STUDY OF DIMENSIONAL LIMITATIONS OF ELECTRO-CHEMICAL MICRO-MACHINING

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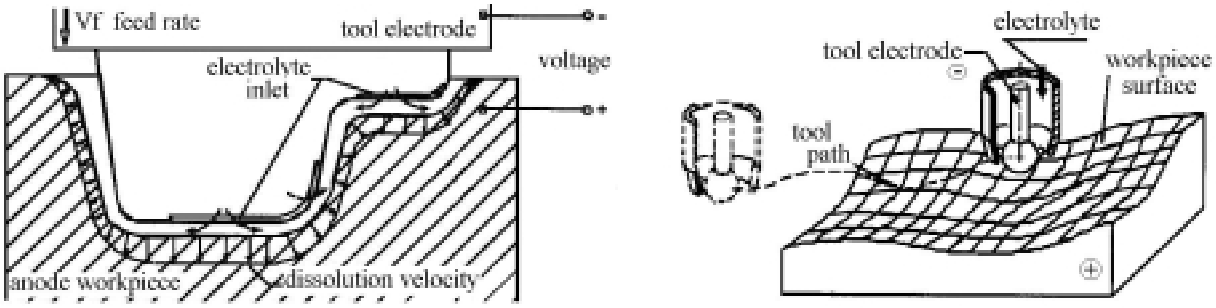
Introduction. Electrochemical Machining (ECM) has established itself as one of the major alternatives to conventional methods of machining difficult - to - cut materials of and/or generating complex contours, without inducing residual stress and tool wear. It has been applied in diverse industries such as aerospace, automotive and electronics, to manufacture airfoils and turbine blades, die and mold, artillery projectiles, surgical implants and prostheses, etc. [1]. Moreover with recent advances in machining accuracy and precision, based on the development of advanced electrochemical metal-removal processes, demonstrate that the ECM can be effectively used for micro-machining components in the electronics and precision industries [2].

This paper presents a study of detail-transfer by ECM as applicable to micro-machining capabilities. The application of integrating laser with ECM process to improve micro-ECM operations is also presented.

Experimental Results and Analysis of Detail-Transfer in ECM. Electrochemical Machining is employed in micro machining for the copying of mini-features of the cathodic tool electrode onto the anodic surface of the workpiece, i.e. “detail transfer” by ECM (Figure 1a), and for manufacturing mini-shapes, slots, groves and micro-holes without the use of a profile electrode (Figure 1b).



a) **b)**

Fig.1. Electrochemical machining (ECM) using: a) contoured tool electrode, b) numerically controlled non-profiling tool electrode

In most applications, a high rate of machining is maintained by feeding the tool electrode towards the workpiece with a constant feed rate. A steady state is reached in which the machining surface maintains a fixed shape as it recedes in the direction of the tool feed. The equilibrium surface of the anode resembles the tool shape, but is not congruent with it. The difference in shape is particularly significant for the copying of mini-features.

The results of theoretical and experimental investigations of the relationship between the characteristic shape dimensions, imported upon the anode-workpiece surface by the micro-features of the cathode-tool electrode under given machining conditions are presented. This research included the study of electrochemical copying of slots, mini-holes, and grooves and insulating groove features, which are shown in Figures 2, 3, 4 and 5 [4]. Mini-features are defined as those whose dimensions are below 5 S_f (for example, b, h, d < 5 S_f), where S_f is equilibrium gap size in a steady-state ECM process:

$$S_f = \kappa \cdot K_V \frac{U - E}{V_f}$$

where κ is electrical conductivity of electrolyte, K_V is the electrochemical machinability coefficient, which is defined as the volume of material dissolved per unit electrical charge, U is working voltage, E is total overpotential of electrode processes, and V_f is the feed rate of tool electrode.

The experimental investigations were performed on a sinking electrochemical machine tool with a 10% $NaNO_3$ water solution. Workpieces were made of die steel (0.7% Cr, 1.6% Ni, 0.25% Mo, 0.7% Mn, 0.55% C) treated to 55 HRC hardness. The tests were carried out with special electrodes having different mini-features. The tool electrode was fitted with lateral walls ensuring one-dimensional flow of electrolyte. Design of experiments is used to determine the effects of four significant parameters namely the equilibrium gap size, the characteristic feature dimensions (h, b, or d), inlet pressure p(in) and feature position on the tool electrode. Graphs illustrating the most interesting relationships for the chosen ECM parameters are shown below.

