Numerical Investigations on Ultrasonically Assisted Electrochemical Machining Process (USECM)

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Abstract

In the paper application of Computational Fluid Dynamic for analyse of electrolyte flow through the gap in USECM is presented. In this case electrode tool ultrasonic vibration introduces additional, normal to the workpiece, velocity component. Based on Computational Fluid Dynamic (CFD) methods, multiphase, turbulent and unsteady flow between anode and cathode, under assumption that cavitation phenomenon occurs, has been analyzed. Investigations prove that ultrasonic changes condition of electrochemical dissolution and for optimal parameters of vibration amplitude gives possibility to decrease the electrode polarisation.

Keywords:

Electrochemical Machining, Ultrasonic Vibration, Hybrid Methods, CFD

1. INTRODUCTION

Electrochemical machining (ECM) is an important technology in machining difficult-to-cut materials and to shape complicated contours. In ECM material is removed by electrochemical dissolution process what cause that part is machined without inducing residual stresses and without tool wear. In comparison to conventional methods the main advantages of ECM are as follows:

- material removal rate does not depend on material hardness,
- no tool wear during machining (when machining parameters are optimal),
- good surface quality after machining (there is no significant changes in surface layer).

Because of this advantages ECM has traditional fields of application in space, aircraft and domestic industries.

One of the ways to improve technological factors in electrochemical machining is introduction of electrode tool ultrasonic vibration (Ultrasonically Assisted Electrochemical Machining - USECM).

Generally, application of ultrasound to fluid causes a chaotic, turbulent flow. Propagation of the sound wave through the ultrasonically irradiated media creates pressure drop, which can breaks forces holding the liquid molecules together and produces micro bubbles. The literature describes several types of cavitation, but the most interesting, taking into account interaction with electrochemical dissolution is “transient” cavitation [1] [2]. In this case cavitation bubble grows extensively and then undergoes an energetic collapse, which usually occurring in less then one microsecond [2]. Bubble collapse leads to the local generation of extreme conditions of temperature and pressure in very short time. “Hot spot” theory estimates that during collapse temperature reach about 5000 K and pressures is approximately 1700 bar [2].

In case of ultrasonically assisted electrochemical machining ultrasonic gives possibility for creating cavitation microbubbles near the workpiece and electrode surface. Dissolved in electrolyte gas, products of dissolutions and increased electrolyte temperature during machining, cause, that in the gap very good conditions for cavitation bubble grow occurs.

Process of microbubbles collapse in area adjacent to electrode gives possibility for increasing the intensification of mass and electric charge transportation.

Taking into account results of investigation presented in [3] [4] [5] it is right to state that ultrasonic vibrations have a significant influence on the electrode processes conditions. Results of investigations carried out in The Institute of Advanced Manufacturing Technology [4] [5] showed that thanks to ultrasonic vibrations electrochemical reactions products transportation is improved and electrode polarization is decreased.

In the paper application of Computational Fluid Dynamic to analysis of electrolyte flow through the gap in USECM has been presented. Results of these investigations give possibility to predict cavitations bubbles distribution along the gap what can be helpful during experimental data analysis and in USECM manufacturing processes designing.

2. PROBLEM FORMULATION

In case of ECM, flow through the gap is three dimensional, multiphase and unstable. Usually electrolyte flow analysis is carried out under assumption that electrolyte properties are constant along the gap thickness. When machining process is carried out in steady state, such assumption is sufficient. But in case of machining in unstable or quasistable state (as in USECM case) change of electrolyte properties in direction normal to the workpiece should not be neglected.

In USECM vibration of the electrode tool introduce additional, normal to the workpiece electrolyte velocity component. In case of USECM ultrasonic vibration frequency is about 20 kHz what gives wavelength about 70 mm for sea water. So, the ultrasonic wavelength is much greater then typical interelectrode gap during machining. Moreover, in majority cases the amplitude of vibration is less than 10 μm, therefore for small interelectrode gap thickness (≈ 0.1 mm) distance from anode to cathode is varied only ± 10 %. So, it is reasonable to assume that ultrasonic influence on electrochemical dissolution process manifest itself through cavitations and its consequences.

