Study of the Process Accuracy of the Electrochemical Micro Machining using Ultra Nanosecond and Short Microsecond Pulses

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Abstract

This paper reports a theoretical and experimental study of the above both various Pulsed Electrochemical Micromachining (PECMM) processes from the point of view of the machining accuracy and of the surface quality. In the paper is shown that the development of new process energy sources and the applications of new mathematical models and computer simulation, which working on accuracies of the procedure into micromachining can be converted. By selected examples the new qualities of the PECMM/µPECMM are represented.

Keywords:

Electrochemical Micromachining (ECMM), accuracy, nanosecond pulses, microsecond pulses

1 INTRODUCTION

The pulsed electro-chemical micromachining (PECMM) is divided into two fundamentally different variants with an outside and an internal source of process energy (PES). The version with the outside PES is characterized by the fact that the work current of the PES at the same time determines the anodic dissolution. Due to the necessarily high flow rates of the electrolyte in the work gap, the working accuracy of the procedure is reduced. The pulsation of working voltage makes it possible to increase the efficient current density, while the critical temperature in the work gap will not be exceeded. [1], [2], [3], [4]

As for the Nanomachining, µPECMM proves to be a very efficient and exact processing, with the reloading of the capacitive Double layers for the dissolution mechanism being used here. This internal capacity also represents the real PES of the µPECM, while the outside PES supplies the carrier current for the reloading. The goal of the research is, which very high working accuracy, to transfer to larger working surfaces of this variant with microstructures. [5], [6], [7], [8]

This article shows the limits of the two PECMM versions, and which technical conditions are to be fulfilled. The primary task for a machining with high working accuracy is the controlling of a very small work gap. For the PECMM a work gap up to 10 µm is intended, while for µPECMM the gaps may be smaller than 1 µm. These results in the first tasks for the manufacturing processes, such as the types of gap flushing, the selection of electrolytes, the measurement and processing of critical gap conditions, like e.g. short-circuits (see **Fig.1**). Crucial for the solution variants are the effectively operating working surface (removal surface), and the enclosing volume range.

The productivity of both process variants is essentially reduced by the fact that for the regeneration phase the gap width is extremely increased. These productivity losses cannot be compensated by changed process parameters. Hence, the applications are directed towards tasks, where a high working accuracy is demanded.

The investigations in the context of the ERANET project REMM showed that, apart from a high resolution of the step size for the gap regulation for both variants, different PES had to be developed.

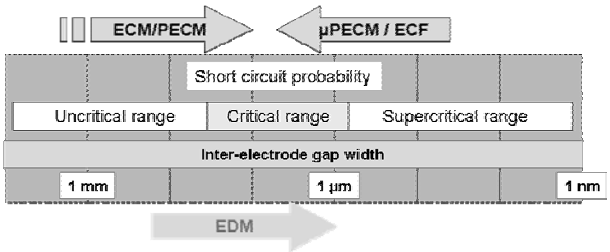

Figure 1: Short circuit probability for PECMM [9]

2 FUNDAMENTAL CHARACTERISTICS OF THE BOTH PECMM VERSIONS

2.1 Pulsed Electrochemical MicroMachining (PECMM)

The main task in PECM processes is to calculate distribution of the material removed on the anode-workpiece surface after a single or pocket pulse. This is determined by the current density distribution in the gap during pulse on-time, in particular in a medium of varying electrical conductivity, with complex processes occurring on the surface of the electrodes and with changes in shape of the machined surface during the course of machining.
Additional tasks are connected with describing the effects of the PECM conditions on the selection of pulse parameters, such as pulse on-time t_p, pulse off-time t_o, and parameters for movements of the tool-electrode. The PECM limitations due to electrolyte boiling have also

been determined particularly critical pulse time t_p^*, causing electrolyte boiling in the gap of the given width S. That corresponds to the determination of the critical S^* width causing boiling for the given t_p pulse time.
In PECMM with application short pulses of microsecond level the main changes in electrolyte properties are result of the heating.

