o)$ for USECM - machining is compatible with relation $V_w(S_o)$ from simulation for ECM – CNC with $E=0\ V$ what prove that ultrasonic vibrations decrease voltage drops on anode and cathode.

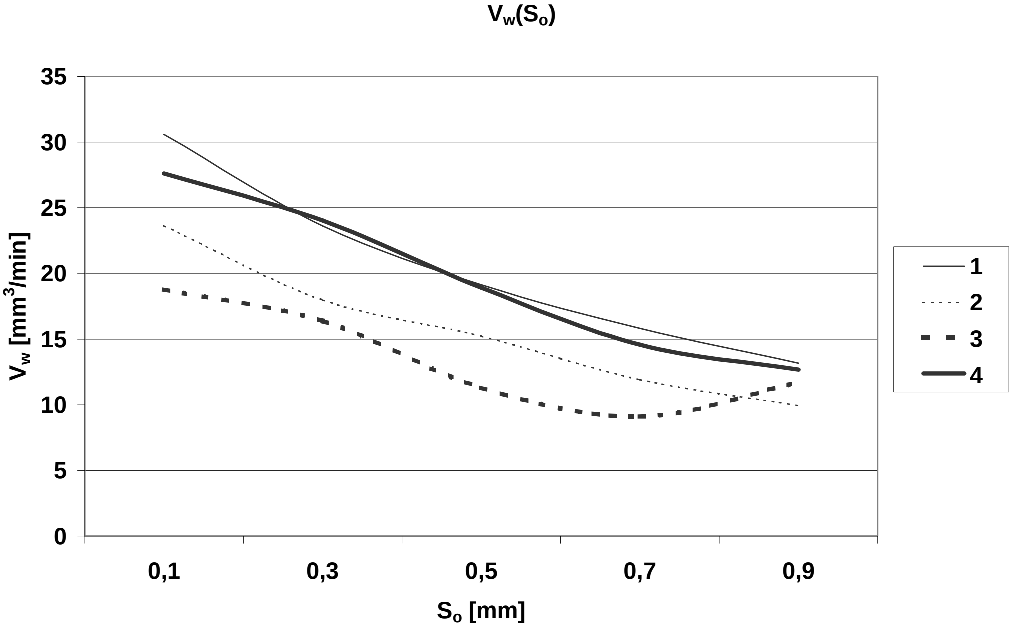


Fig. 8 Relations $V_w(S_o)$ for $U=20\ V$, $Ce=17.5\ \%$, $v_p=30\ mm/min$; 1 – curve from simulation for $E=0\ V$, 2 – curve from simulation for $E=5\ V$, 3 – curve from experiment ECM – CNC, 4 - curve from experiment USECM - CNC

One of the investigated factors was surface roughness parameters. Analysis of it showed that despite increasing of current density there is no differences in R_a and R_z for ECM – CNC and USECM – CNC machining. In ECM the mechanism of smoothing process results from differences in dissolution process for tops and bottoms of roughness During the ECM supported by electrode ultrasonic vibrations the micro-jets, which are created during collapse of cavitation bubbles, can create uniform electrolyte properties for tops and bottoms of roughness. So, in this case, it causes the equalization of dissolution rate.

6 CONCLUSIONS

Above presented results of primary investigations of USECM – CNC process indicate that introduction of electrode ultrasonic vibration in case of machining with universal electrode can change conditions of dissolution process and cause the increase of allowance thickness a and material removed rate V_w without surface quality decreasing. Preliminary analysis of phenomena in electrolyte irradiated with ultrasound show that probably acoustic cavitation is responsible for dissolution intensification. However, in order to explain this problem in more detailed way, the further investigations are necessary. They should also include recognizing of relation between Δa and angle α because this relationship can be useful not only for machining with universal electrode but also for electrochemical sinking assisted by ultrasonic electrode vibrations. In this case of machining relation $\Delta a(\alpha, A)$ can be useful on stage of designing electrode tool shape and dimensions.

Presented in this paper way of improvement of electrochemical machining with universal electrode can cause that ECM – CNC will wide its range of practical applications. Despite of increase of material removal rate in ECM – CNC process, this way of improvement doesn’t cause that electrochemical machining with universal electrode starts competition with classical electrochemical sinking of sculptured surfaces. USECM – CNC should be used in finishing operations of surfaces initially machined by other methods.

7 ACKNOWLEDGEMENTS

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REFERENCES

1 **Davydov, A. D., Kozak, J** (1990) High Rate Electrochemical Shaping. Nauka, Moscow. (in Russian).

2 **McGeough, J.A.** (1976) Principles of Electrochemical Machining. Chapman and Hall, London.

3 **Gawlik, J., Karbowski, K., Ruszaj, A.** (1999) The neural – genetic optimisation of the electrochemical machining. In *Computer Integrated Manufacturing,* Vol. 1, WNT Warszawa, pp. 166 – 173.

4 **Kozak, J.** (1997) Analiza procesu obróbki elektrochemicznej elektrodą drgającą. In *Obróbka erozyjna – Materiały Konferencyjne*. Bydgoszcz – Golub Dobrzyń, pp. 204 – 212 (in Polish).

5 **Kozak, J., Chuchro, M., Ruszaj, A., Karbowski, K.** (1999) The computer aided simulation of electrochemical process with universal spherical electrodes when machining sculptured surfaces. In *Proceedings of the 15th International CAPE Conference,* pp. 425 – 430.

6 **Kozak, J., Rajurkar. K. P., Malicki S.** (2000): Study of electrochemical machining utilizing a vibrating tool electrode. In *Proceedings of the 16th International Conference on Computer – Aided Production Engineering*. pp. 173 – 181.

7 **Perusich, S. A., Alkire, R. C.** (1991) Ultrasonically induced cavitations studies of electrochemical passivity and transport mechanism. I. Theoretical. In *J. Electrochemical Soc.* Vol. 138/3, pp 700 – 707.

8 **Perusich, S. A., Alkire, R. C.** (1991) Ultrasonically induced cavitations studies of electrochemical passivity and transport mechanism. II. Experimental. In *J. Electrochemical Soc.* Vol. 138/3, pp. 708 – 713.

9 **Rajurkar, K. P., Zhu, D., McGeough, J. A., Kozak, J., De Silva A.** (2000) New Developments in Electro-Chemical Machining. In *Annals of the CIRP*. Vol. 48 (2), pp. 567 – 579.

10 **Ruszaj, A., Zybura – Skrabalak, M., Skoczypiec, S., Żurek R.** (2001) Electrochemical machining supported by electrode ultrasonic vibrations. In *Proceedings of the 13th International Symposium of Electromachining*. pp. 953 - 964.

11 **Ruszaj, A., Zybura, M., Żurek, R., Skrabalak, G.** (2001) Some aspects of electrochemical machining process supported by electrode ultrasonic vibrations optimisation. *2nd International Conference on Advances in Production Engineering*. Warsaw, Poland, vol. II, pp. 281 - 290.

12 **Ruszaj A., Zybura – Skrabalak M., Żurek R., Skoczypiec S., Skrabalak G.** (2001) Electrochemical machining supported by electrode ultrasonic vibrations. In *Proceedings of The Symposium on Research on Clean Hybrid Micromachining (HMM) Processes*. Krakow, Poland, paper number B6.

13 **Suslick, K.S, Didenko, Y., Fang, M.M., Hyeon, T., Kolbeck, K.J., Mcnamara, W.B., Mdleleni, M.M., Wong M.** (1999) Acoustic cavitation and its chemical consequences. *Phil. Trans. Roy. Soc.* A, vol. 357, pp. 335 – 353.