Research on electrochemical dissolution localization in case of micro machining with ultra short pulses

S. Skoczypiec[1], A. Ruszaj[1], P. Lipiec[1]
[1] Institute of Advancend Manufacturing Technology, Cracow, Poland
*Email：piotr.lipiec@ios.krakow.pl

Abstract
The electrochemical machining (ECMM) one of the most attractive method for micromachining of conductive materials. The industrial application of ECMM is limited by unsatisfactory dissolution localisation (what decrease machining accuracy). In recent years, thanks to nanosecond voltage pulse application, accuracy of electrochemical micro machining was significantly improved up to micrometers range, but the machined surface is also limited to micrometers size. However, in case of microstrucutes machining with area about 1 mm^2 (i.e. tools for micro forming) this method is not effective, and the "classical" microsecond PECM has to be applied. Therefore, to find out limits of PECM accuracy the research on dissolution process localization are necessary. In the paper results of investigation carried out in order to investigate $q(S)=A/S^n$ characteristic for microsecond voltage pulses machining has been presented. The research has been carried out for different interelectrode voltages and electrolytes. Thanks to experimental data there was possible to find out dissolution localisation factors "n" and estimate limits of microsecond voltage pulse machining accuracy.

Keywords:
electrochemical micromachining (ECMM), accuracy, dissolution localization

1. INTRODUCTION

Production of micro - details is a dynamically developing area of production technologies application. In group of methods worked out for machining of technological equipment, MEMS parts and tools for micro-casting and micro-forming special attention is paid for application of unconventional processes such us the laser beam, electrodischarge and electrochemical machining.

The advantages such as no tool wear, good surface layer quality after machining and possibility to obtain small surface roughness makes the electrochemical micromachining (ECMM) one of the most attractive method for manufacturing of micro 3D structures made of conductive materials [1, 3]. In electrochemical machining allowance is removed by anodic dissolution process (atom by atom) in temperature lower than 100 K, which does not introduce any significant changes in surface layer of machined product. Also machining allowance does not depend on material mechanical properties. One of the main problems in ECMM is to achieve high dissolution process localisation, what define limits of machined detail dimensions.

For the purpose of high machining localisation small interelectrode voltage (U = 2 – 10 V) and electrolytes with small concentration (ie. 0.1 M $H2SO_4$, 0.2 M HCl or 1 – 3 % NaNO3) have been applied. However, the biggest development in ECMM has given application of ultrashort voltage pulses (i.e. 2 – 60 ns with period 1 – 2 μs) [2, 3, 5, 8]. Thanks to nanosecond voltage pulse applications, accuracy of ECMM was significantly improved up to micrometers range and area of ECMM application dynamically increase. Because of problems with electric supply design with nanosecond voltage pulses and pulse – current in range of amperes, this method has been satisfactory applied only for machining of small areas (i.e 3D-ECMM).

In case of machining of microstructures on area 1 mm^2 (i.e. tools for micro forming - see Fig. 1) this method is not effective, and the "classical" microsecond PECM has to be applied. As was presented in [4, 8, 9] the localization of machining with microsecond voltage pulses is connected with electrolyte temperature increase during pulse time. The temperature increase determines the amount of dissolved material what is connected with electrolyte conductivity increase in gap.

In the paper results of investigation carried out in order to investigate $q(S)=A/S^n$ characteristic (q – charge density, S – gap, A – constants, n – dissolution localisation factor) for microsecond voltage pulses machining will be presented. The research has been carried on for different interelectrode voltages. Thanks to experimental data there was possible to find out dissolution localisation factor "n" and estimate limits of microsecond voltage pulse machining accuracy.

2. PROBLEM FORMULATION

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. 1). 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.

