Simulating the Influence of the Nozzle Diameter on the Shape of Micro Geometries generated with Jet Electrochemical Machining

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Abstract: Jet Electrochemical Machining (Jet-ECM) is an unconventional procedure for micromachining [1, 2, 3]. Based on localized anodic dissolution three-dimensional geometries [4] and microstructured surfaces [5] can be manufactured using Jet-ECM. COMSOL Multiphysics is used at Chemnitz UT to simulate the electric current density in the jet and the dissolution process [6]. Using transient pseudo 3-D models, the dissolution process of Jet-ECM point machining is simulated. A mesh displacement dependent on the normal current density implements Faraday's law in the model to simulate the profile shape.

In this study the influence of the nozzle diameter is investigated. All simulation parameters like electric potential, electric conductivity, specific dissolution volume and current efficiency were taken from own experiments. The results demonstrate that the simulated diameter of Jet-ECM point erosion is a linear function of the nozzle diameter. The function can perspectively be used for interpolation and extrapolation of the Jet-ECM erosion width. The comparison of simulated and measured point erosion profiles demonstrate a good coincidence.

Keywords: Jet Electrochemical Machining, localized anodic dissolution, mesh displacement, closed electrolytic free jet, Electrochemical Micromachining

1 Introduction

Electrochemical Machining with a closed electrolytic free jet is a special procedure to generate complex 3-D microgeometries and microstructured surfaces by help of anodic dissolution. Figure 1 shows as machining example a micro reactor in stainless steel with a length of 218 mm and a depth of 50 µm which was machined within 22 minutes. Remarkable are the sharp edges and scarp flanks within the machining area. The roughness parameters in the cavity are Rz $\approx$ 1 µm and Ra $\approx$ 0,1 µm.

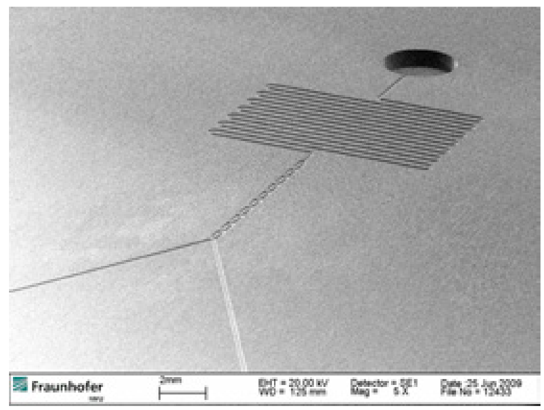

Figure 1: Jet-EC machined micro reactor in stainless steel 1.4301

As second maching example Figure 2 shows a detail of a microstructured surface which was machined with 7000 Jet-ECM point erosions. The generated calottes, which have a processing time of 0,3 seconds, are about 20 µm deep. Especially the high reproducibility is obvious.

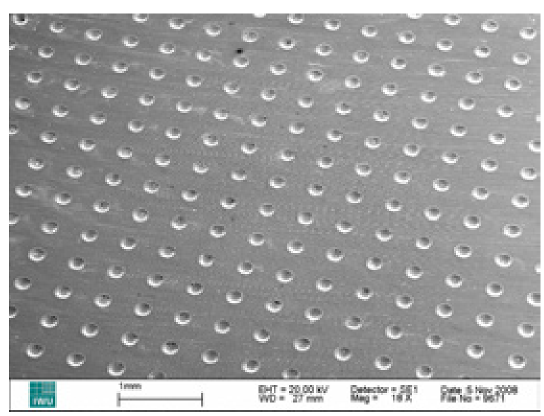

Figure 2: Applying Jet-ECM generated microstructured surface in stainless steel 1.4301

Applying Jet-ECM the work piece shape is fabricated by supplying electrolytic current through an electrolyte jet ejected from a small nozzle. Only the work piece material exposed to the jet is removed because the current is restricted to the area limited by the jet like illustrated in figure 3.