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Analytical solution of the Navier – Stokes equations for multiphase, turbulent and unstable electrolyte flow are quite complicated. In USECM additional, special effort should be also connected with identification of cavitation distribution along the gap. In this case good alternative is application of Computational Fluid Dynamics (CFD). Numerical solution of the Navier – Stokes equations gives possibility to obtain electrolyte pressure and velocity distribution in whole gap area and application of "Full Cavitation Model" gives possibility to include cavitation effects in two-phase flow.

3. NUMERICAL MODEL OF ELECTROLYTE FLOW THROUGH THE GAP

3.1 Assumptions

In presented model two dimensional flow between two electrodes is taking into account. Scheme and boundary conditions of the flow are presented in the Figure 1. Anode (workpiece) is modelled as a stable wall and cathode (electrode tool) is modelled as vibrating with frequency 20 kHz (period of vibration T = 50 μs) wall. During simulations three levels of ultrasound amplitude were taken into account: A = 2.5 μm, A = 5 μm and A = 10 μm. The gap size g = 1 mm is bigger then typical gap during ECM (typically less than 0.5 mm), because for g < 1 mm problem of numerical model stable solution obtaining occurs.

The Fluent software has been applied to solve the problem of electrolyte flow along such gap. One can state that during USECM flow through the gap is turbulent, multiphase and unsteady. Additional assumption connected with electrode ultrasonic vibration is, that cavitation phenomenon occurs in the gap. There is assumed that electrolyte in the gap consist of three phases:

- pure electrolyte,
- vapour of electrolyte,
- non – condensable dissolved gas.

To solve multiphase flow between the cathode and anode, based on the *Euler – Euler* approach, *Mixture model* is applied. The electrolyte and gas phases are treated mathematically as interpenetrating continua and the concept of phasic volume fraction α is introduced. It is a continuous function of space and time, and for the mixture in the gap the following formula is fulfilled:

$$\alpha_e + \alpha_v + \alpha_g = 1 \tag{1}$$

where: α_e – electrolyte volume fraction, α_v – vapour volume fraction, α_g – non – condensable gas fraction. The mixture density and viscosity are described by following equations:

$$\rho_m = \alpha_e\rho_e + \alpha_v\rho_v + \alpha_g\rho_g \tag{2}$$

$$\mu_m = \alpha_e\mu_e + \alpha_v\mu_v \tag{3}$$

where: ρ_e, ρ_v, ρ_g, μ_e, μ_v - density and viscosity of each mixture phase.

3.2 Equations of electrolyte flow

Flow of the electrolyte mixture thought the gap is described by following set of equations [6]:

1. Continuity equation of the mixture:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla\cdot(\rho_m \boldsymbol{v_m}) = \dot{m} \tag{4}$$

where $\boldsymbol{v_m}$ is the electrolyte mass - averaged velocity, $\dot{m}$ represents mass transfer between electrolyte and its vapour due to cavitation.

2. Momentum equation of the mixture (obtained by summing individual momentum equations for all phases):

$$\frac{\partial}{\partial t}(\rho_m \boldsymbol{v_m}) + \nabla\cdot(\rho_m \boldsymbol{v_m}\boldsymbol{v_m}) = -\nabla p + \nabla\left[\mu_m(\Delta \boldsymbol{v_m}) + \Delta \boldsymbol{v_m^T}\right] + \boldsymbol{F} \tag{5}$$

3. Volume fraction equation for the vapour phase (obtained from the continuity equation for vapour):

$$\frac{\partial}{\partial t}(\alpha_v\rho_v) + \nabla\cdot(\alpha_v\rho_v\boldsymbol{v_m}) = 0 \tag{6}$$

Numerical solution of above mentioned equations gives possibility to obtain mixture velocity $\boldsymbol{v_m}(x,y,t)$, mixture pressure $p(x,y,t)$, and electrolyte vapour phase $\alpha_v(x,y,t)$ distribution in the gap.