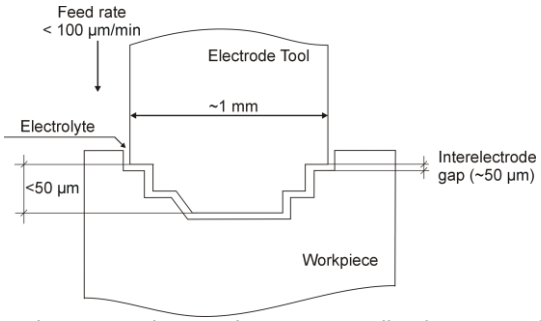

Figure 1: Scheme of PECMM application to matrix machining

Presented in the paper research on PECMM has been carried out in the Institute of Advanced Manufacturing Technology (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:

$$V = const./S^n \quad (1)$$

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 ($\Delta V = \eta k_v \cdot q_{imp,}$ ηk_v – electrochemical machinability) in case of PECMM the below presented relationship can be used to approximate relation between charge and inter-electrode gap:

$$q = A/S^n \quad (2)$$

Where, A - constant, n – localization factor.

3. RESEARCH METHODOLOGY

The test stand for electrochemical micromachining has been built and developed in the Department of Unconventional Production Technologies of the Institute of Advanced Manufacturing Technology. The test stand consists of six main parts:

- the machine body with fixed micro drivers with voltage impulse transmission system and the table for sample fixing,
- microsecond pulse generator,
- drive control system,
- electrolyte delivery system,
- PC computer with appropriate software.

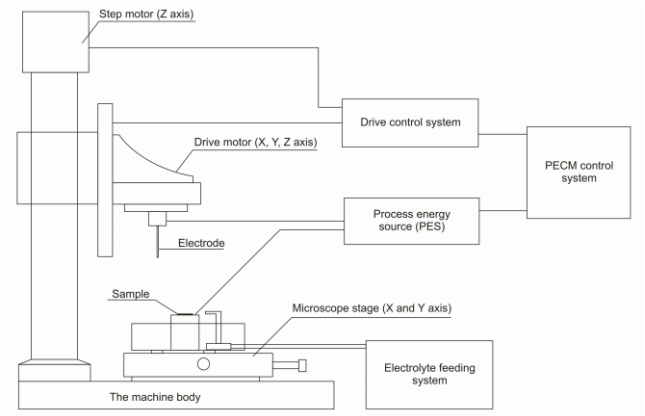

Figure 2: Micro electrochemical machine tool.

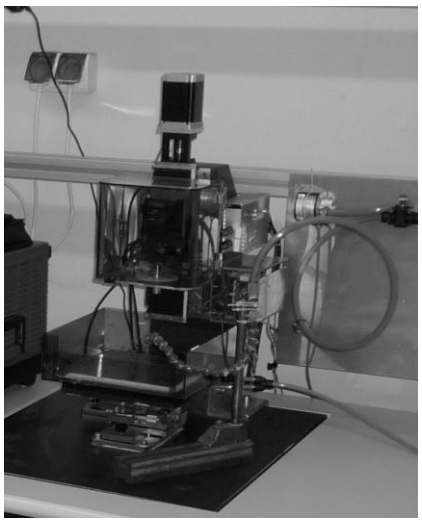

Figure 3: Micro electrochemical test stand

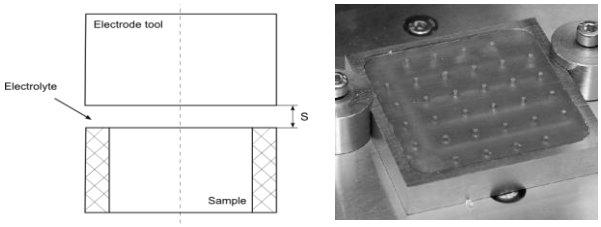

Figure 4: Scheme of the inter-electrode gap during experiment (a) and frame with insulated samples (b).

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 sample 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 4).

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. Based on the power supplier characteristics, the mean charge for first 10 pulses has been calculated based on formula presented in Fig. 5

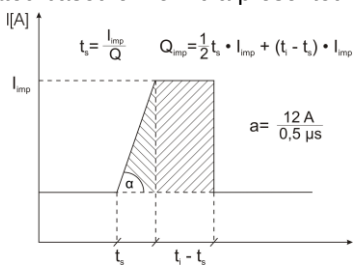

Figure 5: Scheme of the charge calculation method.

