Transient Simulation of the Electrolyte Flow in a Closed Device for Precise Electrochemical Machining

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Abstract: The manufacturing technology electrochemical machining (ECM) finds numerous applications in industrial production. Especially for shaping and surface structuring of metals by controlled anodic dissolution the process is used. The advantages of ECM are mainly the high removal rates, the slight influence on the work piece material structure and the independence of material strength and hardness. Thus ECM is advantage compared to metal cutting manufacturing processes.

Precise electrochemical machining (PEM) is an innovative machining technology which results from further development of the electrochemical sinking. PEM works with pulsed low frequency direct current and oscillation of the tool electrode. It enables the manufacturing of tools and machine elements with high precision requirements and reproduction accuracy. [1, 2] With PEM actually the manufacturing of structure sizes < 1 mm and flatness < 5 µm by front surface machining is possible. As part of the project 'Electrochemical machining of internal precision and micro-geometries with high aspect ratios by process-state-dependent electrolyte management' (ElAs) the aim is to develop a new combination of high pressure flush and a flexible electrode concept. Filigreed electrodes with structure elements smaller than 0.2 mm are targeted for the aimed manufacturing of big aspect ratios. Moreover inner micro structures are obstacle by them self for the needed electrolyte flush in the working cap. Due to this the manufacturing process has to be qualified to a non-flux of electrolyte at the dissolution process. Interaction between conduction and the geometry of the electrodes should be avoided. Therefore a closed process device has to be developed which is able to admit a defined pressure charge. By concerted modifications the oscillation inducted effect of compression should become accessible as input parameter for the process. Experimental research of model geometries regarding to the electrode shape, the inducted compression, the precision, the surface and the current efficiency are content of the project. Multiphysics simulations are applied to characterise the modified process.

For the simulation of the electrolyte flow in the closed device COMSOL Multiphysics™ is used. To get use of the simulation software a suitable model geometry had to be deducted and initial values were defined. The closed device has a cylindrical shape with connections for the electrolyte supply. Thus the device isn't rotationally symmetric. The electrolyte flow results from interaction of the transverse flow and the tool electrode oscillation. One challenge is to develop a model which fits the geometric requirements of the closed device and even the requirements for simulation. The numerical simulations of high turbulent flows are really sophisticated and a lot of computing power is needed [3]. Therefore the simulation was designed in a 2-dimensional environment and the geometric specifications were adjusted accordingly to comply with these claims.

By solving a transient model of turbulent flow the field of velocity in the closed device could be shown. It can be recognized that the field of velocity in the closed device is highly turbulent with many random vortexes. This is due to the interaction of oscillating velocity at the upper edge of the model and the transverse flux in the closed device.

Keywords: ECM, PECM, PEM, Simulation of the Electrolyte Flow, High Turbulent Fluid Flow

1 Introduction

The manufacturing technology electrochemical machining (ECM) is a separating process to produce tools and components or devices with highest demands on precision. The process is based on a localized anodic dissolution of the work piece that is connected to a positive electric potential. A negative or zero potential is connected to the tool which is the cathode. Between these two components a working gap exists which is flushed with an electrically conductive electrolyte. Main advantages of this process are the high removal rates, the slight influence on the work piece material structure and the independence of material strength and hardness.

A further development of the process is precise electrochemical machining (PEM). This technology is characterized through an additional oscillating motion of the cathode. In Figure 1 the process sequence is schematically represented.

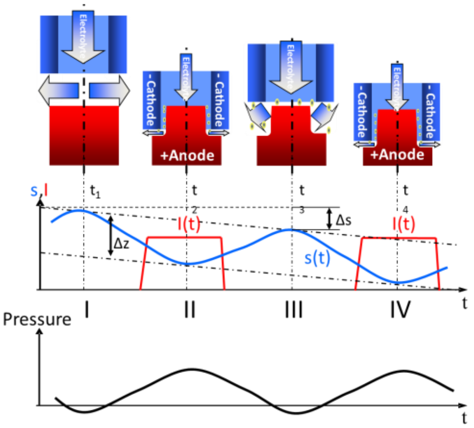

Figure 1. Schematic representation of the process sequence [4]

In a first step tool and workpiece are aligned to each other and the electrolyte flow is started. In the second step the cathode moves towards the workiece (anode) and a short current pulse is initiated at the point of a predefined working gap. After this the cathode moves back, the working gap increases and is flushed with fresh electrolyte. So the removal products are transported out of the process area. With this procedure it is possible to raise the achievable surface quality and the accuracy of the process further.

