Electro Chemical Machining with Oscillating Tool Electrode: Estimation of Maximum Pressure

Thomas Böhlke*, Ralf Förster**

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* Universität Magdeburg, Institut für Mechanik, PSF 4120, D-39016 Magdeburg, Germany
** Universität Freiburg, Institut für Mikrosystemtechnik, Georges-Köhler-Allee 103, D-79110 Freiburg, Germany

Abstract The optimal design of Electro Chemical Machining (ECM) processes is of significant technological importance. In the present work ECM processes with an oscillating tool electrode are considered. It is motivated by the fact that the workpiece electrode may suffer damage or may even fail if the applied load due to hydrodynamic forces is too large. A simple formula is developed for the reaction force acting on the tool electrode. The formula depends on the geometrical, the material and the process parameters. The predictions of the mechanical model are compared with experimental results.

Keywords Electro Chemical Machining, Gap Pressure, Micro Machining, ECM/EDM with Oscillating Tool Electrode

1 INTRODUCTION

A large number of industrial applications, for example sensors and actuators, requires specific microstructures as a main functional feature. Machining processes were functional structures are produced with dimensions smaller than 1 mm are usually called micro machining processes. Most of the currently used manufacturing processes for producing micro system components originate from semiconductor industry and have been used to process silicon based materials. In other branches of industry other materials are used implying that the corresponding manufacturing processes need modification. The ECM process is a very complex process of e.g. dissolution reactions with thermal gradients, the production of gas and the transport of removed material particles inside the gap. In the present paper the only problem under consideration is to understand the hydrodynamical forces arising during the production of microstructures with ECM supported by a vibrating tool electrode.

Electro Chemical Machining is an anodic electro chemical dissolution process of metallic materials in an electrolytic medium (3, 4). The ECM allows for processing metallic materials independently of their specific mechanical properties. The removal rate is relatively high compared to metal cutting manufacturing processing types. In contrast to the Electro Discharge Machining (EDM) process, during ECM the tool electrode wear is extremely low and the subsurface remains almost undamaged. The ECM process is a well established process in many branches of industry. For example in aviation industry it is used to place the cooling air holes in turbine blades. These holes have diameters between $0.5\ \mathrm{mm}$ and $3.0\ \mathrm{mm}$ and have an aspect ratio up to 300:1. Other well known and established applications for ECM are the Electro Chemical (EC) deburring processes, the EC etching processes and a large variety of EC hybrid processes like EC grinding (1, 5, 8). A disadvantage of the aforementioned production processes is the large frontal gap between the tool electrode and the workpiece electrode. The size of the frontal gap of standard ECM types may be up to $0.5\ \mathrm{mm}$. This causes a limitation of the shape accuracy.

For the manufacturing of micro system components the conventional, i.e. continuous feed rate, ECM-sinking process was further developed to the ECM sinking process with oscillating tool electrode (9, 11). The oscillating ECM process enables for manufacturing complex micro structures with a high aspect ratio and an improved shape accuracy. Generally the structures, that can be produced based on this technology, are smaller compared with the conventional ECM sinking process. Another advantage of an ECM process with oscillating tool electrode is the improved flushing conditions. For a wide range of applications ECM allows for machining steel and other metallic construction materials (6, 7, 10). Fig. 1 and 2 show two examples for EC machined microstructures.

The ECM process with oscillating tool electrode works according to the following principle. The tool electrode moves in direction of the workpiece superimposed by oscillations and surrounded by an electrolytic medium. As soon as the tool electrode approaches the workpiece, the electrolyte pressure in the gap increases. Short times before the frontal gap

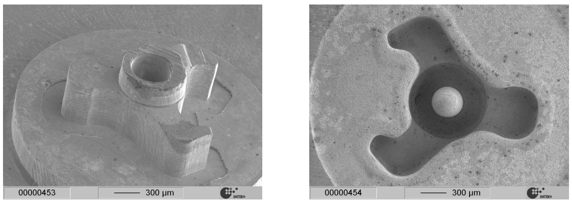

Figure 1: Left: SEM micrograph of tool electrode (material: brass). Right: EC machined work piece (material: hot forming tool steel).