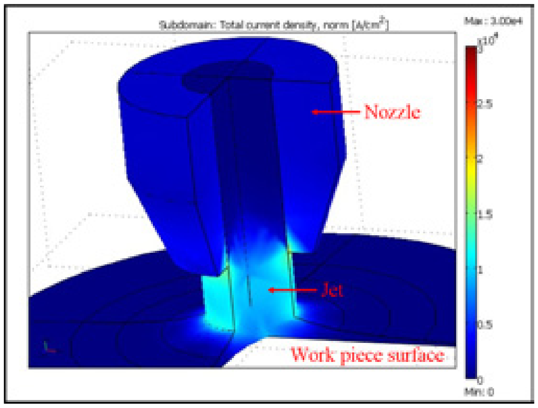

Figure 3: Stationary 3-D model of Jet-ECM current density

Supplying enough fresh electrolyte within the jet continuous direct current with mean current densities up to 1000 A/cm^2 can be applied. Complex three-dimensional micro geometries can be machined by moving the nozzle and controlling the electric current.

In this work a pseudo-three-D model based on COMSOL Multiphysics, developed at Chemnitz UT [6], is used to simulate the influence of the nozzle diameter on the shape of Jet-ECM point erosions.

2 Use of COMSOL Multiphysics

COMSOL Multiphysics is used at Chemnitz UT to simulate several phenomena in micro machining [6, 7, 8, 9]. The time dependent model, which is applied in this study, consists of electrodynamics and mesh displacement conform to Faraday's law. Detailed informations about the model can be found in our former publication [6]. To derive the influence of the nozzle diameter the known model was scaled and all other experimental parameters like voltage, working gap and electric conductivity were taken as the known constant values, which are shown in table 1. Simulations were done for 8 selected nozzle diameters in a range between 25 µm and 300 µm.

Symbol	Name	Value
U	Voltage	56 V
a	Working gap	100 µm
z_A	Conductivity	16 S/m

Table 1: Variables in equation 1 and used values for stainless steel 1.4541

To be able to confirm the simulation results with the shape of real geometries Jet-ECM point erosions were done with available nozzles, which have a diameter d_nozzle of 50 µm, 100 µm, 150 µm and 200 µm. A processing time of 1 s was selected for comparing simulation and experiment. The experiments were performed using a modular Jet-ECM prototype facility, which was developed in cooperation of the Chair Micromanufacturing Technology at Chemnitz UT and the Department of Precision and Micromanufacturing at Fraunhofer-IWU.

3 Anodic Dissolution

The simulated anodic dissolution which takes place on the work piece surface is described as mesh displacement corresponding to Faraday's law with a velocity in normal direction $\vec{v}_\mathrm{n}$ depending to normal current density $\vec{J}_\mathrm{n}$ like shown in equation 1. The variables are shown in table 2.

$$\vec{v}_\mathrm{n} = \eta \cdot \frac{M}{z_\mathrm{A} \cdot \rho \cdot F} \cdot \vec{J}_\mathrm{n} \qquad (1)$$

	Name	Value
η	current efficiency	
M	molar mass	55,06 g/mol
z_A	valency	3,436
ρ	mass density	7,76 g/cm^3
F	Faraday const.	9,65·10^4 C/mol

Table 2: Variables in equation 1 and used values for the simulated and machined stainless steel 1.4541

The current efficiency η for Jet-ECM point processing of the used work piece material stainless steel 1.4541 was found out by help of micro weighing and has a value of about 100 % [6].

4 Results

As main result figure 4 shows the shape of the simulated profiles for 6 equidistant nozzle diameters. As expected the minimum width and depth can be found using the smallest nozzle diameter. It's obvious, that with increasing nozzle diameter the depth and the width of the profiles increases systematically. The aspect ratio changes, too.