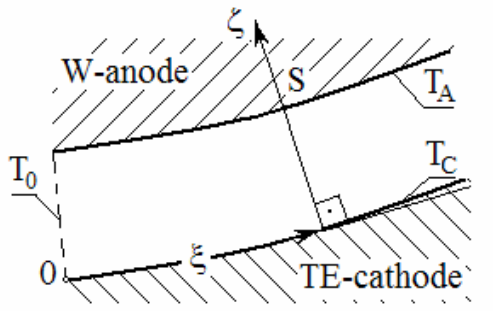

Figure 2: Schematic the system coordinates and boundary conditions

To simplify the calculations let us introduce a curvilinear coordinate system (ξ ,ζ), connected with the tool-electrode in which a coordinate ξ lies on the given electrode and is measured from the inlet of the electrolyte and let axis ζ overlap its normal $\overline{n}_c$ (**Fig.2**).

Generally, the temperature distribution in the gap with respect to Joule's heat generation, convection and heat transfer through the electrode surfaces is described as following:

$$\frac{\partial T}{\partial t}+W(\xi,\zeta,t)\cdot\frac{\partial T}{\partial \xi}=a\frac{\partial^2 T}{\partial \zeta^2}+\frac{i^2}{\kappa_0\cdot\rho_e\cdot C_p\cdot\left[1+\alpha_T\cdot(T-T_0)\right]} \quad (1)$$

$$i=\frac{\kappa_0\cdot(U-E)}{\int_0^S \frac{dy}{1+\alpha_T\cdot(T=T_0)}} \quad (2)$$

where: W is the flow electrolyte velocity, a is the thermal diffusivity, α_T is thermal coefficient of conductivity and ρ_e ,C_p are density and heat capacity of electrolyte, respectively.
The boundary conditions are as follows: at the inlet: $T(\xi=0) = To$, on the electrodes: $T(\xi, 0) = T_A$, $T(\xi, S) = T_C$, where: T_A and T_C are temperatures of the anode and cathode, respectively.
If the time interval between the pulses $t_o = t_{pp} - t_p$ is long enough to ensure a complete renewal of the electrolyte in the gap, it is reasonable to assume that the analysis of the process for a single pulse is valid over a series of pulses.

The heat transfer is described by partial, nonlinear differential equation; therefore, a solution can be obtained by using numerical methods.
The typical current i and temperature $\theta = T-T_0$, characteristics obtained from computer simulation is presented in **Fig.3**.
The change of the critical gap size with pulse on – time for given voltage U=12 V at different shape of voltage pulse, illustrates **Fig. 4**.
In order to improve shaping accuracy and simplify tool design, the down-slope of curves describing average material removal rate $V_a = f(S)$ should be as steep as possible so that the material removal rate will decrease sharply for any increase in the gap and a high degree of anodic dissolution localization can be attained. Typical curve $V_a = f(S)$ is shown in **Fig.5**. Calculations were carried out at assumption that avoid increment of Temperature is equal θ =70 K. The tool-electrode averaged feed rate V_f, in quasi – steady state is $V_f=V_a t_p/t_{pp}$.

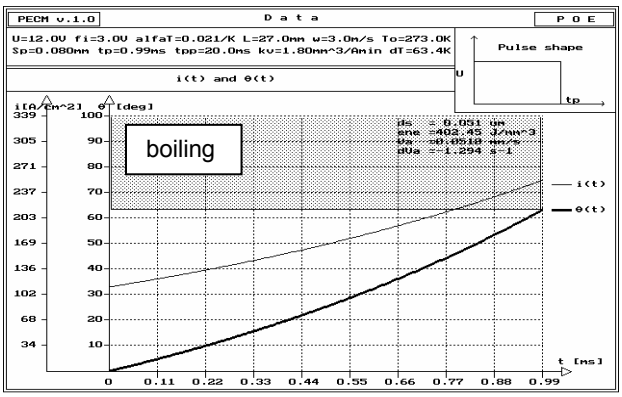

Figure 3: The current and the electrolyte temperature changes for rectangular voltage pulse

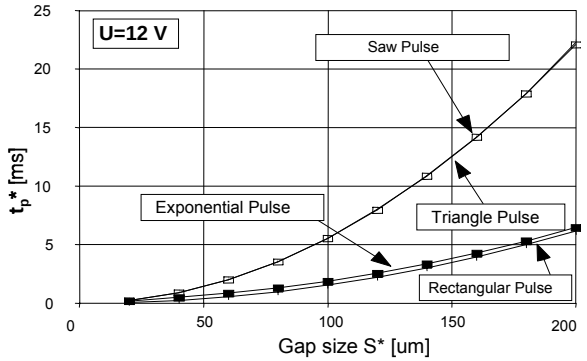

Figure 4: Critical pulse on time, t_p^*, vs. gap size, S^* at different shape of voltage pulse