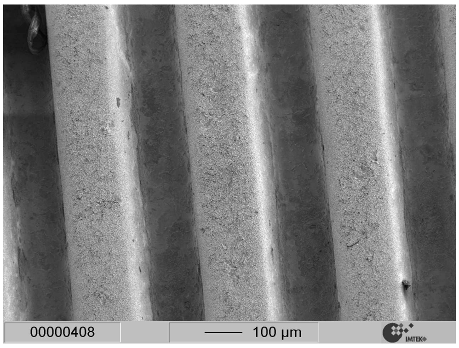

Figure 2: SEM micrograph of a EC machined flow field for fuel cells (material: stainless steel)

reaches its minimum value the voltages switched on and the anodic metal dissolution starts.

This work is motivated by the fact that the tool electrode may suffer damage or may even fail if the applied load is too large (see Fig. 3). During the ECM process the damaged microstructures of the tool electrode is also formed into the workpiece. The functional structures of the tool electrode (micro channels of a flow field) and of the workpiece are smaller than 1 mm, thats why the machining process is called micro machining process. Furthermore, the machine stiffness should correspond to loads occurring during the process which requires reliable theoretical estimates. A simple formula is developed which allows to estimate the reaction force acting on tool electrode and the pressure gradient inside the gap depending on the geometrical, the material and the process parameters. The estimate is derived based on a solution of the Navier-Stokes equations which govern the motion of incompressible and linearly viscous fluids. The outline of the paper is as follows. In Section 2 the experimental setup used for this study is shortly described. In Section 3, a mechanical model for the calculation of the pressure gradient and hydrodynamic forces is presented. In Section 4 the predictions of the mechanical model are compared with experimental data.

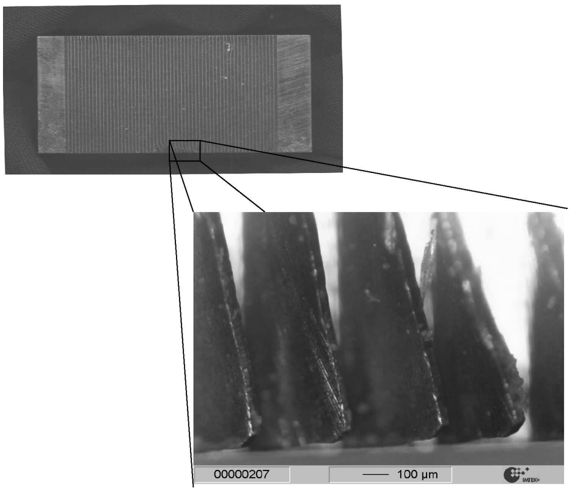

Figure 3: Damaged tool electrode for a flow field (brass).

2 EXPERIMENTAL SETUP

The used electro chemical metal working machine PEM 1360 (Co. PEMtec, Dillingen/Saar, Germany) is designed as a prototype for basic investigations. This machine works with a fixed frequency of 50Hz and an amplitude of 0.2 mm. For the investigations a capacity pressure sensor (Co. GISMA, Bugingen, Germany) was used. This calibrated capacity sensor was embedded in front of a brass tool electrode with a frontal area of $15.975 \text{ mm} \times 15.975 \text{ mm}$. A copper workpiece was spark-eroded with wire EDM giving a square hole of $16.055 \text{ mm} \times 16.055 \text{ mm}$. The workpiece was fixed and sealed with glue on a standard clamping system (Co. EROWA, Büron, Switzerland). This complex system was put into a plastic cylinder. In opposite to the real ECM process for the measurement of the hyrdodynamical forces the cylinder was filled with deionised water. Deionised water must be used because a standard electrolyte, like sodium-nitrate or sodium chloride, can destroy the sensor tool electrode. The sensor tool electrode was put into the square hole of the workpiece and aligned to the hole with a dial gauge. The resulting lateral gap was about $40\ \mu\text{m}$. The pressure inside the gap was measured for three machining depth 5 mm, 10 mm and 15 mm. Fig. 4 shows the experimental setup. The experimentally measured pressure peaks are given in Tab. 2.

