Transient Simulation of an Electrochemical Machining Process for Stamping and Extrusion Dies

M. Hackert-Oschätzchen[1], M. Penzel[*1], M. Kreißig[1], M. Kowalick[1], M. Zinecker[1], G. Meichsner[2], A. Schubert[1, 2]

[1]Professorship Micromanufacturing Technology, Technische Universität Chemnitz, 09107 Chemnitz, Germany

[2]Fraunhofer Institute for Machine Tools and Forming Technology, 09126 Chemnitz, Germany

*michael.penzel@mb.tu-chemnitz.de

Abstract: Precise electrochemical machining (PEM) is a non-conventional machining technology, based on anodic dissolution of metallic workpieces. In this study an additional extension of the precise electrochemical machining with a precise angle-controlled cylinder positioning is aimed. Due to the help of the angle-controlled cylinder positioning, with PEM e.g. stamping and extrusion dies can be machined. To investigate the modified process transient simulation models have been developed. The models are based on the modules deformed geometry, electric current and wall distance to compute the resulting ablation.

Keywords: PEM, ECM, transient simulation, non-conventional machining.

1. Introduction

The manufacturing technology electrochemical machining (ECM) is an ablating 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. Ground or zero potential is connected to the tool which is the cathode. Between these two components a working gap exists which is flushed with electrically conductive liquid called electrolyte. The electrolyte closes the circuit between cathode and anode and is responsible for the transport of ions. Main advantages of this process are the high removal rate, 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 represented schematically.

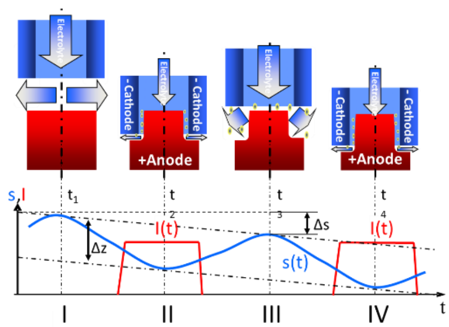

Figure 1. Schematic representation of the process sequence [1]

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 anodic workpiece and a short current pulse is initiated at the point of a predefined working gap. After the short current pulse the cathode moves back, the working gap increases and is flushed with fresh electrolyte. Thus, the removal products are transported out of the process area. Due to this, it is possible to enhance the achievable surface quality and the accuracy of the process significant. In this study an additional extension of the precise electrochemical machining with a precise angle-controlled cylinder positioning is aimed. By the use of the angle-controlled cylinder positioning, in combination with PEM e.g. stamping and extrusion dies can be machined. Figure 2 shows an example for a device for the angle-controlled PEM process and Figure 3 presents the machined workpiece.

To analyse the ablation process with the given cathode geometry several simulation models were developed with COMSOL Multiphysics.

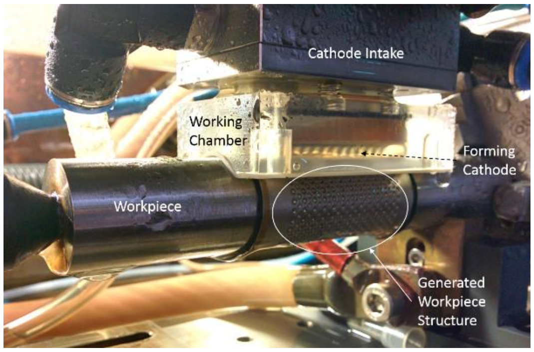

Figure 2. Device for the angle-controlled PEM process generating a calotte structured surface

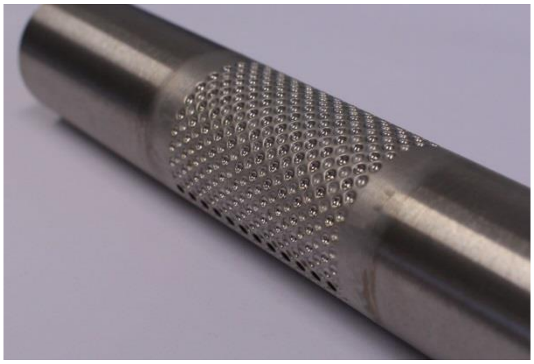

Figure 3. Embossing roll with a calotte structured surface

2. Model Description

2.1 Geometry

The 3D geometry of the experimental setup was transferred to two 2D slice geometries, 2D - axial and 2D – radial, to reduce the simulation effort. Figure 4 shows the 2D model geometry of the radial slice consisting of slide contact, workpiece, electrolyte and cathode. The materials defined to bronze for the slide contact, steal 1.4301 for the workpiece and the cathode and $NaNO_3$ with mass fraction of 8 % for the electrolyte.