The PEM technology is advanced within the cooperation project ‘Electrochemical machining of internal precision and micro-geometries with high aspect ratios by process-state-dependent electrolyte management‘ (ElAs) by the Boenig Präzisionswerkzeugbau GmbH, the Technische Universität Chemnitz and the Fraunhofer Institute for Machine Tools and Forming Technology. Within the project a new combination of high pressure flush and a flexible electrode concept is developed. Filigreed electrodes with structure elements smaller than 0.2 mm are targeted for the aimed manufacturing of big aspect ratios.

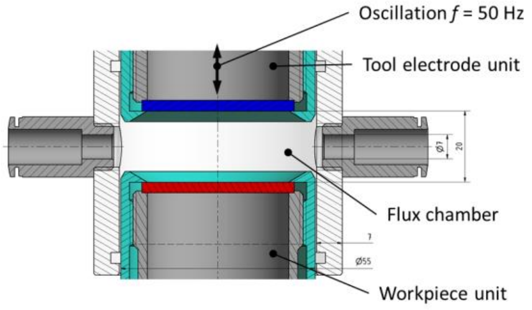

Figure 2. Sectional view of the closed device with flushing chamber

The experiments within the project are performed with a PEMCenter 8000. The closed device which is applied in the PEMCenter shows Figure 2 in a sectional view. The flushing chamber has a cylindrical geometry. The inflow of the electrolyte occurs on the left. The outlet is located on the right side. The workpiece unit located on the lower level is surrounded by the flux/flushing chamber. The electrode unit is arranged in the upper region of the chamber. In the performed investigations the electrolyte flow through the flushing chamber is focused. Therefore a model was developed with COMSOL Multiphysics to analyze the fluid flow in the closed device.

2 Model Description

2.1 Geometry

Based on the dimensions of the flushing chamber the geometry for simulation was derived. The simulation of the electrolyte flow will be investigated as a 2D–model. Because of the laterally positions of the inlet and outlet a 2D–axisymmetric model cannot be used. Therefore the cylindrical geometry of the flushing chamber was transformed. Figure 3 shows this transformation from a cylindrical in a cuboidal geometry.

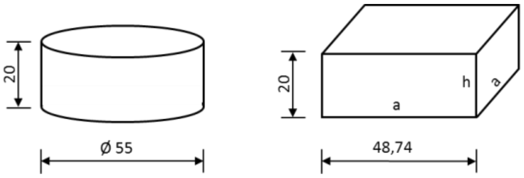

Figure 3. Representation of the geometry transformation

It can be seen, that as a result of the transformation while maintaining the volume the diameter of 55 mm becomes an edge length of 48.74 mm. The heights of both geometries are equal. The resulting geometry for simulation is shown in Figure 4.

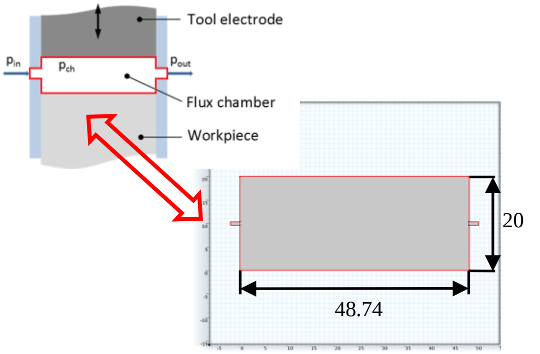

Figure 4. Representation of the flushing chamber geometry implemented in COMSOL Multiphysics^{TM}

For a better visualization the elements of the connections for the supply of electrolyte were modeled, too.