3 MECHANICAL MODEL

Basic Equations. In order to derive an approximate solution of the fluid motion in the gap between the workpiece and the electrode tool, it is assumed

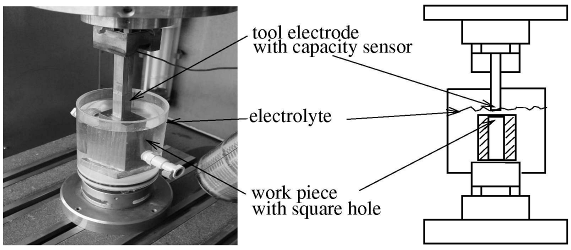

Figure 4: Experimental setup.

that the fluid is linearly viscous and incompressible. The temperature is taken to be constant, such that the mechanical problem can be considered independently from the balance of internal energy. As a result the motion of the fluid is governed by the balances of mass and linear momentum (Navier-Stokes equations) which are given by

$$\frac{\partial v_i}{\partial x_i} = 0 \qquad (1)$$

and

$$\frac{\partial v_i}{\partial t} + \frac{\partial v_i}{\partial x_j} v_j = f_i - \frac{1}{\varrho}\frac{\partial p}{\partial x_i} + \frac{\eta_{\text{eff}}}{\varrho}\frac{\partial^2 v_i}{\partial x_j^2}, \qquad (2)$$

respectively (see, e.g., 2). Note that the summation convention is applied in the case of repeated indices. v_i and x_i denote the components of the velocity vector and the position vector with respect to a fixed orthonormal coordinate system. ϱ is the mass density and p is the hydrostatic pressure. η_{eff} represents the effective dynamic shear viscosity of the fluid. η_{eff} can be decomposed into the dynamic shear viscosity η of the fluid and a turbulent shear viscosity η_{eddy} (eddy viscosity), i.e. $\eta_{\text{eff}} = \eta + \eta_{\text{eddy}}$ (2). η_{eddy} is not a material property of the fluid but depends strongly on the flow type and the position in the flow. A discussion of this rough approximation of η_{eff} is given in Section 4.

Velocity Profile. In the following the flow of the fluid through the gap is considered. The field of gravity forces f_i is neglected. The flow in the four sections of the channel is approximated separately by a flow between two parallel plates which extend to infinity in both directions. For simplicity such a part of the channel is considered where the normal vector of the surface of the electrode coincides with the opposite of the x_1-direction. The coordinate system is specified in Fig. 5.

For the aforementioned problem a solution of the Navier-Stokes equations can be derived, if the veloc-

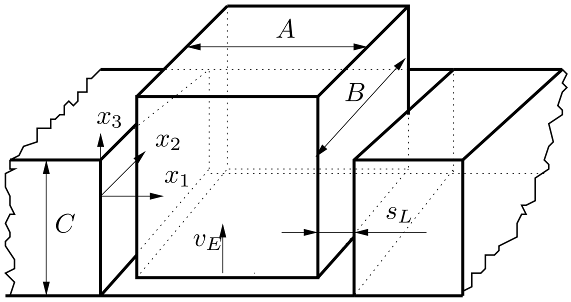

Figure 5: Geometry

ity field is assumed to be given by

$$v_1 = 0, \qquad v_2 = 0, \qquad v_3 = v_3(x_1). \qquad (3)$$

This velocity field satisfies the mass balance given in equation (1). Equation (2) gives for $i = 1$: $p \neq p(x_1)$ and for $i = 2$: $p \neq p(x_2)$. The third component of the equation is

$$0 = -\frac{\partial p}{\partial x_3} + \eta_{\text{eff}}\frac{\partial^2 v_3}{\partial x_1^2}. \qquad (4)$$