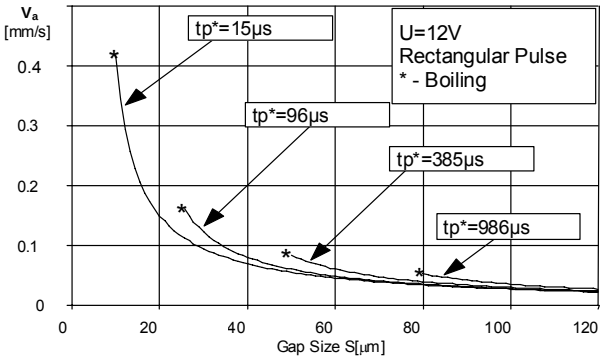

Figure 5: The effect of the initial gap size, S, on the average MRR, V_a during a single rectangular pulse of voltage with different pulse on-times, t_p

It has be been proven that the slope of this function encountered in PECM is indeed steeper than that in the ECM with continuous current [10].

2.2 Micro-Pulsed Electrochemical MicroMachining (µPECMM)

The applications of µPECMM are developed for very small working surfaces, small gaps (< 1 µm), and small dissolution volumes [5]. The removal principle is based on the reloading of the Double layers (interface between electrodes and electrolyte). Contrary to the PECMM contributes not the entire carrier current to the dissolution, but only a small Faraday current, which cannot be measured. Only by a sufficiently good simulation of voltage conditions this Faraday current can be measured.

The very high working accuracy of the µPECMM is obtained by the fact that the anodic dissolution only starts from a boundary voltage that is defined by the gap distance. Thus, the necessary pulse duration is given over

the time constant, too. For the machining of small structures are only ultra short voltage pulses (pico- and nanosecond range) with current magnitudes smaller than 1 A are therefore meaningful.

As regards modern working tasks in the medical technology, there is a big interest in reproducing this high working accuracy on larger working surfaces, allowing the strongly reduced productivity to be increased again. In **Fig. 6** is shown how the current and voltage curves change, if the µPECMM must use higher carrier current magnitudes. For this, the boundary conditions of the feeder and the contacts are crucial, as well as the changed gap parameters.

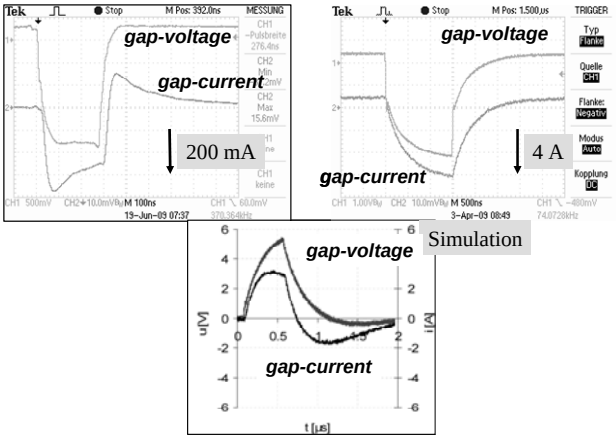

Figure 6: Measured and simulated gap current and gap voltage for different machining surfaces.

The transient current curves severely deviate from the ideal processes (**Fig. 6, 200 mA**), while the process instabilities increase. A second influence factor, the electrolyte parameters, strongly increases in its sensitivity, so that additional current parameters and/or potential values must be regulated.

The gas bubbles which may be created during the process because of heating and/or chemical processes are of special significance. Apparently, the bubbles are an additional flushing, if the work surface is very small and the voltage pulses are ultra short (lower nanosecond range). Due to the enlargement of the effective work surface and longer pulse durations, there is no regeneration of the work gap any longer.

3 SELECTION OF SPECIAL APPLICATIONS FOR BOTH VERSIONS

3.1 Methods of the investigation

Essentially, the methods of the accuracy analysis in these ranges can be accomplished only by means of optical measurement systems. The topologies were primarily analyzed with the Scanning Electron Microscope (SEM XL 30 ESEM-FEG), and the Microscope PMG3. Comparable structures could also be produced with the EDEX of SEM XL 30 ESEM-FEG.