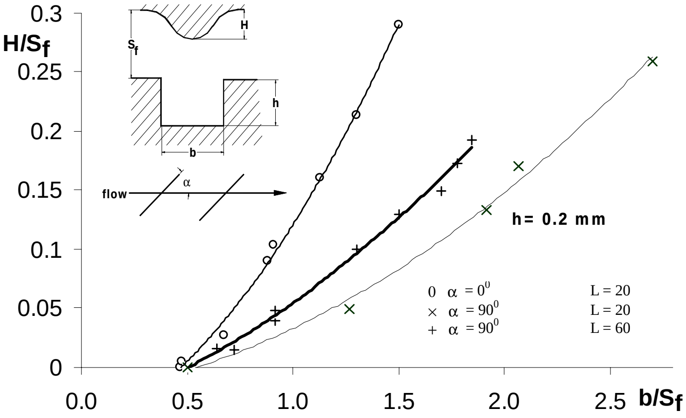


Fig. 3. Detail transfer height vs. relative groove width b/S_f

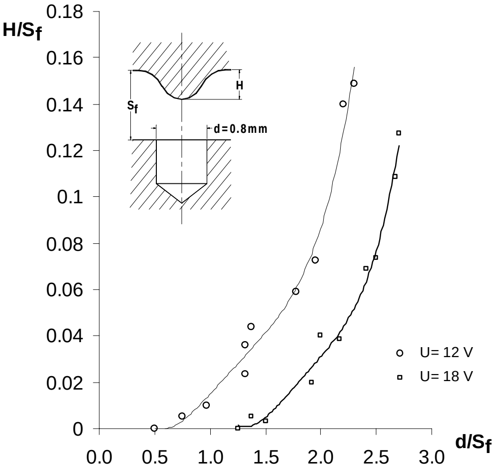


Fig.4. Detail transfer height vs. diameter hole d/S_f

The shape details transfer and its dimensions depend not only on the dimensional features of the tool electrode and equilibrium gap size but also on position details in the gap (distance to inlet of electrolyte *L* and slope of features to flow direction α), working voltage, and hydrodynamic conditions.

The influence of position details on the gap is shown in Figures 3. Two limiting orientation of the grooves with respect to the flow are investigated: flow transverse to the grooves $\alpha = 0^o$ and flow parallel to the grooves $\alpha = 90^o$. Results are shown in Figure 3. The difference in results for various α is related to the distribution of diffusion layer thickness on the anode surface.

The effect of voltage on copying of mini-holes on the tool electrode is shown in Figure 4. Under the same conditions, in particular at S_f = constant, intensity of heating increases occur as a result of increased voltage. This factor causes a limiting effect on the accuracy of copying of smaller features on the tool electrode.

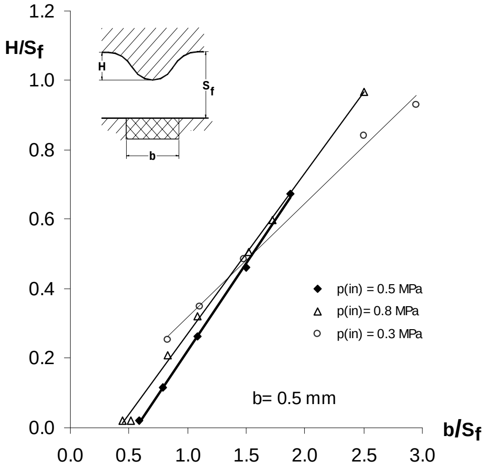


Fig. 5. Detail transfer height vs. insulating relative groove width b/S_f

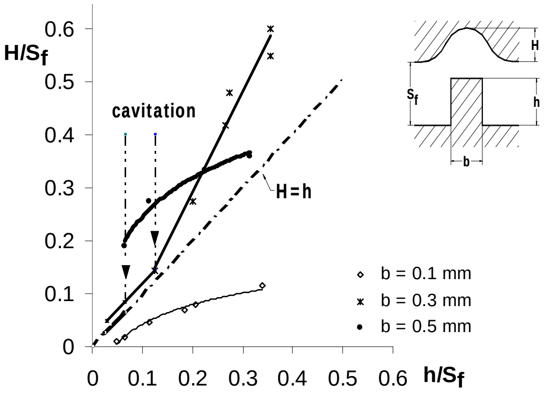


Fig.6. Detail transfer height vs. feature relative height h/S_f

The Figures 5 and 6 illustrates the influence of hydrodynamics on copying process. The effect of inlet pressure of the electrolyte is shown in Figure 5 for copying insulating grooves. Disturbances of copying of rectangular projections by cavitation phenomena can be seen in Figure 6.

The transfer of mini-features of the tool electrode on the anode workpiece are connected with problem of limiting conditions of ECM from the point of view of copying. Of particular importance is geometric limitation in copying, i.e. the limiting dimension below which the transfer of details from tool does not occur. The limiting dimension of the features depends mainly on its shape, the equilibrium gap size and working voltage. In an example for copying holes, on the tool electrode and insulating grooves, the limiting dimensions were following: d_L = (0.7-1.4) S_f in Figure 4 and b_L = (0.4-0.6) S_f in Figure 5.