Assuming a constant pressure gradient $G = \mathrm{d}p/\,\mathrm{d}x_3$ in the channel one obtains the velocity profile $v_3(x_1)$ by integrating equation (4) twice with respect to x_1

$$v_3(x_1) = -\frac{1}{2}\frac{G}{\eta_{\text{eff}}}x_1^2 - \left(\frac{v_E}{s_L} + \frac{1}{2}\frac{G s_L}{\eta_{\text{eff}}}\right)x_1. \qquad (5)$$

The two unknowns obtained during the integration have been determined by the boundary conditions v_3 $(x_1 = 0) = 0$ and $v_3(x_1 = s_L) = v_E$. v_E is the tool electrode speed and s_L is the lateral gap dimension between the workpiece and the electrode. The gap dimension is assumed to be constant. Note that the specific velocity field considered here excludes cavitation like phenomena.

Pressure Gradient. Until now the profile still depends on the unknown pressure gradient. In order to derive a simple estimate of this pressure gradient it is necessary to neglect the complex flow pattern near the front surface of the electrode and to exploit the constraints given by the mass balance. The pressure gradient G can be determined by balancing the flow rate $\dot{V}$ of the fluid in the channel with the flow rate $\dot{V}_D$ equal to the fluid volume displaced per unit time by the electrode. As a result one obtains

$$G = \frac{6\eta_{\text{eff}} v_E}{s_L^2}\left(\frac{AB}{A + B + 2s_L} - s_L\right). \qquad (6)$$

The details of the derivation are given in Appendix A.

Resulting Force. For the stress and the force acting on the tool electrode one obtains

$$P = \frac{F_3}{AB}, \qquad F_3 = F_3^P + F_3^S \tag{7}$$

where

$$F_3^P = \frac{6\eta_{\text{eff}} v_E}{s_L^2} \left(\frac{AB}{A+B+2s_L} - s_L \right) ABL \tag{8}$$

and

$$F_3^S = \tau M = \left(G s_L - 2\eta_{\text{eff}} \frac{v_E}{s_L} \right) L(A+B). \tag{9}$$

The details of the derivation are given in Appendix B. Inspection of the formula for F_3^P and F_3^S shows that the former contributes to the force F_3 much more than the latter, i.e. $F_3 \approx F_3^P$. Furthermore, if one exploits the fact that s_L is much smaller than A and B, the following simplified equation is found

$$P = \frac{6\eta_{\text{eff}} v_E L}{s_L^2} \frac{AB}{A+B}. \tag{10}$$

Electrode speed. The electrode speed is governed by its harmonic motion

$$x_E(t) = H \sin(\omega t) = \frac{1}{2} H \sin(2\pi f t), \tag{11}$$

where H is the amplitude and f is the frequency. The maximum value of the electrode speed is used in the following to estimate the forces. It is given by

$$v_E = \max(\,\mathrm{d}x_E(t)/\,\mathrm{d}t) = 2\pi f H. \tag{12}$$

Note that the coordinate system shown in Fig. 5 implies that $v_E < 0$ if the electrode moving forward, i.e. penetrating the workpiece, and $v_E > 0$ if the electrode is moving back. Equations (10) shows that F_3 and P obey the same sign convention.

4 RESULTS AND DISCUSSION

The derived formulae (10) depends on the turbulent viscosity η_{eddy}. The approach based on an constant η_{eddy} gives a parabolic velocity profile which should not be expected if the flow is turbulent. More physically based turbulence models have been suggested in the literature (see, e.g., 2). But in the present paper the aim is to estimate the resulting forces and therefore the details of the fluid motion in the gap are neglected.