For the analysis of the current-voltage characteristics a test machine was developed with adjustable electrode gaps to 25 nm. The individual potentials are measured in reference to a PtH2 reference electrode (Gaskatel). A Potentiostat (xxx) was used for selected investigations.

3.2 Matrix machining with PECMM

Taking into account advantages of PECM such as good surface quality and high material removal rate PECMM is good alternative for machining. In comparison to electrochemical machining with nanosecond pulses (t_i < 100 ns) PECMM gives possibility to machining bigger areas and its advantages may be applied to micro molds and matrices shaping with size 200 – 1000 µm and other.(**Fig. 7**). From technological point of view, to achieve such PECMM application efficient following issues needs to be solved:

- determine limits of PECM accuracy (dissolution process localization) with pulses > 500 ns,
- find out the efficient way of solving the problems with electrolyte flushing.
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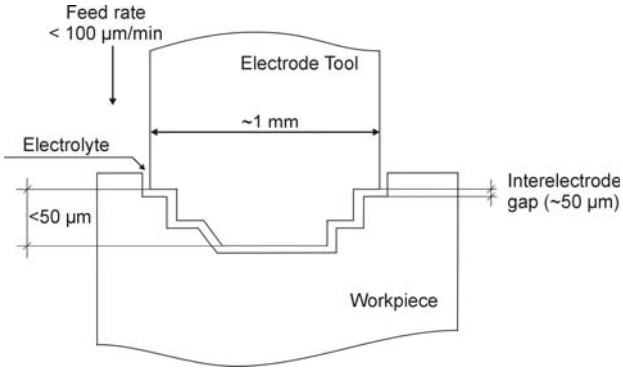


Figure 7: Scheme of PECMM application to matrix machining.

3.3 Hole and channel sinking with µPECMM

As regards the µPECMM version, structures were selected that had already been published in [5] and/or [9]. Two problems had to be solved. In the first part, the new pulse units were tested as to whether they can reproduce the well-known results. The primary goal is to attain this high working accuracy.

Primary, it can be attained this high working accuracy. In the second part, larger working surfaces were selected, with which this high working accuracy was kept by means of µPECMM. In the second part, larger working surfaces were selected, where this high working accuracy could be kept by means of µPECMM. The investigations focused on the machining of nickel samples and selected steel types, using gold-coated tool electrodes for that.

4 RESULTS OF THE INVESTIGATIONS

4.1 PECMM

The research on PECMM has been carried in the IAMT Krakow, and the goal of the investigation was to find PECMM localization characteristics what is connected directly with machining accuracy The localization of the electrochemical dissolution process can be determined based on the relation between machining velocity and inter-electrode gap thickness V(S), which can be described by following function:

$$V = \text{const.} / S^n \qquad (2)$$

where, n – localization factor (n = 1 for ideal process).

In order to determine localization of dissolution during PECMM the material (mass or volume) removal rate during one pulse should be evaluated. Because of the fact that material removal rate is proportional to electrical charge ($\Delta V = k_V \cdot q_{imp}$, k_V – *electrochemical machinability)* in case of PECMM the below presented relationship can be used to approximate relation between charge and inter-electrode gap:

$$q = A / S^n \qquad (3)$$

where, A - constant, n – localization factor.

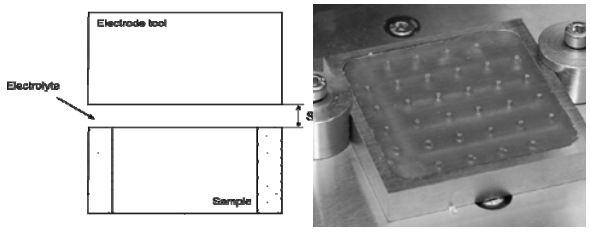


Figure 8: Scheme of the inter-electrode gap during experiment (a) and frame with insulated samples (b).