Reynolds number of the electrolyte flow during machining depends on the interelectrode gap thickness and kind of electrolyte. In typical applications minimal Re is in range $10^3 \div 10^4$, what cause that is difficult to state that flow is laminar or turbulent. Usually, for ECM analysis is carried out based on assumptions that flow is laminar. However in USECM, when cavitation phenomena is taking into account turbulences can not be neglected, because of its significant influence on cavitation. Majority of turbulence models are appropriate to model single phase flow. Information about turbulence modelling in multiphase flow with cavitation is limited, therefore k-ε model, which has reasonable accuracy for wide range of flows is assumed.

3.3 Mass transfer through cavitation

The applied cavitation model is based on *Full Cavitation Model* presented by Singhal et al. in [7]. The phase change rate expressions are derived from a reduced Rayleigh-Plasset equation for single bubble dynamics and their final form are described by following equations [7]:

$$R_e = Ce\frac{\sqrt{k}}{\sigma}\rho_e\rho_v\left[\frac{2}{3}\frac{p_v - p_\infty}{\rho_e}\right]^{\frac{1}{2}}\left(1 - f_v - f_g\right) \tag{7}$$

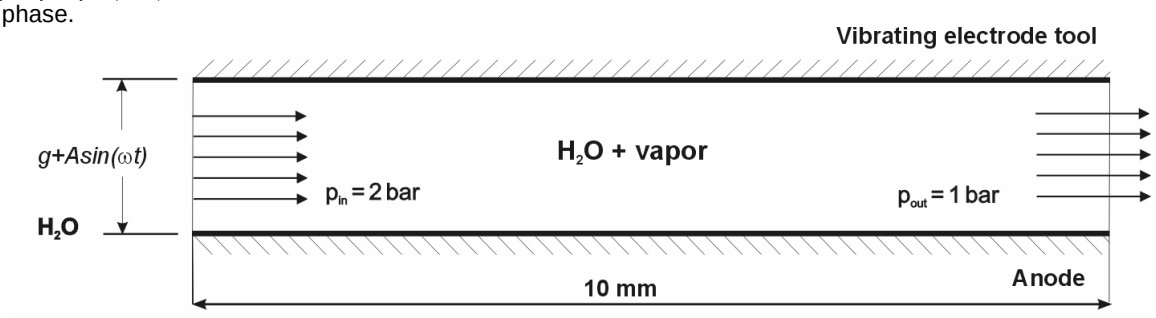

Figure 1: Scheme of modelled gap, g = 1 mm, frequency of vibration: 20 kHz.

$$R_c = Ce\frac{\sqrt{k}}{\sigma}\rho_e\rho_v\left[\frac{2}{3}\frac{p_\infty - p_v}{\rho_e}\right]^{\frac{1}{2}} f_v \quad (8)$$

where: R_e, R_c are the vapour generation and condensation rate terms, $C_e = 0.02$, $C_e = 0.01$ are the empirical constants, f_v, f_g are the phase mass fraction ($f_i = \alpha_i \frac{\rho_i}{\rho_m}$). The phase change threshold p_v is estimated from equation (9) which describes the local values of the turbulent pressure fluctuation and from equation (10):

$$p_{turb} = 0.39\rho k \quad (9)$$

$$p_v = p_{sat} + p_{turb}/2 \quad (10)$$

where p_{sat} is the electrolyte saturation vapour pressure. Due to problems occurring on electrolyte saturation vapour pressure estimation, surface tension for water at temperature 300 K was assumed.

4 RESULTS OF SIMULATION

During analysis of results main attention is focused on pressure p and vapour phase α_v change in the gap. Results shown that flow in the gap has periodical character with time constant equal to ultrasonic vibration period. In the Figure 2 and 3 changes of the pressure and vapour phase fraction in time, for amplitude of vibration A = 5 μm is presented. When electrode moves in direction opposite to machining direction, pressure in the area adjacent to anode decreases. In the same time amount of vapour in this area increases up to 14 % of electrolyte volume. When electrode tool moves towards the anode pressure increases, and reaches maximal value for time t = nT. In this moment amount of vapour has minimal value. Such relationships of pressure and vapour phase fraction can point that, after phase of cavitation bubbles grow, rapid collapse appear. For each value of analyzed amplitude, character of pressure and vapour phase fraction changes is similar, however range of pressure and vapour phase fraction depends on amplitude of vibration.