Beside the simplicity of the applied turbulence model another rigorous simplification has been introduced. The flow in the four sections of the channel is approximated separately by a flow between two parallel plates which extend to infinity in both directions. The pressure gradient G is estimated by balancing the flow rate of the fluid in the channel with volume displaced per unit time by the electrode. Hence, the chosen approach for the computation of the pressure gradient neglects the complex flow behavior near the front surface of the electrode, which is generally nonstationary. Nevertheless, the approximation is based on an exact solution of the Navier-Stokes equations and relates the geometrical parameters and the effective viscosity with the stresses induced by a specific speed of the tool electrode.

Symbol	Value	
A, B	15.975 mm	lateral electrode dimension
L	$5, 10, 15$ mm	machining depth
s_L	0.04 mm	lat. gap dimension
f	50 Hz	frequency
H	0.2 mm	amplitude
η	$1 \cdot 10^{-3}$ Pa s	dynamic viscosity
η_{eddy}	$\approx 24\eta$	eff. eddy viscosity

Table 1: Geometrical parameters, machining conditions, and material parameters

For the estimation of the effective eddy viscosity η_{eddy} two different approaches are used. The first is as follows. Using the geometrical parameters of the experimental setup, the machining conditions, and the viscosity of water at room temperature (see Tab. 1) η_{eddy} can be estimated based on one experimental pressure value. For that the value of 60 bar for a machining depth of 5 mm is chosen. Based on this selection one obtains the following estimate of the effective viscosity

$$\eta_{\text{eddy}} \approx 24\eta. \tag{13}$$

Based on this value the pressure in the tool electrode is computed for the two other machining depths using equation (7) and the approximation (10). The results are given in Tab. 2.

The previous approach is rather empirical but shows that η_{eddy} is really a characteristic parameter of the flow type considered here. In order to make the approach more reasonable, one may look for an estimation based on other experimental data. First it is noted that for a flow between two parallel plates with fixed flow rate a turbulent flow requires higher pressure gradients than a laminar flow. Equation (6) reflects this since the pressure gradient is proportional to η_{eff}. For a pipe flow the (Darcy) friction factor is given by $f = -2D\partial p/\partial x_3/U^2$ where D is the pipe diameter and U is the mean velocity. For a laminar flow $f = 64/\text{Re}$ holds. Here $\text{Re} = \varrho DU/\eta$ is the Reynolds number. For a turbulent flow f can be determined based on the Moody diagram. Details concerning the friction factor can be found in the monograph (2). The mean velocity and the characteristic length of the ECM process considered here are $U = (v_E AB)/(2s_L(A+B)) \approx 6.3\ \text{ms}^{-1}$, $D = 5$–$16\ \text{mm}$. This gives $\text{Re} = 30,000$- 100,000. The corresponding Darcy friction factors for a hydraulically smooth pipe flow are $f \approx 0.02$ and $f \approx 0.016$. Since the ratio of the 'turbulent' and the 'laminar' Darcy factor relates the corresponding pressure gradients, it can also serve as indicator for the ratio of η and η_{eddy}. For the aforementioned Reynolds numbers the ratio of the 'turbulent' and 'laminar' Darcy factors is in the range from 9 to 25. Since the aim is an approximation of the largest possible load for the ECM process, the largest value is taken into account. It can be concluded that the second approach for estimating η_{eddy} yields approximately the same value for η_{eff} as the first one. The fact that the second approach is based on pipe flow data may be justified by the fact that the details of the flow geometry have been already considerably simplified.

Machining depth [mm]	Pressure P exp. [bar]	Pressure P calc. eqn. (7) [bar]	Pressure P calc. eqn. (10) [bar]
5	60	59	59
10	**128**	**119**	**118**
15	**173**	**178**	**177**

Table 2: Comparison of experimental and calculated pressure values

If the effective viscosity η_{eff} has been estimated, equation (10) gives surprisingly accurate predictions for the pressure P. This fact indicates that the suggested model still describes the essential mechanical features of the ECM process with oscillating tool electrode. Note that the equation for the pressure is independent of the electrical conductivity of the fluid. It is only assumed that the fluid is linerly viscous.

