Numerical Investigation of Electrolyte Flow in a Multi-cathode System for Electrochemical Machining

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Abstract

Manufacturing and finishing of components with complex internal features are significant challenges. Industrial sectors like automotive industry, aeronautics or medical technology require these internal features with highest precision and repeatability. Such components are often machined in temporarily and locally separated manufacturing processes. Due to these separate processes, form deviations and positioning errors increase and lead to more narrow tolerances for each manufacturing process. The technology that is aimed within the project SwitchECM is supposed to enable machining of components with different complex internal features in one single production stage and simultaneously enable highest precision. SwitchECM is a cooperative research project of SITEC Industrietechnologie GmbH, Leukhardt Schaltanlagen Systemtechnik GmbH, IfU Diagnostic Systems GmbH, Porzellanmanufaktur Reichenbach GmbH, Benseler Sachsen GmbH & Co. KG and Chemnitz University of Technology.

Basis of the aimed technology is electrochemical machining (ECM). Within the project a multi-cathode system will be developed, in which every single cathode can be controlled with specific parameters. Essential switching parameters are adjusted according to requirements of the predefined features.

The electrolyte flow is a major variable for the process design and the prediction of the machining results. For example, the dissipation of removed material and process gases are necessary for process stability and manufacturing quality with highest precision. By simulating the variation of the volume flow at the inlet of the multi-cathode system, it is possible to analyze the fluid velocity, to detect areas with adverse fluid circulation and pressure drop as well. Due to the narrow gap and the variation of the volume flow at the inlet, the turbulence module k-ω and 3D modeling were selected. The simulation will show a circulation of the electrolyte in the aimed machining geometries. This circulation can increase the accumulation of ablated products, process gases and therefore can cause machining challenges. The generated knowledge of the fluid flow is a basis for further design of the multi-cathode system and the strategy for the electrolyte management.

Introduction

The electrochemical machining (ECM) process is based on the principle of anodic metal dissolution which is influenced by the chemical composition of the workpiece material and the used electrolyte. The material is dissolved without mechanical contact between the cathode and the workpiece and transported away via the electrolyte flow. [1, 2] Thus, there is no mechanical or thermal impact to the workpiece.

Since in ECM, the electrolyte flow is an essential process parameter, it is important to design and set up a suitable flushing strategy, in order to continuously supply fresh electrolyte to the machining zone and thus realize constant machining conditions during the ECM process. In the present study, the flushing of a multi-cathode system is investigated to show the fluid flow and the pressure drop at different volume flow rates. This is done to make sure that the supply of electrolyte is maintained in the machining area during the machining process. In order to reduce costs and time consuming iterative steps, simulations are used to assist in designing the cathode and the electrolyte supply flushing.

Concept of multi-cathode system

The designed multi-cathode system enables the usage of two separately controllable cathodes for parallel machining and iterative machining of two machining zones in one device. The multi-cathode system is designed for deburring or shaping applications of multiple bores with different shapes or with varying burrs in one machining step without the need for changing cathodes.

The workpiece geometry is based on a cylindrical tube shape with different internal features. Based on the predefined geometry, a multi-cathode system along with a specific machining equipment was designed. The geometrical shape of the electrolyte is derived from CAD data of the workpiece and the multi-cathode system.

Geometry

During ECM the gap between the cathode and the anode is filled with electrolyte. In this simulation the fluid domain is derived from this gap. Due to the complex geometrical 3D shape and the symmetrical design, the 3D geometry of the fluid domain was split apart in a 3D half shelf. The fluid domain from both sides, inside and outside can be seen in **Figure 1**.
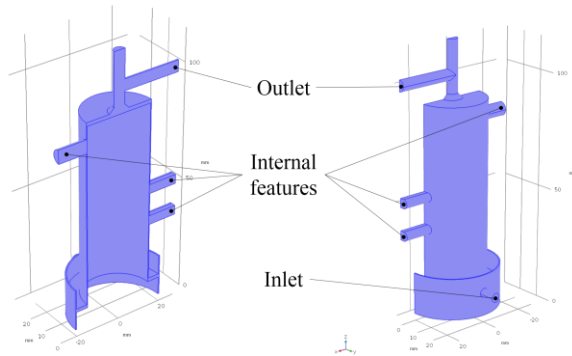

Figure 1. Design of the 3D fluid domain, split at the plane of symmetry in a 3D half shelf