In Figures 4, 5, 6 and 7 comparisons of the pressure and vapour volume fraction distribution along the gap for A = 2.5 μm, A = 5 μm, A = 10 μm are presented. These relationships are shown distributions for two characteristic moments of the machining: t_1 = (nT+T/2) and t_2 = nT, when size of the gap is 1 mm. One can state that:

- for t = t_1 (Figures 4 and 5) value of the maximal pressure depends on amplitude of ultrasonic vibration and appears in area close to the electrode tool. Maximal pressure drop in the gap is observed for A = 10 μm. For analyzed amplitudes pressure and vapour volume fraction in areas adjacent to the anode has similar value (p ≈ 0.8 bar, $\alpha_v \approx 0.1$). One can notice that distribution of cavitation bubbles along the gap is non – uniform, and for *A = 2.5 μm* maximal intensity of cavitation is only in areas close to the anode;
- for t = t_2 (Figures 4 and 5) maximal pressure value are in areas close to the anode and also depends on amplitude of ultrasonic vibration (maximal for A = 10 μm). Maximal intensity of cavitation is in layers of electrolyte adjacent to the cathode.

From presented relationships one can state that ultrasonic vibrations are responsible for pressure gradient in direction normal the electrolyte flow. Value of the pressure drop depends on amplitude of ultrasonic vibration. Thickness of the electrolyte layer, where cavitation appears with their maximal intensity depends on vibration amplitude (from 0. 25 mm for A = 2.5 μm up to 0.7 mm for A = 10 μm). Increase of ultrasonic vibration amplitude results in increase of cavitation intensity inside the interelectrode gap (not only in areas adjacent to electrodes).

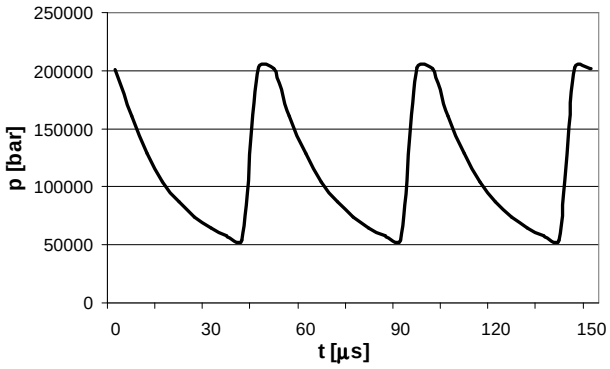

Figure 2: Changes of the electrolyte pressure in the layer close to the anode surface for time period 150 μs, amplitude of electrode vibration A = 10 μm, period of electrode vibration T = 50 μs, .

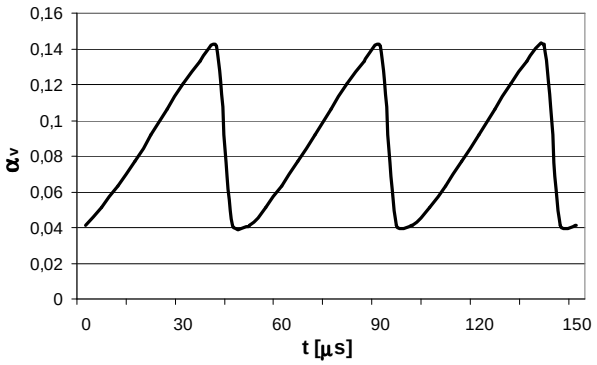

Figure 3: Changes of the vapour volume fraction in the layer close to the anode surface for time period 150 μs, amplitude of electrode vibration A = 10 μm, period of electrode vibration T = 50 μs.