The height of the model geometry is 72.05 mm and the diameter of the workpiece is 40 mm. The relevant part of the cathode for the ablation process has a height of 3 mm, a width of 2 mm and is rounded with a radius of 1 mm. The working gap at the beginning of the transient simulation is s_{E_0} = 50 µm.

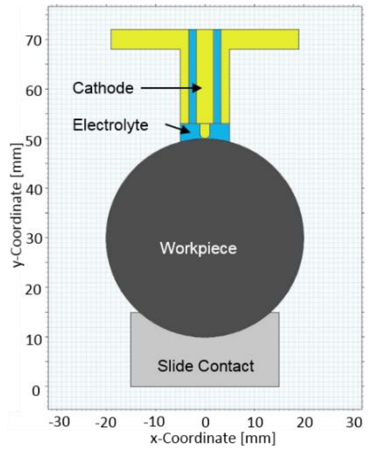

Figure 4. 2D radial model geometry for the ECM process simulation

2.2 Physics

The investigation of the ablation process was performed in two steps. The first step was the stationary simulation of the electro dynamics with the physics module "electric currents". Figure 5 shows the boundary conditions for the stationary simulation.

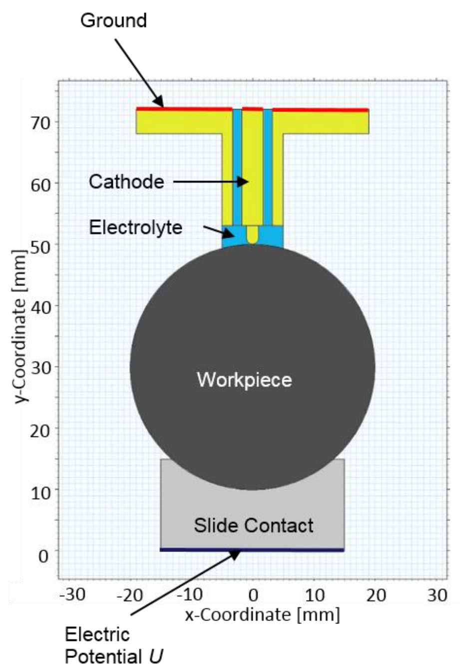

Figure 5. Boundary conditions for the "electric currents" module

The upper boundary of the work tool was defined as "Ground" and the lower boundary of the slide contact is defined with "Electric Potential" $U = 6.2$ V. All outer boundaries are defined as "Electric Insulation".
In the second step a transient simulation of the ablation process was done. For this the modules "electric currents", "wall distance" and "deformed geometry" were used. The electro chemical ablation process is a multi-physical process with highly complex interaction of the different domains. To simplify the simulation these interactions were described with 2 simple models in form of equations. Both functions were determined by complex experiments of the ECM process. They can describe different physical interactions in the ablation process for the given materials. The first function is the electrical conductivity of the electrolyte in dependence of the working gap. The graph of the function is shown in Figure 6.

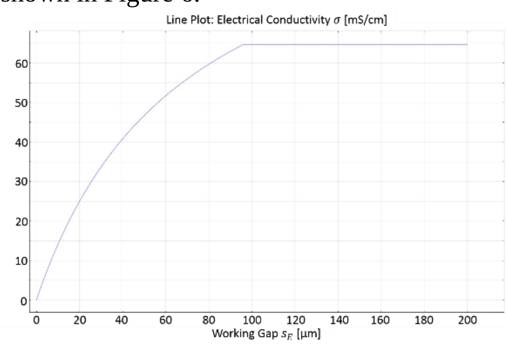

Figure 6. Electrical conductivity σ of the electrolyte as function over the working gap s_E

The function of the electrical conductivity sinks with lower value of working gap. When the working gap is about 95 µm or higher the electrical conductivity has a constant value of 65 mS/cm. It describes process influencing factors like pollution of the electrolyte, gas bubble generation and heating of the electrolyte. To be able to use the function of electrical conductivity the value of the current working gap is needed. To calculate the gap two modules of "wall distance" are used. They compute the distance of each point within the electrolyte domain to the two opposing boundaries of the workpiece and work tool surface.
The second function is the ablation velocity in dependence of the current density. The graph of the function is shown in Figure 7.