The q(S) characteristics have been worked out for the following parameters:

- Inter-electrode voltage: U = 6, 9, 12, 15, 18 and 25 V,
- electrolytes: $NaNO_3$ (5, 10 and 15 %) and H_2SO_4 (0.1 M) in temperature: T = 30°C,
- voltage pulse parameters: t_i = 1 μs, t_p = 10 μs,
- machined material: 304 steel, sample diameter d = 1 mm,
- electrode material, copper, tool diameter d = 1.2 mm,

For each voltage level the following inter-electrode gap thickness values have been taken into account: 0.01, 0.02, 0.04, 0.06, 0.08, 0.1, 0.15, and 0.2 mm. To reduce dissolution only to frontal area samples has been pressed into specially designed steel frame, which has been filled in by active resin. Than, the frontal areas of the samples have been expose by grinding operation (**Fig. 8**). During experiment the voltage have been turn on for 50 ms, and the current signal for whole time of machining with resolution 40 ns has been registered by Tektronix TDS7154B oscilloscope. For q(S) characteristic purpose the mean charge from firs 10 pulses has been taken into account.

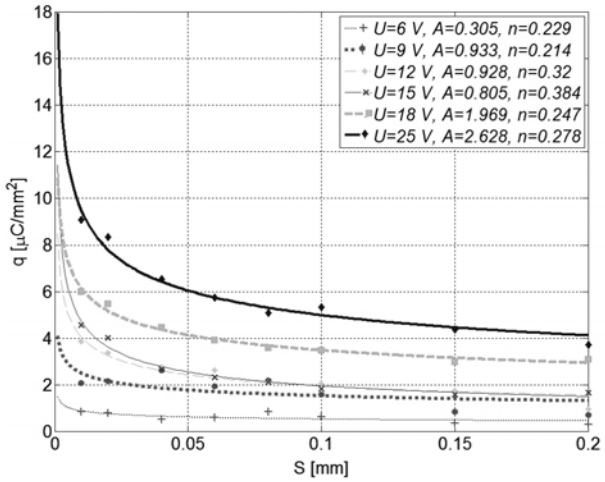


Figure 9: Set of q(S) characteristics for 10% $NaNO_3$ electrolyte, pulse time t_i = 1 μs, pause time t_p = 10 μs

As an example of obtained results the set of characteristics for electrolyte $NaNO_3$ 10% has been presented on the **Fig. 9** and the comparison of the localisation factors n for investigated parameter has been presented on **Fig. 10**. One can state that the best localisation is for inter-electrode voltage U = 15 V.

Detailed analysis of the current signals shows that after a short time of machining the pulse current significantly decrease (about 50% decrease). To make the comparison possible the time $t_{10\%}$ has been defined as the time of machining in which the current decrease $\Delta I = 0.1 * I_{max}$. As was presented on the **Fig. 11** the $t_{10\%}$ depends on inter-electrode gap thickness and inter-electrode voltage and for majority cases is less than 5 ms. Pulse current decrease is connected with contamination and gas bubbles generation in the gap. The photographs of the frontal area of the sample after 50 ms machining time shows that gas bubbles are adjacent to workpiece and theirs size are between 0.05 to 0.2 mm (**Fig. 12**).

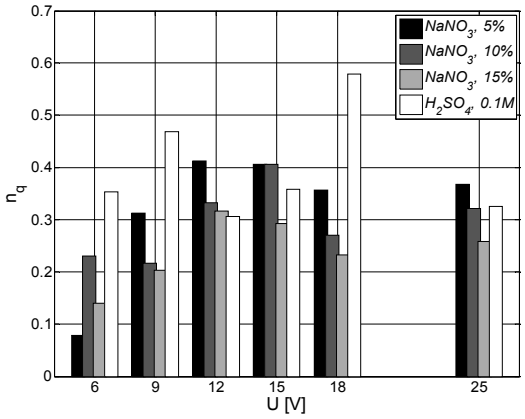


Figure 10: Comparison of localisation factor "n" for investigated electrolytes.

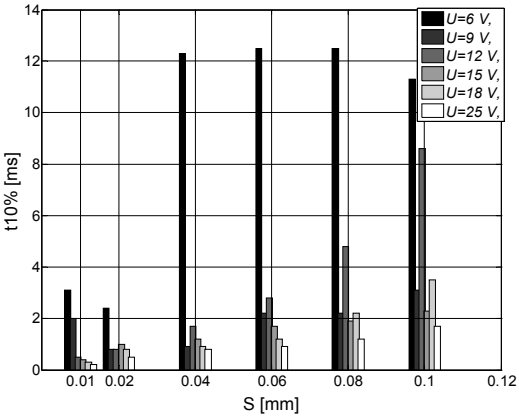


Figure 11: Comparison of $t_{10\%}$ times for different inter-electrode gap and inter-electrode voltage, electrolyte: 10% $NaNO_3$.