Analysis of the pulse current change during machining has shown that after a short time of machining the pulse current significantly decrease (about 50% decrease). To make the comparison for different machining parameters possible the time $t_{10\%}$ has been defined as the time of machining in which the current decrease is described by formula: $\Delta I = 0.1 * I_{max}$ (Fig. 6).

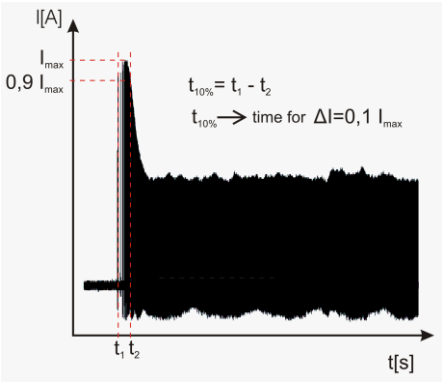

Figure 6: Exemplary current signal registered during 50 ms machining.

4. RESULTS DISCUSSION

As an example of obtained results the set of characteristics for electrolyte $NaNO_3$ 10% has been presented on the Figure 7, but to make the analysis more clear the relations has been presented in logarithm scale for both axis (Fig 8 10). In the Fig. 11. comparison of the localisation factors for investigated parameter has been presented. From this obtained results one can state that:

- the localisation depends on pulse voltage. The smallest n (poor localisation) is for U = 6 and 9 V and the biggest n values are for U = 12, 15 and 18 V (depend on electrolyte).
- small localisation for U = 6 and 8 V can be explained by hydrodynamic phenomena in the gap. Voltage pulse turn on is followed by electrolyte pressure increase in the gap. In the first stage of machining (millisecond range) it can support dissolution products evacuation. Electrolyte pressure wave increases with voltage increase, that improve machining conditions.

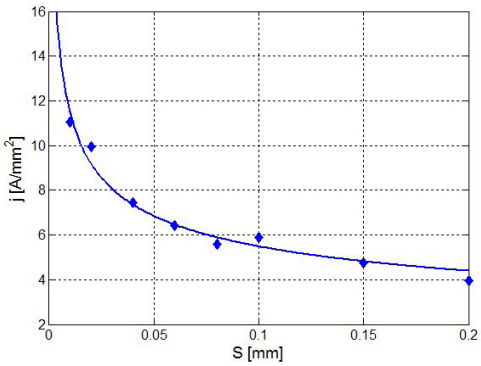

Figure 7: Example of j(S) characteristic for electrolyte $NaNO_3$ 10%.

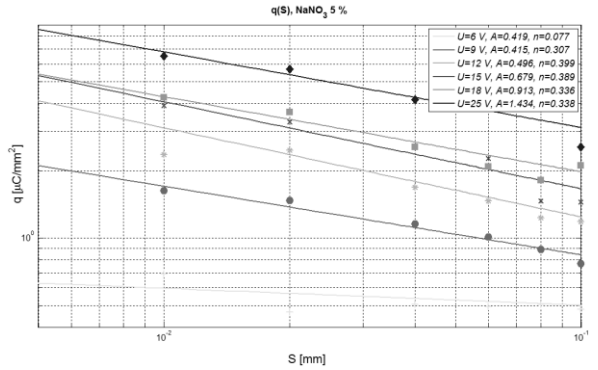

Figure 7: Set of q(S) characteristics for 5% NaNO3 electrolyte, pulse time ti = 1 μs, pause time tp = 10 μs.