2.2 Meshing

The FEM mesh that was used in the simulation for the calculation of the electrolyte flow was created using the automatic mesh creator of COMSOL. To generate this mesh a user-defined mesh with rectangular elements and the general size setting fine was chosen. Additionally the mesh was manually distributed. Along the 48.47 mm width boundary there are 220 elements with a maximal element width of 0.2 mm and a minimal width of 0.05 mm. In the area of the electrolyte inlet and outlet there are 10 elements distributed in horizontal direction. The resulting mesh consists of 22520 elements and is shown in Figure 5.

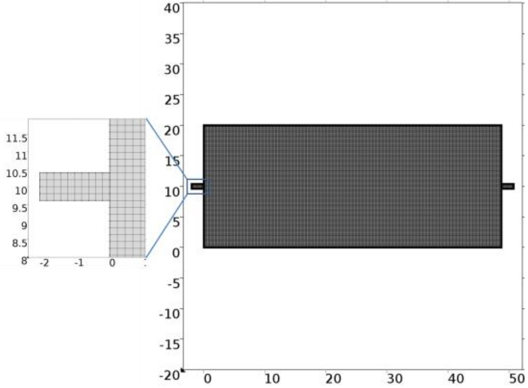

Figure 5. FEM mesh for the calculation of electrolyte flow

The advantage of rectangular elements is that the fluid flow especially in the region near the wall can be better represented.

2.3 Physics

The investigation of the electrolyte flow behavior through the flushing chamber was performed in two steps using the turbulent flow, k-ε interface. In the first part of the simulation a stationary model was solved. Therefore domain and boundary conditions were defined as shown in Figure 6.

As it can be seen, the whole domain of the flushing chamber is assigned to electrolyte. From the material library of COMSOL the electrolyte is defined with the properties of water. The inflow on the left hand side is set to the option mass flow with a mass flow rate in normal direction of 0.5 kg/min. The outflow is defined on the right boundary of the geometry and is set to the option pressure, no viscous stress. The value that is used is the default one of 0 Pa. The remaining boundaries are set to the condition wall with the setting no slip.

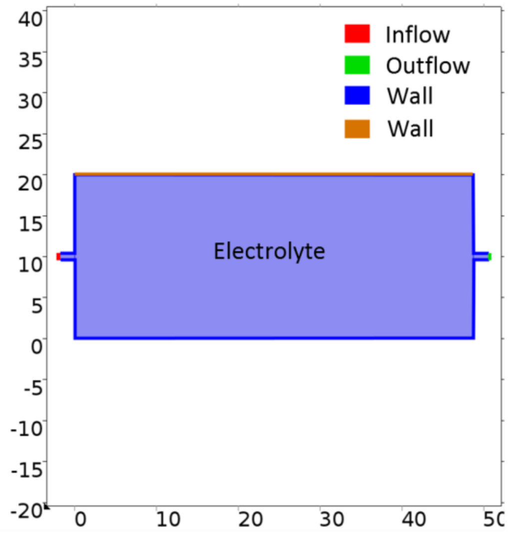

Figure 6. Representation of the domain and boundary conditions - stationary model

A summary of the settings and conditions used for solving the stationary model gives Table 1.

Table 1. Values for the stationary simulation

Condition	**Symbol/Name**	**Value**
Initial Values	u_0 Velocity field	0 m/s
	p_0 Pressure	0 Pa
Inflow	M Mass flow rate	0.5 kg/min
Outflow	p_{out} Pressure	0 Pa
Wall	condition	No Slip

In the second simulation step an oscillation is superimposed the electrolyte flow. Therefor some changes in the domain and boundary conditions are necessary. The initial values are based on the results of the simulation step one. So the velocity field as well as the pressure is used from the stationary model. The option pressure, no viscous stress is used for the boundary condition inflow, which is defined on the left boundary of the model. Within this condition the reference velocity scale is set to 0.217 m/s and the pressure to 1 bar. The outflow is again on the right hand side and has the same setting as in step 1. Figure 7 shows the definitions of domain and boundaries.