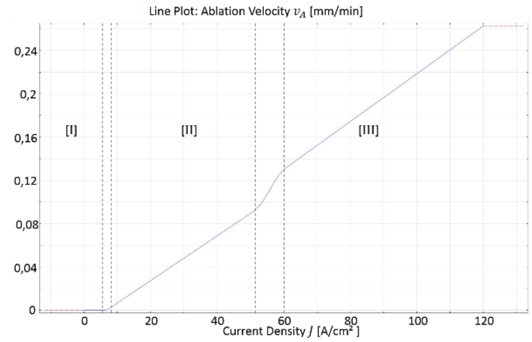

Figure 7. Ablation velocity v_a as function over the current density J

The function of the ablation velocity is parted into three linear functions which are connected by smoothed transition areas. It considers process parameters like cathode oscillation and pulse time.
The cathode feed speed is defined in y-direction with $v_f = 0.046$ mm/min. The ablation velocity is defined as velocity in normal direction on the boundary of the workpiece surface.

2.3 Meshing

The FEM mesh that was used in the simulation of the electro chemical ablation process was created using the program internally mesh creator of COMSOL. The generated mesh can be seen in Figure 8.

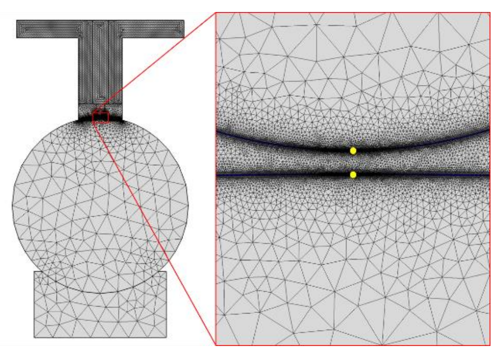

Figure 8. Model geometry meshed with triangular mesh elements

To generate this mesh a user-defined mesh with triangular elements and the general size setting normal was chosen. For the ablation relevant boundaries a maximum element size of 0.01 mm was defined. The points with the lowest distance together on these boundaries (yellow highlighted) were defined with a maximum element size of 0.001 mm and a maximum element growing rate of 1.005. The resulting mesh consists of 74,500 Elements. During the simulation of the ablation process the mesh will be deformed. The deformation leads to numerical instabilities. To avoid or at least to limit this effect the function of automatically remeshing was used. As condition for the remeshing the parameter “minimum element quality” was defined to 0.5.

3. Results of the Simulation

In the following the simulation results will be discussed exemplary for the model of the radial slice.

After completing the first simulation step the values relevant for electrochemical ablation process were analysed. Figure 9 shows a 2D-plot of the electric potential.

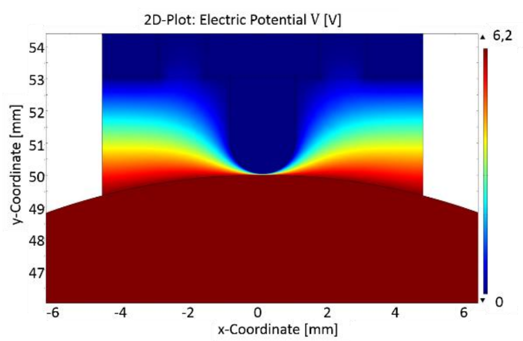

Figure 9. Distribution of the electric potential

It can be seen that the main part of the electric potential decreases over the domain of the electrolyte because of its high electrical resistance. Another important and ablation determining value is the current density which is shown in Figure 10.

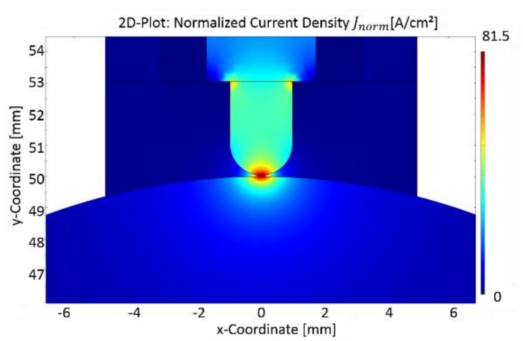

Figure 10. Distribution of the normalized current density

The distribution of the current density shows the maximum in the area with the lowest working gap. This maximum of J_{norm_max} = 81.5 A/cm² leads to a high ablation velocity within the first seconds of the machining process. Within the cathode secondary maxima can be find. These maxima arise because of the geometrical conditions and will have no influence on the ablation.