On the basis of these investigations it can be concluded that ECM process includes “damping” of small disturbances of primary electric fields between the electrodes. If details on the tool electrode produce a change of intensity of the primary electric field at the anode below (0.07- 0.14) U/S_f, the detail transfer will not take place.

Therefore, for improveming shape accuracy and simplification of tool design, the gap size during ECM should be as small as possible. Additionally, reducing non-uniformity in the electrical conductivity and other physical conditions, which are significant for dissolution process, needs more stable gap state. All these requirements for ECM performance at continuous working voltage are very limited. The minimum practical tool gap size, which may be employed, is however constrained by the onset of unwanted electrical discharges. This short circuit reduce the surface quality of the workpiece, and lead to electro-erosive wear of the tool-electrode, and usually hinders machining progress. Intense heating, hydrogen generation and sometimes choking phenomena, and cavitation within the gap can lead to evaporation and subsequent gas evolution. This gas is believed to cause the onset of electrical discharge. All these constraints in continuous ECM can be eliminated, also the requirements with the point of view of machining accuracy can be achieved, by application of pulse voltage in the electrochemical microshaping and smoothing [5]. Additional positive effects can be achieved by introducing special complex controlling movement of the tool electrode. Thus, the continuous ECM can be replaced with a discrete process, resulting in the reduction of gap size below 0.1 [mm] and improving micro-shaping accuracy.

Micro-ECM with Laser. The laser activation of the electrode processes during electrochemical dissolution (ECM) and/or deposition (electroforming) is required for localised enhanced dissolution/deposition of material for improvement accuracy and productivity of micro-areas being machined (deposited). The laser beam in provides an acceleration of electrochemical reactions during non-destructive illumination of metal-workpieces. The results of experimental investigations of laser electrochemical micro machining (LECMM) are described below. The experiments carried out using the experimental set up, which consists of electrochemical shaping and laser assistance systems. CO_2 laser with 20W power and power supply 20V and 50A for ECM is used for LECMM. The workpiece *W* is mounted on a sample holder, which is attached to a controlled table capable of micron precision movement in the X-Y directions. The scheme of experimental set up is shown in Figure 7

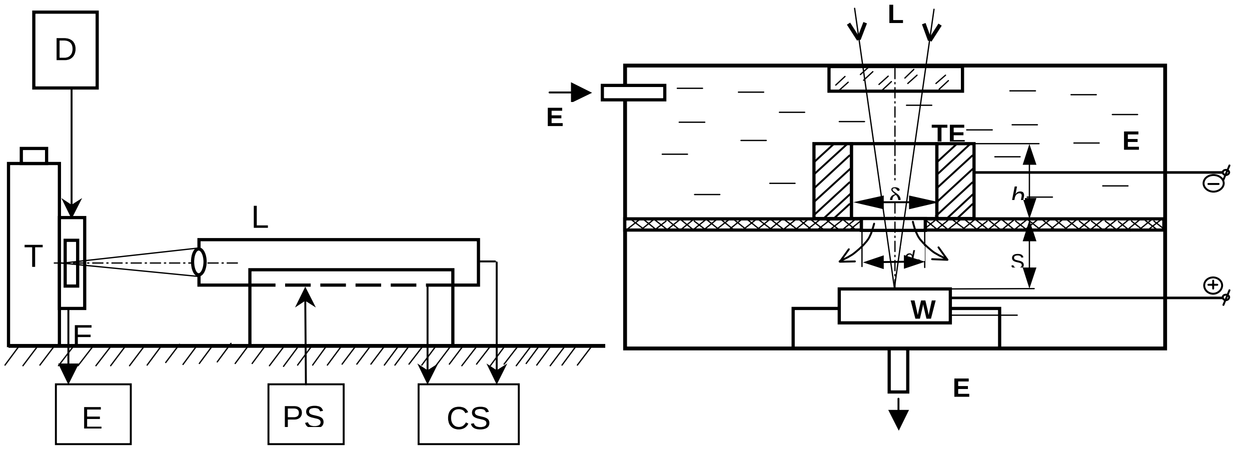


Fig 7. Experimental system for Laser Electrochemical Micro-Machining (LECMM): D-drive, T-workpiece table, E-electrolyte supply, L-laser, PL-power supply, CS-cooling system, W-workpiece, TE-electrode, E-electrolyte

The following settings were used during experiments: distance between cathode and anode – *S* = 5 mm; interelectrode voltage *U* = 0 – 30 V; current density *i* = from 4 A/cm^2 to 40 A/cm^2, flow rate Q = 1.14 l/min and machining time t = 60 -180 s. Experiments were performed on chromium steel using 15 % NH_4NO_3 electrolyte.