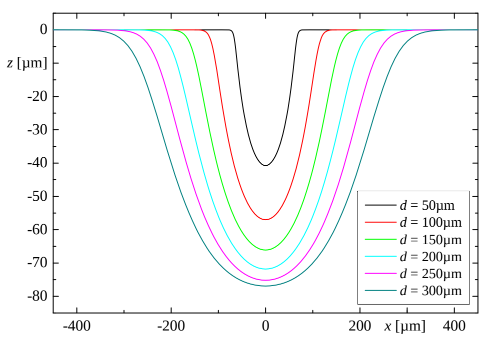

Figure 4: Profiles of Jet-ECM point erosions for different nozzle diameters, $t = 1\,\mathrm{s}$

For a quantitative geometry analysis of the profiles the values depth h and width w were derived. The depth as function of the nozzle diameter is shown in figure 5. It becomes clear that the depth rises systematically from 29 µm to 77 µm and the increase continuously decreases. For a further rise of the diameter an asymptotic expansion has to be expected for this function. The experimental results confirm the simulation especially for the nozzle diameters 50 µm, 100 µm and 150 µm. Only the point erosion with $d_{\mathrm{nozzle}} = 200\,\mathrm{µm}$ is about 10 µm deeper in the simulation.

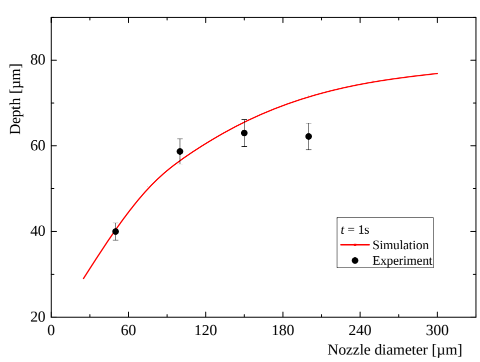

Figure 5: Depth of Jet-ECM point erosion profile as function of the nozzle diameter

The widths of the calculated calotte profiles as function of the nozzle diameter are shown in figure 6. It appears that the widths w continuously increase from 79 µm to 608 µm and the increase is steady. The widths follow very well the marked linear function

$$w_{\mathrm{simulation}} = 1,91 \cdot d_{\mathrm{nozzle}} + 37,6\mathrm{µm}\,. \quad (2)$$

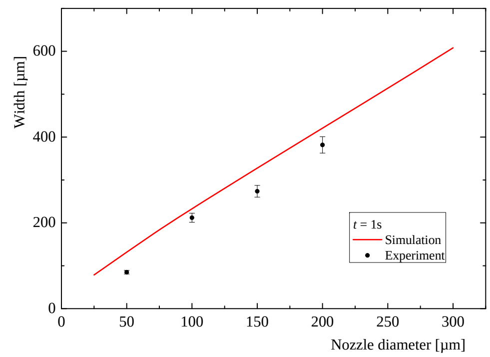

Figure 6: Width of Jet-ECM point erosion profile as function of the nozzle diameter

All simulated widths are systematically larger than the real values. The experimental results confirm the linear behaviour for all nozzle diameters with a function

$$w_{\mathrm{experiment}} = 2,01 \cdot d_{\mathrm{nozzle}} - 13,5\mathrm{µm}\,. \quad (3)$$

Deductive the increase of the two functions has a small mismatch of about 5%, but the absolute term has a divergency of about 50 µm.

5 Conclusions

In this study COMSOL Multiphysics was used to simulate electrochemical point processing with a closed electrolytic free jet. Concrete the influence of the nozzle diameter on the shape of Jet-ECM point erosions could be derived qualitative and quantitative. Experimental results confirm the simulation very well.

In the model only electrodynamics and mesh displacement were used. It seems that due to the very good electrolyte supply in the closed electrolytic free jet and the localization of the current density within it, Jet-ECM can more easily be simulated than other applications of anodic dissolution where the total complex phenomenology of ECM has to be implemented in COMSOL Multiphysics [10, 11].

To increase the quality of the simulation the up to now neglected interaction of the free jet with the erosion shape should be implemented in the model. Therefor the calculated movement of the work piece surface should be projected on the electrolyte geometry by which the localisation of the current density should increase and the dissolution rate is reduced in horizontal direction.

6 Acknowledgment

The authors thanks the German Research Foundation and the Federal Ministry of Economics and Technology for the financial support.

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