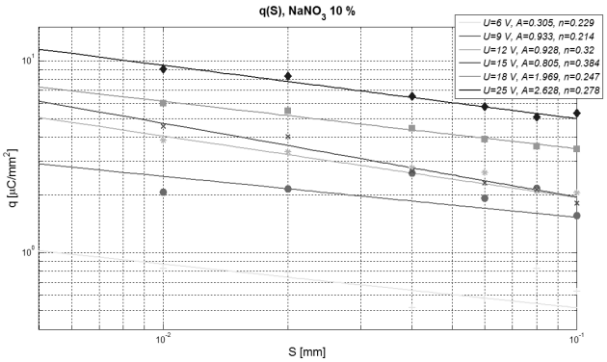

Figure 8: Set of q(S) characteristics for 10% $NaNO_3$ electrolyte, pulse time ti = 1 μs, pause time tp = 10 μs.

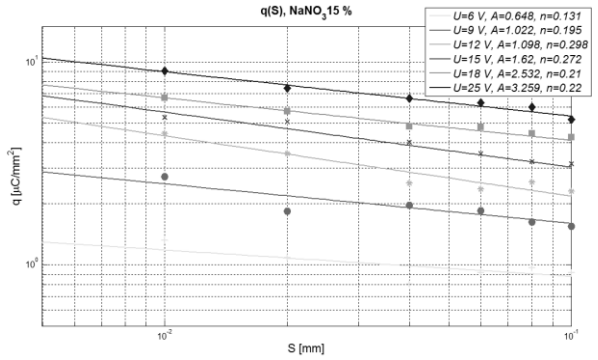

Figure 9: Set of q(S) characteristics for 15% $NaNO_3$ electrolyte, pulse time ti = 1 μs, pause time tp = 10 μs.

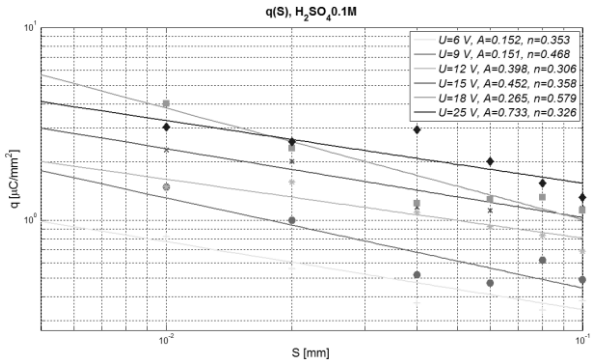

Figure 10: Set of q(S) characteristics for 0.1M $H2SO_4$ electrolyte, pulse time ti = 1 μs, pause time tp = 10 μs.

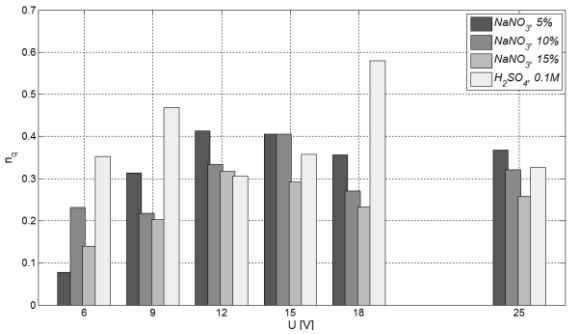

Figure 11: Localization factor "n" for $NaNO_3$ and 0.1M $H2SO_4$

In the **Fig. 12** values of $t_{10\%}$ time for 10% $NaNO_3$ has been presented. One can state that $t_{10\%}$ 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 samples after 50 ms machining time shows that gas bubbles are adjacent to workpiece and theirs size are between 0.05 to 0.35 mm (Fig. 13).

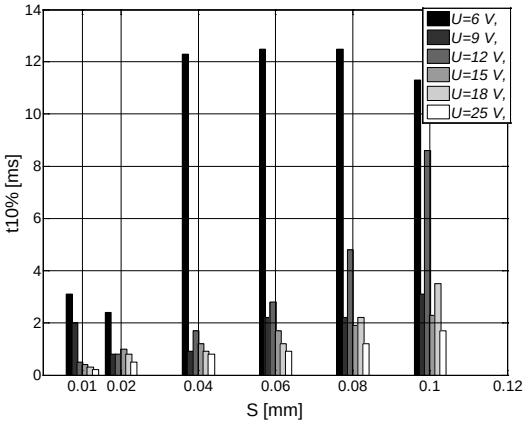

Figure 12: Comparison ot $t_{10\%}$ times for different inter-electrode gap and inter-electrode voltage, electrolyte: 10% $NaNO_3$.