In addition the upper boundary of the model now represents the oscillation of the tool electrode. Therefore a time dependent velocity is defined. For this the vibration function of the tool electrode is formed. Equation 1 is the corresponding alternating function.

$$u_{osci} = \omega \bullet z_{osci} \bullet \cos(\omega t + \pi/2) \qquad (1)$$

In the course of this ω is defined as $2\pi f$ with a frequency of 50 Hz. The amplitude of the tool electrode is set to 190 µm.

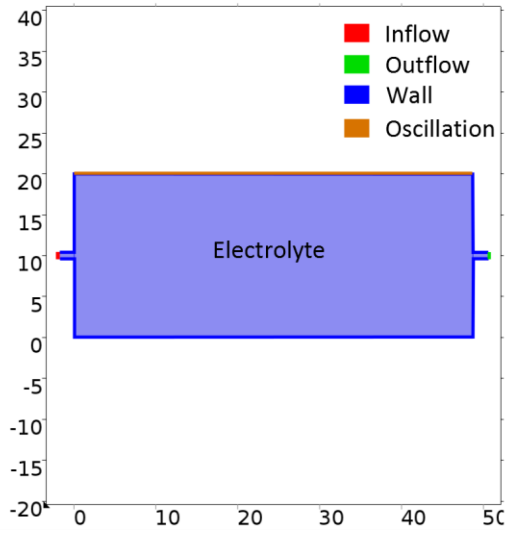

Figure 7. Representation of the domain and boundary conditions - transient model

Figure 8 shows the resulting function. Additionally the time range of the simulation as well as certain timesteps are marked, which will discussed in chapter 3.

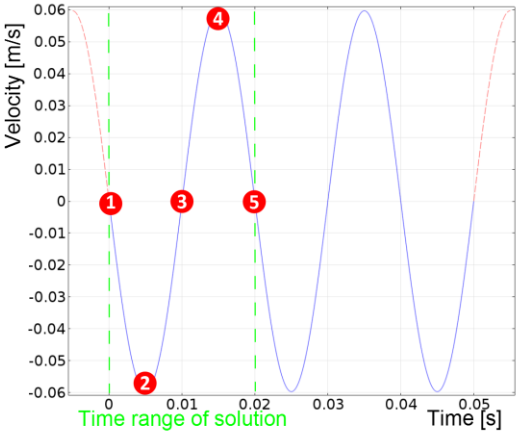

Figure 8. Representation of the oscillation as a function of the velocity over the time

By the definition of the alternating function of speed the oscillation of the tool electrode can be modeled without the use of mesh movement. Subsequently the electrolyte flow depends on the inflow and outflow conditions as well as on the oscillation of the tool electrode.

All remaining boundaries of the electrolyte domain are defined as wall with the setting no slip. In Table 2 a short summary of the defined conditions is given.

Table 2. Used values for the transient simulation

Condition	Symbol/Name	Value
Initial Values	u, v Velocity field	From step 1
	p_0 Pressure	From step 1
Inflow	p_0 Pressure, no viscous stress	1 bar
	u_{ref} Reference velocity scale	0.217 m/s
Outflow	p_{out} Pressure	0 Pa
Oscillation	u_{Osci} Velocity	$\omega \cdot z_{osci} \cdot \cos(\omega t + \pi/2)$
	ω angular frequency	$2\pi f$
	f frequency	50 Hz
	z_{osci} amplitude of the tool electrode	190 µm
Wall	condition	No Slip

3. Results of the Simulation

The stationary and transient models of the process-state-dependent electrolyte management are solved sequentially. The results of the stationary simulation are used for the initial values of the calculation of the turbulent electrolyte flow with superimposed oscillation. A representation of the velocity field for the stationary simulation, which corresponds to point 1 in Figure 8, is given in Figure 9.