5 SUMMARY

In the present paper a simple equation is derived for the estimation of the reaction force due to hydrodynamic forces acting on the tool electrode. The formula for the load depends on the geometrical, the material and the process parameters. It is based on a solution of the Navier-Stokes equations. The resulting pressure P is proportional to the tool electrode speed and to the effective viscosity of the electrolytic medium. Furthermore, the pressure is inversely proportional to the square of the lateral gap dimension. The developed formula is useful for the design and construction of electro chemical metal working machines which are working with oscillating tool electrode. It is possible to estimate the forces for the clamping systems. After an adaptation of the material parameters of the fluid the equation for the maximum pressure can be used for other electrolytic media in ECM and also for EDM die sinking processes with vibrating tool electrode using dielectric media.

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APPENDIX

A - Computation of the Pressure Gradient

Integrating the velocity field over the gap length gives the flow rate $\dot{V}^*$ per unit length in the circumferential direction of the channel

$$\dot{V}^* = \int_0^{s_L} v_3(x_1)\,\mathrm{d}x_1 = -\frac{1}{12}\frac{G s_L^3}{\eta_{\text{eff}}} - \frac{1}{2} v_E s_L. \quad (14)$$

For constant s_L the flow rate $\dot{V}$ can be computed by multiplying $\dot{V}^*$ by an effective circumferential length L_C of the gap. For the geometry considered here L_C is given by

$$L_C = 2(B + s_L) + 2(A + s_L). \quad (15)$$

As a result, the flow rate $\dot{V} = \dot{V}^* L_C$ is

$$\dot{V} = -\left(\frac{1}{6}\frac{G s_L^3}{\eta_{\text{eff}}} + v_E s_L\right)(A + B + 2s_L). \quad (16)$$

$\dot{V}_D$ is obtained by multiplying the cross-sectional area AB with the electrode speed v_E

$$\dot{V}_D = AB v_E. \quad (17)$$

From $\dot{V} = \dot{V}_D$ one derives finally the pressure gradient in the gap between the workpiece and the electrode tool

$$G = \frac{6\eta_{\text{eff}} v_E}{s_L^2}\left(\frac{AB}{A + B + 2s_L} - s_L\right). \quad (18)$$

B - Computation of the Resulting Force

In order to compute the resulting force vector F_i on the electrode, one has to integrate the stresses over its surface. Due to the symmetry of the considered problem $F_1 = 0$ and $F_2 = 0$ hold. Furthermore, on the front surface only the pressure difference

$$\Delta p = GL \quad (19)$$

is relevant, which acts on the cross-sectional area of size AB. As a result, the corresponding force is

$$\begin{aligned} F_3^P &= \Delta p AB \quad (20) \\ &= \frac{6\eta_{\text{eff}} v_E}{s_L^2}\left(\frac{AB}{A + B + 2s_L} - s_L\right) ABL \end{aligned}$$

where L is the machining depth. The outside surface of the electrode is of size

$$M = 2L(A + B). \quad (21)$$

The shear stresses on this surface depend linearly on the effective viscosity

$$\tau(x_1 = s_L) = \eta_{\text{eff}} \frac{\partial u_3}{\partial x_1}(x_1 = s_L) \quad (22)$$

with

$$\frac{\partial u_3}{\partial x_1}(x_1 = s_L) = \frac{1}{2}\frac{G s_L}{\eta_{\text{eff}}} - \frac{v_E}{s_L} \quad (23)$$

As a result, the shear stresses induce the following force

$$F_3^S = \tau M = \left(G s_L - 2\eta_{\text{eff}} \frac{v_E}{s_L}\right) L(A + B). \quad (24)$$