Figure 8 shows the results of experiments carried out at *i* = 19 - 20 A/cm^2 In this case it is observed that there is not significant difference between the metal removal rates in ECM and LECMM. However, the profile shapes are different. In LECMM the profile shape has more sharp edges and is more uniform and smoother profile than in ECM.

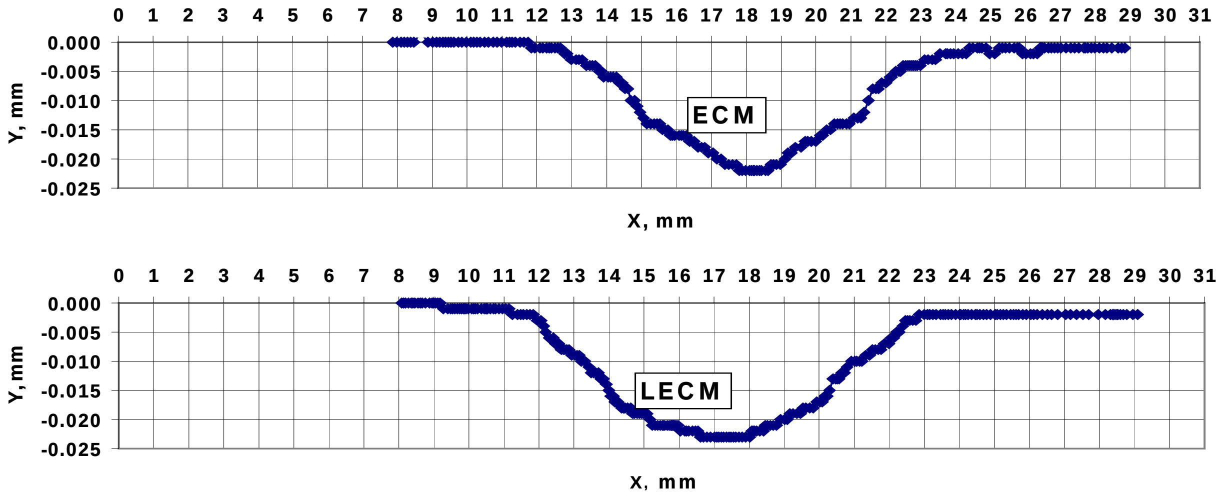


Fig. 8. Profile of machined surfaces after ECM and LECM
Parameters: material: LH15, electrolyte: 15% NH4NO3, i = 19 A/cm^2,
U = 24 V, S = 5 mm, t_m = 120 s, Q_v = 1.14 l/min

Results were significantly different, when electrochemical dissolution is performed at low current density with passivation phenomena occurring in the process. For example, at: i = 4.4 A/cm^2, U = 12 V, L = 2.7 mm, Q_v = 1.14 l/min, t = 90 s. The difference in the profile shapes for ECM and LECMM and increases in process localization are shown in Figure 9.

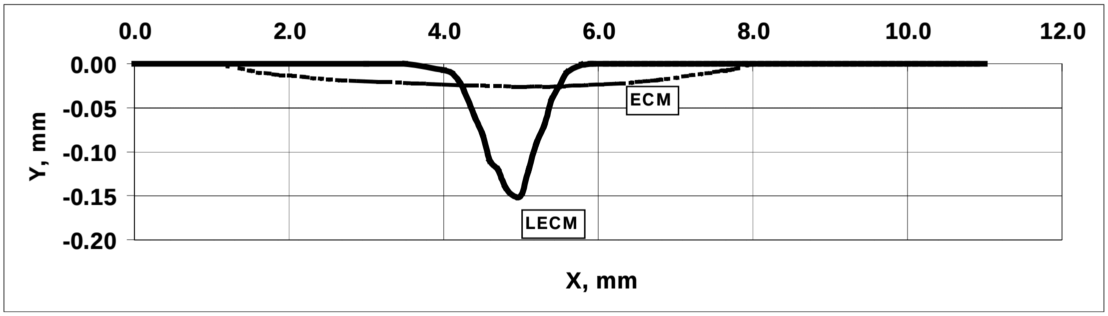


Fig.9.Machined profiles at i = 4.4 A/cm^2. Parameters: material: NC6, electrolyte: 15% NH_4NO_3,
U = 12 V, L = 2.7 mm, t_m = 90 s, Q_V = 1.14 l/min

Conclusions. Study of micro-ECM process demonstrate that an ECM using small gap and pulse current, and a laser assistance of ECM can be effectively used for improving of micro-machining processes by increasing localization of anodic dissolution and increase of metal removal rate.

References

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Key words: electrochemical micro-machining, accuracy, dimensional limitation, pulse current, laser activation