5. SUMMARY

Taking into account above presented considerations and analysis of experiments one can state that presented methodology is effective way of anodic dissolution process localization determination. In further research should concern:

- measuring of the ηk_v as a function of current density j. Based on j(S) (or q(S)) and $\eta k_v(j)$ for differenc voltages and electrolytes it is possible to set up optimal parameters of machining from accuracy point of view,
- research in order to link n factors with real accuracy of machining.

In order to go on with experimental tests the problem of efficient dissolution products removal from the gap should be resolved. In this case the obtained during tests values of $t_{10\%}$ can be helpful during setting up the further experiments.

It is also worth to underline, that q(S) (or j(S)) characteristics can be effectively applied to build up electrochemical machining process simulation software.

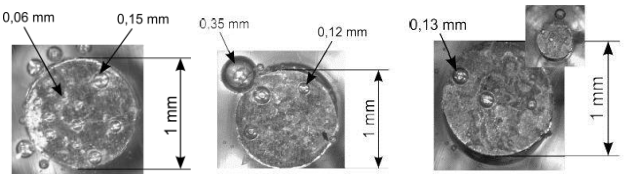

Figure 13: Photograph of the samples frontal area after 50 ms of machining, inter-electrode gap S = 0.02 mm, inter-electrode voltage U = 6 V, 15 V and 25 V, electrolyte 10% $NaNO_3$.

ACKNOWLEDGMENTS

The support of the Polish Ministy of Science and Higher Education is (grant No Era-Net MNT/102/2006) is gratefully acknowledged.

REFERENCES

[1] Rajurkar, K. P., Zhu, D., McGeough, J. A., Kozak, J., De Silva, A. 1999, New Developments in Electro-Chemical Machining, Annals of the CIRP V. 48/2/1999, pp 567-579.

[2] Hyun, K. B., Hyong, R. S., Ki,C. D., Nam, C. C., 2005, Micro electrochemical milling. Journal of Micromechanics and Microengineering, 15(2005) pp 124-129.

[3] Bhattacharyya, B., Munda, J., 2003, Experimental investigation on the influence of electrochemical machining parameters on machining rate and accuracy in micromachining domain, International Journal of Machine Tools and Manufacture, V.44, No.15, pp. 1577-1589.

[4] Kozak, J., 2004, Thermal models of pulse electrochemical machining, Bulletin of the Polish Academy of Sciences Technical Sciences, Vol 52, No. 4, 2004, pp. 313-320.

[5] Kock M., Kirchner V., Schuster R.: Electrochemical micromachining with ultrashort voltage pulses – a versatile method with lithographical precision. Electrochemica Acta 48 (2003), 3213 – 3219.

[6] Kozak J., Gulbinowicz D., Gulbinowicz Z.: Investigations of MICRO electrochemical Machining with ultrashort pulses, Proceedings of the 5th International Conference of the European society for precision engineering and nanotechnology, 8th – 11th May 2005, Montpelier, France.

[7] Burkert, S., Schulze, H.-P., Gmelin, T., Leone, M., 2009, The Pulse Electrochemical Micromachining (PECMM) – Specifications of the Pulse Units, Proceedings of the 12th International ESAFORM Conference on Metal Forming (MS13), April 27-29, 2009, Twente, Nederlands,

[8] Kozak J., Gulbinowicz D., Gulbinowicz Z.: The Mathematical Modelling and Computer Simulation of Pulse Electrochemical Micromachining", Engineering Letters, Volume 16, Issue 4, 2008,

[9] Kozak, J., Rajurkar, K. P., Wei, B. 1994, Modelling and Analysis of Pulse Electrochemical Machining (PECM), Transactions of the ASME- Journal of Engineering for Industry, vol 116/3, pp. 316-323