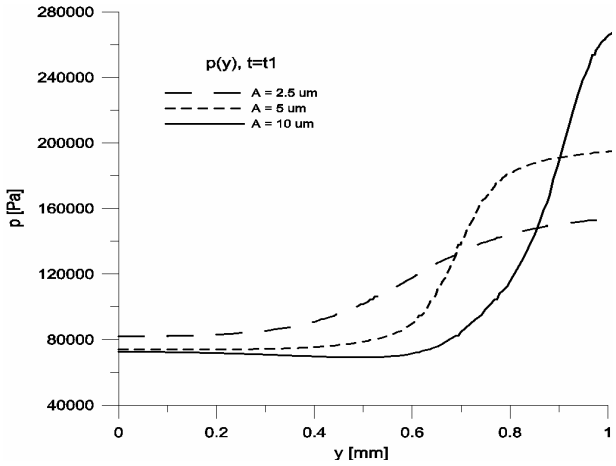

Figure 4: Comparison of the pressure distribution along the gap thickness for A = 2.5 μm, A=5 μm, A=10 μm, t = (nT+T/2) μs, 0 – anode surface, 1 – electrode tool surface.

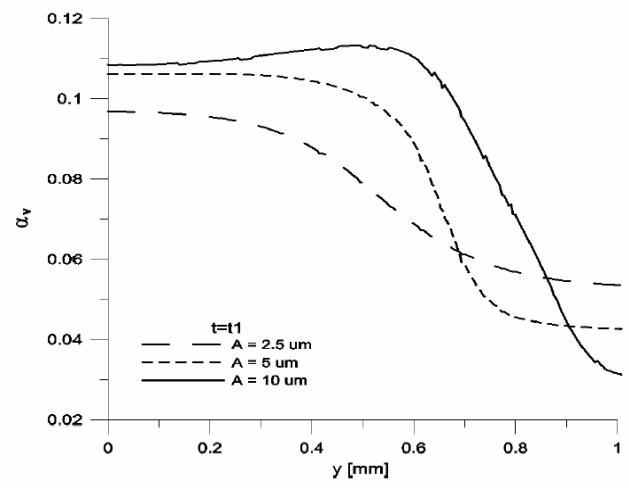

Figure 5: Comparison of the vapour volume fraction α_v distribution along the gap thickness for A = 2.5 μm, A = 5 μm, A = 10 μm, t = (nT+T/2), 0 – anode surface, 1 – electrode tool surface.

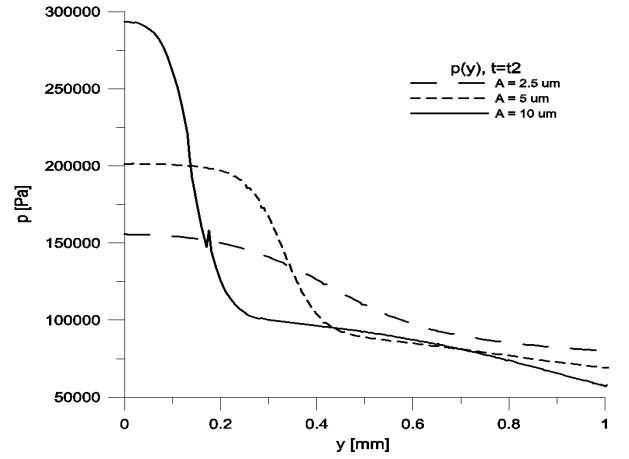

Figure 6: Comparison of the pressure distribution along the gap thickness for A = 2.5 μm, A = 5 μm, A = 10 μm, t = nT, 0 – anode surface, 1 – electrode tool surface.

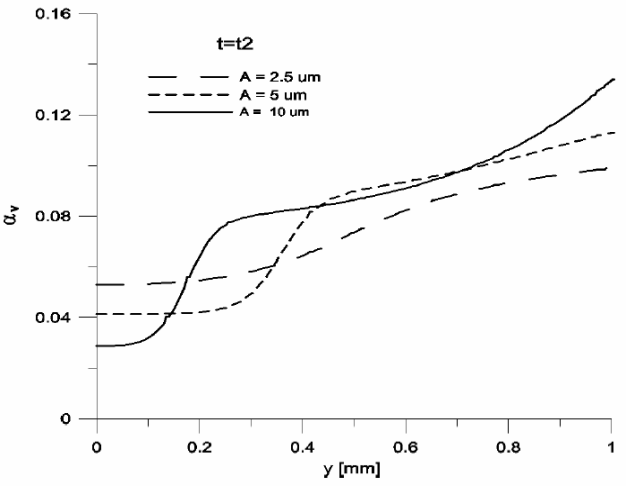

Figure 7: Comparison of the vapour volume fraction α_v distribution along the gap thickness for A = 2.5 μm, A = 5 μm, A=10 μm, t = nT, 0 – anode surface, 1 - electrode surface.