It can be seen that the geometry of the surrounding gap is very narrow and is interrupted in form of three internal features. These internal features represent the machining areas of the multi-cathode system. A detailed view of the area of the internal features is shown in **Figure 2**.
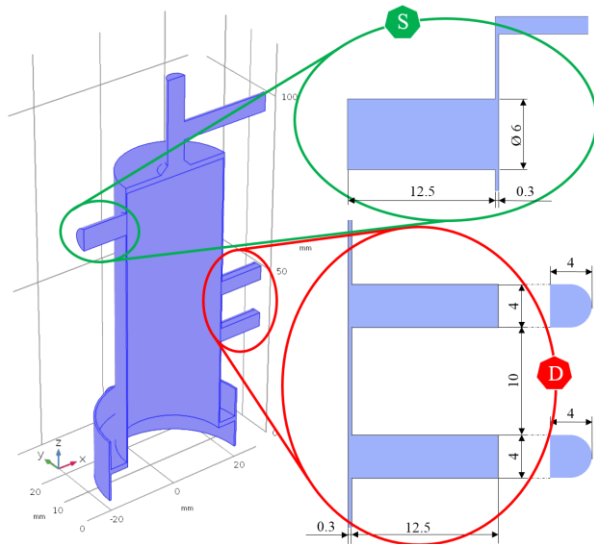

Figure 2. Detailed view of the gap for electrolyte supply, the two internal features (D) and the single internal feature (S)

In the detailed view, the dimensions of the internal features and the gap can be found. (S) is a cylindrical feature where the edge of the workpiece at the transition from the internal feature and the gap gets electrochemically shaped until the edge has a radius of 0.2 mm. (D) consists of 2 internal features in the shape of slotted holes, where the edge of the workpiece gets electrochemically deburred at the transition from the internal feature and the gap. The transition from the gap and the internal features is particular of interest in this simulations.

Mesh

To analyze the fluid flow in the multi-cathode system especially in the narrow surrounding gap, boundary layer meshing is mandatory. A close up of the meshed area of the two internal features (D) is shown in **Figure 3**.
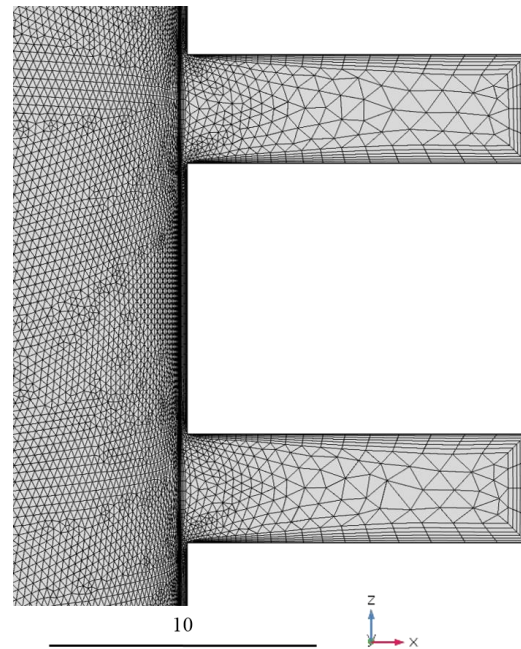

Figure 3. Detailed view of the mesh in the area of the two internal features (D)

Boundary layers are added to every wall of the model to enhance the resolution of the fluid movement in the multi-cathode system. Therefore, each stack of boundary layers starts with an automatic thickness of the first layer at the wall of the fluid domain and stretches out for each next layer by the factor 1.2. The number of boundary layers for each wall is defined to be 6. The total number of mesh elements in the model is 1.936.833 with an average element quality of 0.7. For meshing free tetrahedral mesh elements are used.

Physics and material

To simulate the electrolyte flow in the multi-cathode system the turbulence module k-ω is used and the model is defined to have incompressible flow. The turbulence model type is chosen to be Reynolds averaged Navier Stokes. The reference temperature in these simulations is defined to be 293.15 K. The inlet is defined with a mass flow rate ṁ as follows:

$$\dot{m} = \frac{1}{2} * \dot{V}_{in} * \rho_{H2O}. \qquad (1)$$

Since the entire multi-cathode system is equipped with two inlets, ṁ must be divided by 2. The volume rate, $\dot{V}_{in}$, is variated with flow rates of 125 ml/min, 255 ml/min and 500 ml/min. For calculating ṁ the density ρ_{H2O} of the fluid is defined to be constant with 998.2 kg/m^3. To the outlet, the boundary condition environmental pressure is applied and backflow is suppressed. For the split plane of the geometry the boundary condition of symmetry is chosen. The dynamic viscosity and the thermal expansion used are taken from the COMSOL data base for material properties. The material for the simulations is defined to be water. All simulations have been solved stationary with the PARDISO solver.

Results and discussion

The 3D flow path of the electrolyte is visualized in **Figure 4**. This figure shows the velocity distribution of the electrolyte in the multi-cathode system at a flow rate of 255 ml/min. From the inlet the electrolyte distributes in the perimeter in the gap and rises from the bottom to the top of the device. At the top the electrolyte gets influenced like in a funnel and leaves the device passing through an elbow shaped pipe.