The stationary model considers the velocity field between inlet and outlet in the flushing chamber. It can be seen, that the velocity of the fluid decreases after leaving the inlet due to the change in cross section of the flushing chamber. This is similar to a flow generated by a diffuser. In the area in front of the outlet and in the outlet the velocity of the fluid rises because the cross section is narrowed.

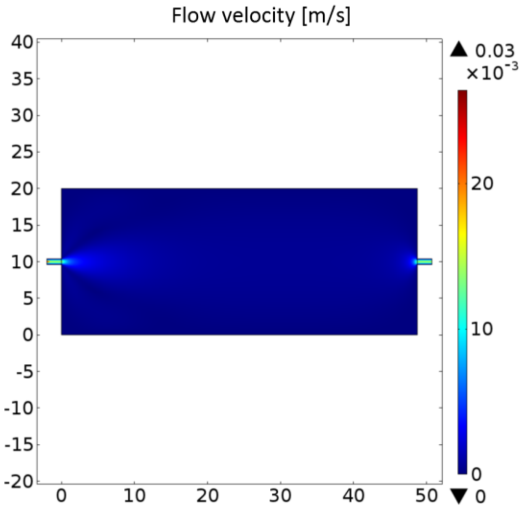

Figure 9. Representation of the velocity field from the stationary model (Timestep 1)

This velocity profile is transferred to the transient model and is used for the initial values. As it is illustrated in Figure 8 the transient turbulent electrolyte flow in the flushing chamber was solved in a time range of 0 s to 0.02 s. These results are presented for four chosen time steps in the following illustrations. These figures show the turbulences in the electrolyte flow. In this case the spread of the different vortexes can be seen.

Figure 10 presents the velocity field of point 2 from Figure 8, which is after a processing time of 0.005 s.

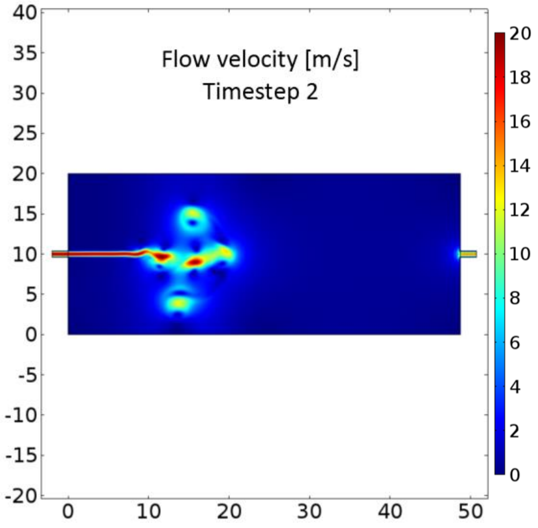

Figure 10. Velocity field of the transient model at t = 0.005 s

It can be seen, that the inflow of electrolyte is quiet straight and the turbulences occur about 10 mm away from the inlet. At this time the maximum fluid velocity is reached in the considered time range and is about 22 m/s in the area of the inlet. Here the tool electrode is fully lifted up and the electrolyte is sucked in the chamber.

Figure 11 shows the fluid behaviour at 0.01 s.

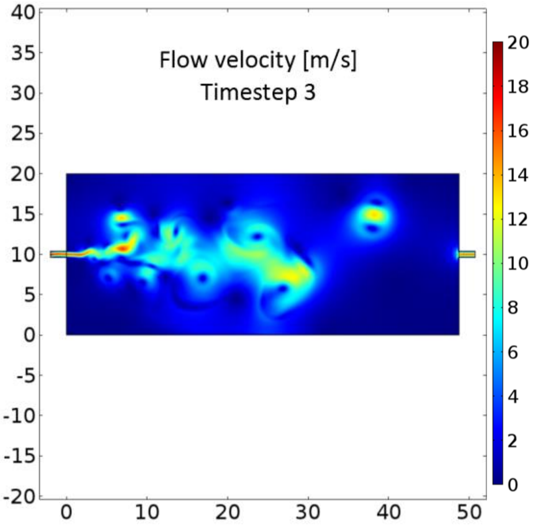

Figure 11. Velocity field of the transient model at t = 0.01 s

At this time the tool electrode has moved towards the workpiece and in consequence of this the formation of vortexes starts already near the inlet. In addition turbulences have extended further into the flushing chamber and the maximum velocities decreases.