5 RESULTS DISSCUSION IN ASPECT OF ELECTROCHEMICAL DISSOLUTION PROCESS

Ions transport in the gap is driven by migration (transport driven by electric forces), convection and diffusion. In areas of electrolyte adjacent to the anode surface migration and convection play less significant role than diffusion, which is the main transport mechanism via anode – electrolyte layer. Increase of anode ions concentration gradient increase the speed of anode dissolution. The value of concentration polarization is mainly connected with electrolyte hydrodynamics conditions in the gap.

As has been shown during numerical simulation, cathode ultrasonic vibrations cause that in the gap cavitation phenomena occurs. Cavitation bubbles in electrolyte can occur in two forms [2]:

- as homogeneous cavitation – temporary thermal motions in electrolyte can cause microscopic voids which are growing into bubbles;
- as heterogeneous cavitation, where weaknesses occur at the boundary between the electrolyte and the solid (e.g. electrode wall) and than are growing into bubbles.

Dissolved in electrolyte gas, products of dissolution and increase of electrolyte temperature during machining, cause, that in the gap very good conditions for bubble collapse occurs [8].

In above presented model non-condensable, with equal for whole volume mass friction was assumed. In real ECM dissolution products concentration changes along gap thickness. Close to anode electrolyte temperature and amount of hydrogen concentration is higher, what cause better physical conditions for bubble creations in this area (products of dissolution - gas, heat and sludge in electrolyte decrease a tensile strength necessary to bubble creation). In these areas cavitation occurs with higher intensity than simulation shown.

After creation of bubble begins the phase of bubble grow and than phase of rapid collapse [1] [2]. The bubble collapse near the anode surface produce mechanism of microjet impact on this surface [8] [9]. The potential energy of expanded bubble is converted into kinetic energy of liquid jet motion. Such jet can reach velocity about 100 m/s. The extremely fast bubble collapse cause local electrolyte refreshment and increase of concentration gradient. This effect is responsible for depolarisation and depasivation what results in material allowance thickness and removal rate increase during USECM.

In the [9] application of electrode ultrasonic vibration in case of electrochemical was investigated. Research was carried on for ultrasonically assisted electrochemical sinking and electrochemical machining with universal electrode tool. Results of this experiments prove that in both investigated kinematics variants of ECM electrode tool ultrasonic vibrations increase machined allowance and material removal rate.

In the Figure 8 and 9 the relationships of machined allowance thickness and material removal versus interelectrode voltage for ECM and USECM is presented. For whole range of interelectrode voltage tested during investigations increase of machined allowance thickness and material removal rate is observed. From this investigations results also that that ultrasonic vibration influence on technological factors depends on others parameters of machining – mainly electrode velocity and interelectrode gap thickness [9].

One of investigated factor was surface roughness parameter Ra. Comparison of results for ECM and USECM presented in [8] showed that for some machining

parameters, despite of current increasing the Ra for USECM is higher then for machining without ultrasonic vibrations. Presented in [8], detailed analysis of this effect shown that extremely fast bubble collapse in roughness depression cause local electrolyte refreshment and increase local machining rate. This effect is responsible for dissolution velocity equalize in peaks and bottoms of roughness what results in roughness increase during USECM.

Based on the detailed analysis of phenomena in the gap during USECM the following hypothesis can be formulated [9]: in aspect of ions transport in the interelectrode gap the most important is heterogeneous cavitation. This phenomenon is responsible for electrode polarization decrease. Increase of amplitude of ultrasonic vibration, cause that homogeneous cavitations occurs, what results in cavitation bubbles amount in the gap interior increase. It cause increase of hydrodynamic losses, decrease of electrolyte conductivity, and makes diffusion of the anode ions more difficult.