The result of pressure distribution at a flow rate of 255 ml/min is shown as 3D stream lines in **Figure 5**. The pressure is shown as pressure difference. The maximum pressure difference occurs in the area of the inlet and decreases gradually to the outlet. Thereby a maximum pressure difference of 15.8 mbar can be found.

The maximum electrolyte flow velocities and the maximum pressure differences in the multi-cathode system for the investigated flow rates are given in **Table 1**.
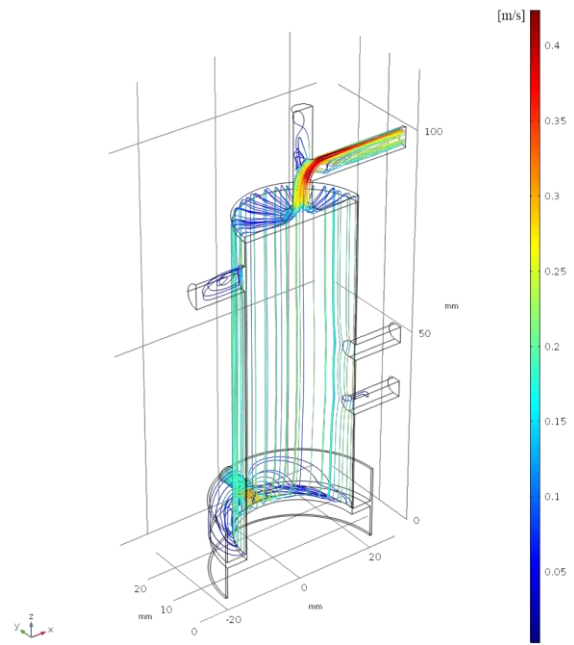

Figure 4. Flow path of the electrolyte in the 3D half shelf electrolyte at 255 ml/min flow rate
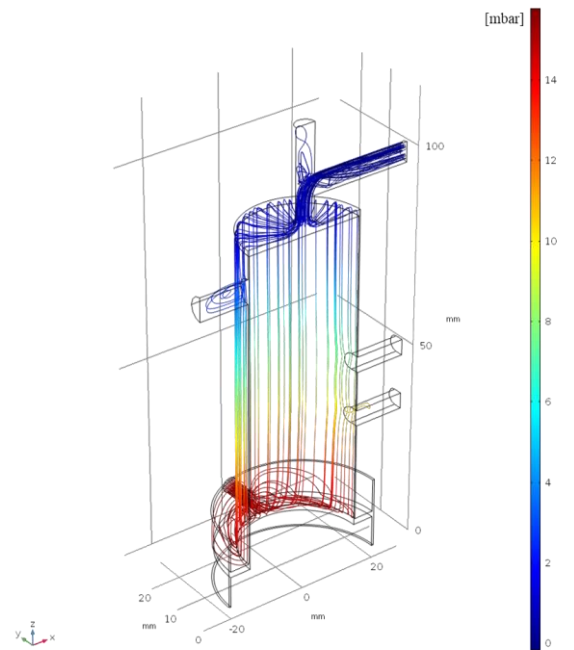

Figure 5. Pressure distribution in the 3D half shelf shown as 3D stream lines electrolyte at 255 ml/min flow rate

Table 1: Maximum flow velocities and maximum pressure differences at given flow rate

Flow rate [ml/min]	125	255	500
Maximum velocity [m/s]	0.21	0.44	0.85
Maximum pressure difference [mbar]	7.3	15.8	34.0

As expected the maximum average velocity increases linear with the flow rate of the electrolyte.

The highest pressure difference appears at the highest flow rate of 500 ml/min, as expected. The lowest pressure difference is found in the area of the outlet, since the outlet is defined to have a pressure difference of 0 mbar to environmental pressure. In none of the conducted simulations a pressure difference below 0 mbar was found. Hence there is no risk of cavitation. [3, 4] Summarizing it can be stated that the three investigated flow rates are suitable for machining.

For a more detailed analysis the velocity field for the fluid flow rate of 255 ml/min is shown in Figure 6.
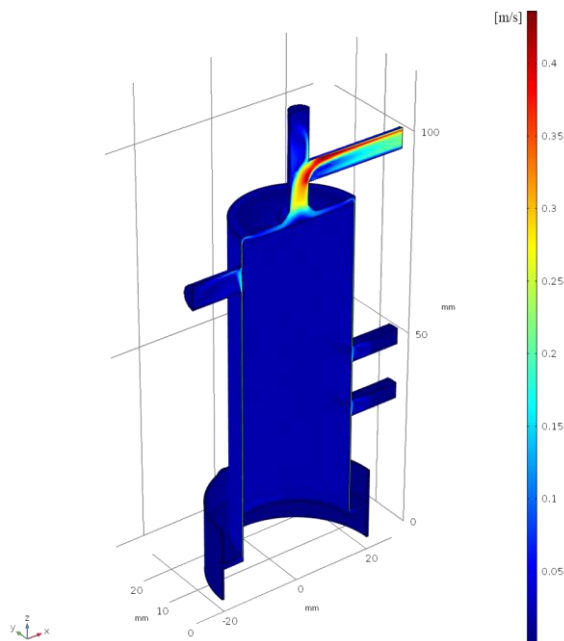