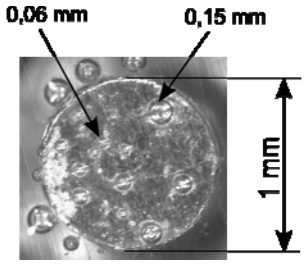


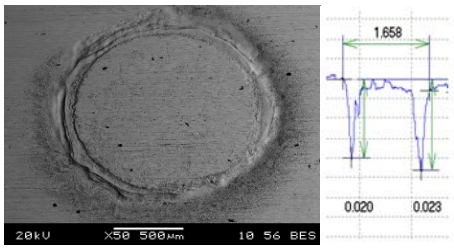
Figure 12: Photograph of the sample frontal area after 50 ms of machining, inter-electrode gap S = 0.02 mm, inter-electrode voltage U = 6 V, electrolyte 10% $NaNO_3$.

As was presented on the **Fig.13 and 14** during 60 s of machining it is possible to remove from about 20 to 60 μm of allowance, but successful application of PECMM to machining microstructures by sinking needs to solve the problem of the electrolyte flushing into the gap. When machining is carried out with rod electrode and electrolyte

is supplying through the nozzle, for gap thickness < 0.06 mm the allowance from circumference is only removed.

Taking into account above presented considerations and analysis of experiments one can stated that the problem with dissolution process localization was generally solved. In further research the obtained localisation factors values needs to be linked with real accuracy of machining. In order to go on with experimental tests the problem of efficient removal from inter-electrode gap: the heat, hydrogen, and other products of electrochemical reactions. As it is showed in **Fig. 12** hydrogen during machining can cover partly workpiece what is the reason of selective surface machining. The obtained during tests values of $t_{10\%}$ can be helpful during setting up the further experiments.

(a)



(b)

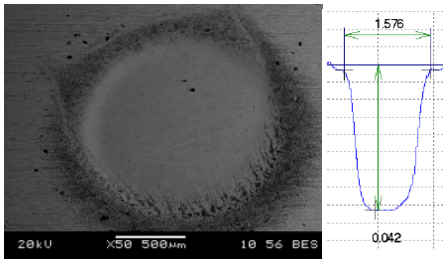


Figure 13: Photograph and profile of machined samples: electrolyte 10% $NaNO_3$, inter-electrode voltage U = 18 V, machining time: 60 s, no electrode motion, (a) S = 0.02 mm, (b) S = 0.08 mm.

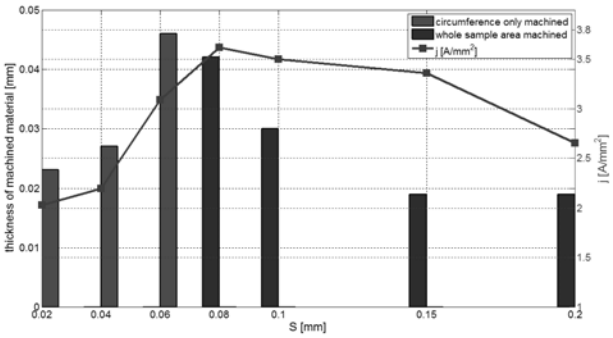


Figure 14: Relationship between the inter-electrode gap and thickness of machined allowance for electrolyte 10% $NaNO_3$, inter-electrode voltage U = 18 V, machining time: 60 s, no electrode motion.

4.2 µPECMM

For µPECMM an example increased tenfold the working surface selected with by arrangement in form of crown. **Fig.15** shows this tool electrode, which were machined up to a depth of 100 µm into a nickel electrode (workpiece). The individual crown parts are not equivalent (**Fig. 15**) and show an uneven surface texture. With such an electrode the initial gaps of the crown parts are not ideally alike, so that during inclination of the workpiece electrode deviations in the crown-machining can occur.