Figure 12 and Figure 13 show the velocity fields of timestep 4 and 5 marked in Figure 8. Here it can be seen, that the vortexes have spread in the whole flushing chamber. The distribution of these vortexes is highly stochastically.

Due to the further movement of the tool electrode towards the workpiece the fluid is pressed against the inlet and outlet and the velocities decline.

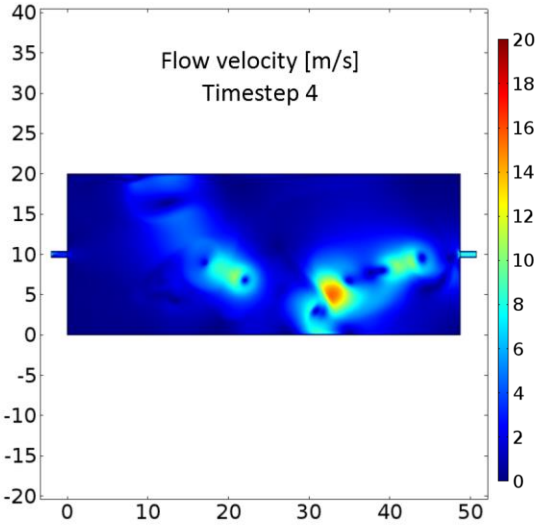

Figure 12. Velocity field of the transient model at t = 0.015 s

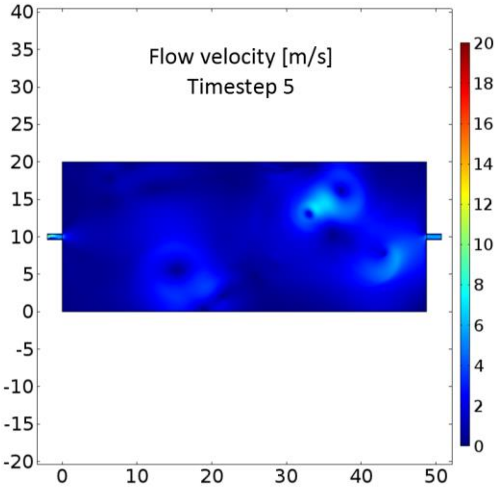

Figure 13. Velocity field of the transient model at t = 0.02 s

5. Conclusion

With the help of simulations it could be shown, that the electrolyte flow in the closed device during the PEM process is very turbulently. With this knowledge, solutions to minimize this turbulence, especially the forming of numerous vortexes can be worked out. For example the integration of a hydraulic accumulator or the reduction of the oscillating frequency should be tested.

6. Summary

In this study a part of a PEM process was investigated, in special the electrolyte flow through a flushing chamber. Therefor a model was created using the turbulence flow, k-ε interface from COMSOL Multiphysics. In a first step the model geometry was derived from the dimensions of a closed PEM device. The second step was the meshing of the model geometry. Here a user defined mesh was built that allows depicting the complex flow mechanisms. After that the definition of the domain and boundary conditions were set. Because of the complexity of the fluid flow the simulation was divided in two parts which were solved sequentially. At first a stationary simulation was performed to get the flow profile within the chamber. This profile was used for the initial values of the transient simulation, which was performed as a second step. In this simulation an oscillation of the tool electrode was superimposed the fluid flow through a speed function. Here the turbulence fluid flow could be simulated in a time range of 0 s until 0.02 s. Within this range the formation of many vortexes could be observed, which are highly stochastically distributed over the flushing chamber. Finally suggestions for minimizing the number of vortexes were derived as a result of the simulations.

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