Figure 6. Average velocity field of the electrolyte at 255 ml/min flow rate

It can be seen, that the highest average velocity of the electrolyte occurs in the elbow part of the pipe element in front of the outlet. The maximum average velocity is 0.44 m/s. The areas of the transitions from the gap and the internal features are shown as detailed views in Figure 7 and Figure 8.

The detailed view of the two internal features (D) shows a fluid velocity around 0.25 m/s in the gap between the internal features (D).
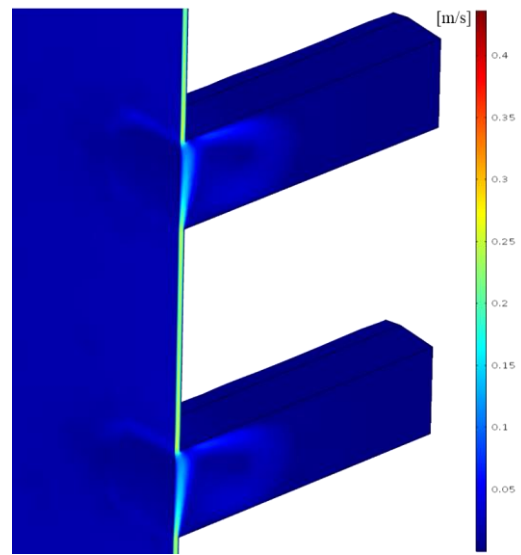

Figure 7. Detailed view of the two internal features (D) and the gap at 255 ml/min flow rate

The fluid velocity decreases directly in the area of the internal features (D) and circulations can be found in the internal features. At the right hand side of the internal features (D) almost no movement of the fluid can be observed. This indicates that ablated materials and process gases could be trapped inside, too.

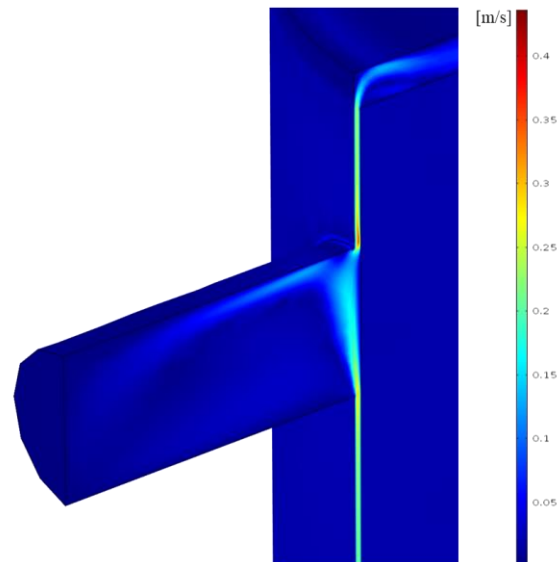The electrolyte flow in the internal feature (S) is shown in detail in Figure 8.

Figure 8. Detailed view of the internal feature (S) and the gap at 255 ml/min flow rate

In the detailed view of the internal feature (S) circulation of electrolyte can be found. The electrolyte streams bottom up in the gap and into the internal feature (S). Due to the change of geometrical shape caused by the internal feature (S), the velocity of the electrolyte is reduced and the electrolyte is dragged into the internal feature. Thereby ablated products and process gases could be trapped inside the internal feature which influences the quality of machining. It also can be found, that the wider opening of the internal feature (S), in comparison to internal features (D), leads to circulations with higher magnitude. The velocity in this detailed view is highest at the transition from the internal feature (S) back to the gap in direction of flow, with a value of 0.35 m/s.

Summary

In this paper the fluid flow in a multi-cathode system was investigated regarding flow velocity and pressure distribution.

By simulating a variation of the volume flow at the inlet of the multi-cathode system, it was possible to analyze the resulting fluid flow in the system.

Results of the simulation show the existence of electrolyte circulation in the three internal features. It can be derived, that removed material and process gases can be trapped and accumulate inside the internal features. Such accumulation will influence the machining process and the machining quality.

By investigating the pressure difference in the multi-cathode system, a maximum electrolyte pressure difference of approximately 34 mbar at a flow rate of 500 ml/min was calculated. It could be shown, that a critical pressure loss and as result a risk of cavitation will not occur in the system.

In further studies the formation of circulation in all three internal features will be investigated more in detail to analyse particularly the influence of the direction of flow and the influence of gravity to removed material and process gases.

Acknowledgement

References

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