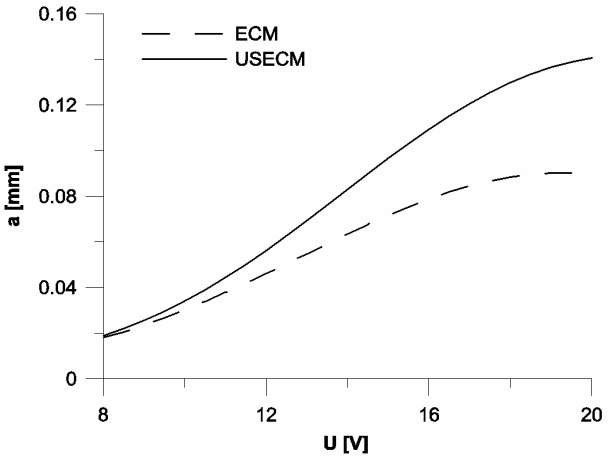

Figure 8. Relationships between machined allowance thickness a and interelectrode voltage U for electrochemical milling with universal ball ended (R = 5 mm) electrode tool; electrode velocity v = 30 mm/min, initial interelectrode gap S = 0.5 mm, amplitude of ultrasonic vibration A = 5.7 μm, electrolyte: 17.5 % water solution of $NaNO_3$.

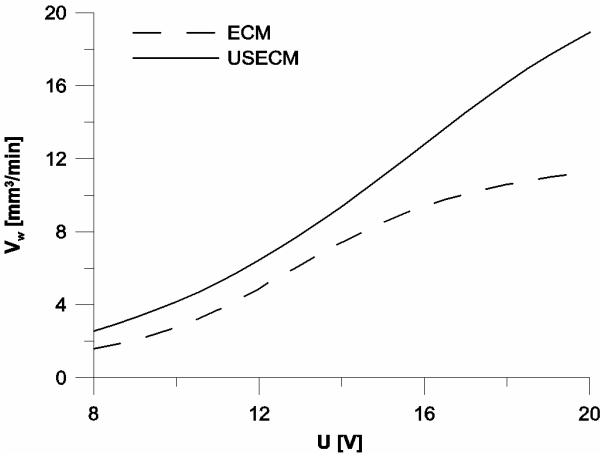

Figure 9. Relationships between material removal rate V_w and interelectrode voltage U for electrochemical milling with universal ball ended (R = 5 mm) electrode tool; parameters of machining as in Figure 8.

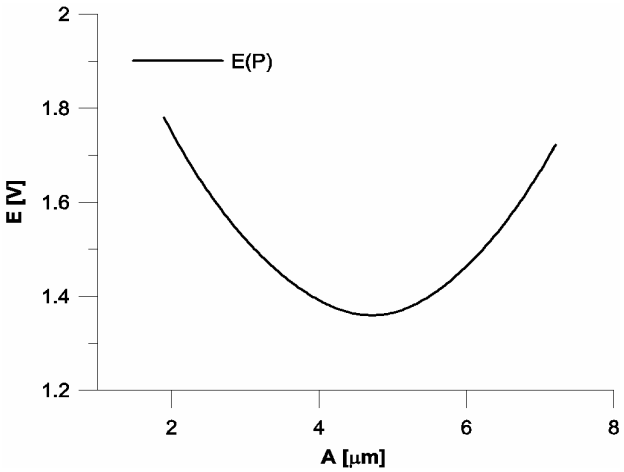

Figure 10. Relationship between amplitude of ultrasonic vibration A and electrode polarisation E for electrochemical sinking; interelectrode voltage U = 15 V, electrode feed rate v_f =0.8 mm/min.

Presented in Figure 10 relationship shows that for considered parameters of machining optimal value of vibration amplitude should be found. It also prove that increase of vibration amplitude affects negative on electrode polarisation.