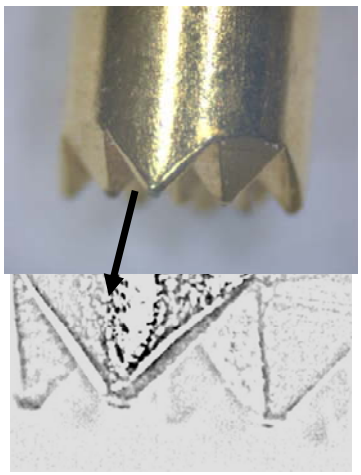


Figure 15: Tool electrode (crown) with 12 individual parts and image of the surface structure

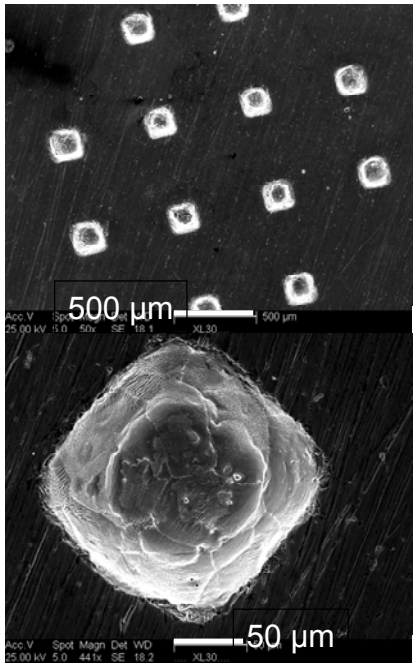


Figure 16: Time-parallel µPECMM of 12 crown parts in the nickel electrode (deep ~ 100 µm)

Fig.16 shows the time-parallel processing of a nickel sample with µPECMM using the new PES with increased carrier current. The result of the machining shows very high precision in the copy (negative) of the tool. The arrangement of these structures (crown parts) is very favourable on the part of the flushing and the gas bubble removal. Large surfaces (not divided) will have the largest problems with flushing and gas bubble removal concerning the productivity and the accuracy µPECMM.

How accurately the surface topology is worked, may be recognized in **Fig.17**. At the ground of a hole-sinking, the structure (<< 1 µm) of the Ni 99.2 is fine etched.
Main problem µPECMM is the formation and prevention of short-circuits of their arrangement in gaps with smaller 1 µm is very high probability. The past solution methods exclude „hard short-circuits "(electrode damage), interrupt the dissolution procedure in addition, in the case of „soft short-circuits ", which are uncritical for process and electrodes [9].

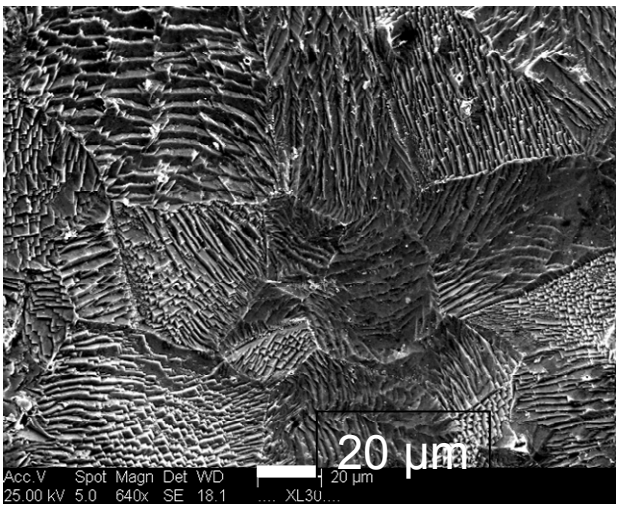


Figure 17: Nickel structure after µPECMM in the ground of a hole sinking.

5 SUMMARY

Both versions of the PECMM show their authorization for the micromachining with high accuracy.

The investigations showed that the PECMM with their high productivity in questions of gap temperature, contamination and minimum gap can be analyzed and optimized in advance.

µPECMM the very high precision can convert on more extensive microstructures by the development of new PES with higher carrier currents.

The restrictions in applications are appropriate in both cases (PECMM/MPECMM) in the solutions of the gap flushing (decontamination) and the gas bubble removal for the working field as well as the selection of electrolytes.

6 ACKNOWLEDGMENTS

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