Using 2D-slice geometries instead of a 3D-model includes some simplifications which are accompanied by inaccuracies in solution. To estimate the resulting inaccuracies a 3D-model of a sub region of the cathode was designed. With this model the first simulation step was run through and the solutions compared to the solution of the 2D-model. The resulting deviation was about 1.5 %. The time for simulation raised up to 330 times. So the deviation was taken in purchase and the simulation of the ablation was accomplished with the 2D-model.

The solution of the second step of the simulation gives important information about the manufacturing result of the machined geometry. Figure 11 shows the distribution of the normalized current density after a simulated machining time of 1500 s.

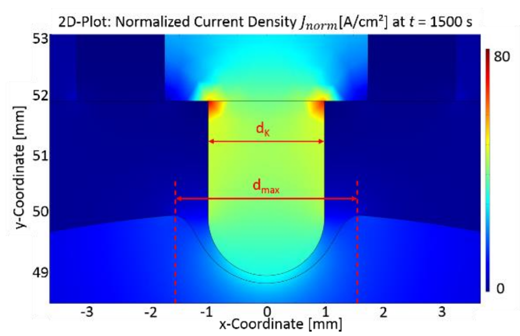

Figure 11. Distribution of the normalized current density after a simulated machining time of 1500 s

After a machining time of 1500 s the feed rate is about 1.15 mm. It can be seen that the maximum current density was reduced during the machining process. Within the working gap the current density is about 30 A/cm². The structure recessed into the workpiece surface has a diameter of d_{max} =3.17 mm and shows typically edge rounding of the ECM process. The front working gap is about 110 µm and the machining depth is 1210 µm.

Figure 12 depicts the current density in normal direction for machining times of 500 s, 1000 s and 1500 s.

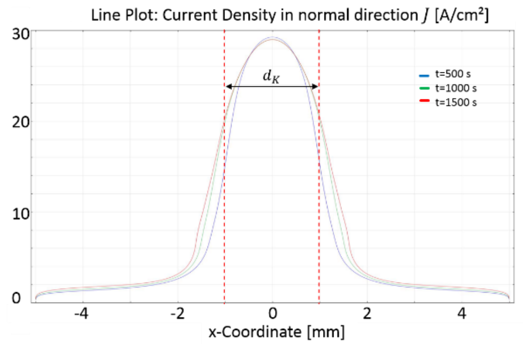

Figure 12. Line plot of the current density in normal direction after the machining times 500 s, 1000 s and 1500 s

Even after 500 s the current density at the front working gap stabilises to values that will be constant for the remaining processing time. The parameter d_k describes the diameter of the forming part of the cathode. It can be seen that the current density outside of d_k increases during the processing time. This leads to an increasing secondary ablation.

4. Conclusion

With the help of simulations the electrochemical ablation process can be described and important information about the localization of the electric current as well as the resulting geometry can be derived. By using the functions for electrical conductivity of the electrolyte and the ablation velocity the simulation effort could be considerably reduced. The simulation model can help to develop different cathode geometries and reduces costs and extensive experiments.

5. Summary

In this study a PEM process with angle-controlled cylinder positioning of the work piece was investigated. Therefore different models were created using the "electric current", "wall distance" and "deformed geometry" interface of COMSOL Multiphysics. In a first step the 3D-geometry of the experimental setup was simplified to two slice geometries. The second step was the meshing of the model geometry. Here a user-defined mesh with triangular elements was used. After that the definition of domain and boundary conditions were set. Because of the complexity of the electrochemical ablation process the simulations were divided in two parts which were solved sequentially. At first a stationary simulation of the electric currents was performed to get the distribution of the current density. The stationary solution of the electric currents was used as initial values for the transient simulation, which was performed as a second step. In this simulation step a machining time of 1500 s was realized which corresponds to a cathode feed rate of 1.15 mm. The simulations use functions for the electrical conductivity of the electrolyte and for the ablation velocity. These functions can only be used for the given material combination with the given process parameters and describes difficult physically interactions. Finally the results of the simulations can be used to improve the cathode geometry and process parameters to achieve the desired machining result.

Acknowledgements

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References

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