One of the most important factors which influence on technological machining factors in ECM is electrolyte conductivity κ. Local changes of κ are the main reason of workpiece inaccuracy. Generated during machining heat and electrolyte vapour in driven by ultrasonic vibration cavitation bubbles significantly affect on electrolyte properties. Taking into account electrolyte as quasi-homogeneous media (the properties are averaged along the gap thickness) and that changes of electrolyte temperature connected with electrolyte flow can be neglected (temperature depends only on time), condition of machining during on vibration period can be calculated from following equations [9]:

$$j = j_0(1+\alpha\Theta)(1-\beta)^{\frac{3}{2}} \tag{11}$$

$$qT = j_0\int_0^T (1+\alpha\Theta)(1-\beta)^{\frac{3}{2}}\,dt \tag{12}$$

$$\Theta(t) = \frac{1}{\alpha}\left[\exp\left(\frac{\alpha j_o^2}{\kappa_0\rho_0 C_p}\int_0^t\sqrt{(1-\beta)}\delta t\right)-1\right] \tag{13}$$

where: α - temperature coefficient of electrical conductivity, $\Theta(t)$ - electrolyte temperature increase in time t, β - volume concentration of the dispersed in electrolyte gas, j – current density, $j_0 = \kappa_0\frac{U-E}{S}$, C_p – electrolyte specific heat.

Taking into that $\beta = \alpha_v$ (50 μs is to short time to hydrogen generation), S = g (gap thickness – the same as in numerical simulation) and U = 30 V the Equations (11), (12) and (13) were solved for vibration amplitude A = 5 μm. In the Figure 11 the transferred electric charge distribution is presented. Amount of transferred electric charge is equivalent to mass of dissolved material. From Figure 11 results that cavitation bubbles in electrolyte can be a reason of irregular anode dissolution and decrease accuracy of machining. In presented analysis local effects of bubble collapse was omitted and obtained results

shows that not optimal selection of ultrasonic vibration amplitude for desired parameters of ECM machining may be a reason of machining parameters deterioration. One can also state that application of ultrasonic vibration in ECM needs to improve the electrolyte supply to the gap (i.e. increase electrolyte velocity).

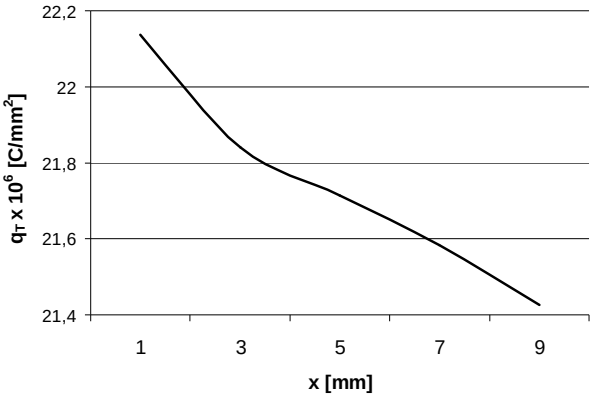

Figure 11. Distribution of electric charge transfered through the gap during 50 μs period, A = 5 μm, x – length of the gap.

6 CONCLUSIONS

Numerical investigations on USECM prove that ultrasonic vibrations change condition of electrolyte flow in the gap. Solution of the equations describing electrolyte flow along the gap gives possibility to obtain pressure, velocity and cavitation intensity distribution in the machining area. Numerical investigation shown that intensity of cavitation affect significantly on conditions of dissolution process and depends on amplitude of ultrasonic vibration. Proper selection of machining parameters (especially amplitude of ultrasonic vibrations) cause that heterogeneous cavitation plays significant role in electrode potential decrease.

Verification of above presented model during electrochemical machining is quite difficult. The main problem is connected with the size of interelectrode gap and short time of cavitation phenomena. Electrode tool ultrasonic vibrations influence on electrochemical dissolution process can be observed by changes of machining parameters (i.e. increase of material allowance thickness) and presented model can be applied to machining results analyse.

Presented results of USECM research prove that ultrasonic change condition of dissolution process in interelectrode gap. In result increase of machined allowance and removal rate is observed.

Presented work, shown also that Computer Fluids Dynamics can be successfully applied for modelling of phenomena occurring in the interelctrode gap, especially when machining is carried on in quasistable or unstable state.

7 ACKNOWLEGMENTS

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