

Design of Electrochemical Machining Processes by Multiphysics Simulation

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Abstract: The basic principle of all applications of electrochemical machining (ECM) is the anodic dissolution of a metallic workpiece at the interface to a liquid ionic conductor, the electrolyte, under the influence of electric charge transport. This erosion principle works independently from the mechanical hardness of the workpiece. In addition, the removal is basically free of mechanical forces, and the maximum process temperature is about 80 °C. Thus, in comparison to competing manufacturing processes like milling, grinding, spark erosion, or laser beam machining, the generation of complex geometries with damage-free surfaces is possible. Particularly for machining of micro geometries and micro-structured surfaces, the principle of anodic dissolution is useful, since the erosion mechanism works on the atomic level. The design of electrochemical machining processes is still performed empirically by the most applicers of ECM. The reason is, that so far no comprehensive scientific description is available for the manufacturing principles of this method. The material erosion in EC processes depends on an interaction of a multitude of chemical and physical properties such as electrodynamics, thermodynamics, electrochemical reactions, fluid flow, and geometry modification which makes the machining result hardly to predict. Therefore the application of multiphysics simulations can be an effective method for designing EC processes [1, 2, 3, 4, 5, 6, 7]. In most cases the modeling steps for the simulation of ECM are accompanied by an iterative validation, which allows a gradually optimization of the model.

In this study the actual limits and possibilities of multiphysics simulations of electrochemical machining processes are systematized and demonstrated on selected examples. The potential of multiphysics simulation for the design of Electrochemical Machining processes can be derived.

Keywords: Electrochemical Machining, anodic dissolution

1 Introduction

ECM processes are a result of a complex interaction of various physical and chemical phenomena (Figure 1). For example, the charge transport leads to a heat evolution and the heat is absorbed by the electrolyte. This leads to a change of temperature-dependent quantities of the electrolyte such as electrical conductivity and viscosity. Also fluid dynamics are an important issue. The electrolyte flow affects the concentration of the dissolved material and the charge carriers in the machining gap. The machining gap needs to be supplied steadily with "fresh" electrolyte during machining to ensure a constant electrolyte conductivity and the removal of dissolved material and arising heat.

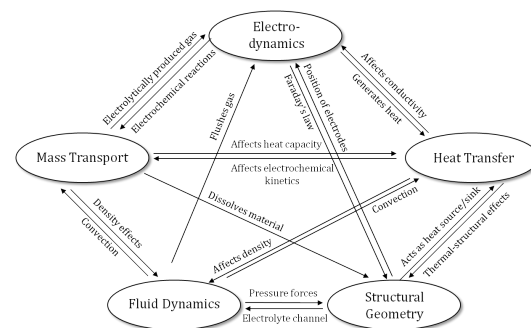


Figure 1: Relevant physical phenomena (according to [4]).

An FEM simulation of an ECM process is a challenging task concerning convergence and computing time. Depending on the goals of the simulation, available input data, and available computer power, the simulation needs to

be reduced concerning geometry and applied physic modules. The principle procedure for the FEM simulation of ECM processes is depicted in Figure 2. Out of the real process an adequate geometry model needs to be deduced, which should be as simple as possible but comprises necessary process features according to the concrete goals of the simulation. In many cases 2D models of certain areas and symmetric geometries are leading to useful information. After that a physical model, equipped with (multi-)physical parameters, needs to be designed which considers, on the one hand, the physical interactions (cf. Figure 1) but, on the other hand, which allows a simulation with a reasonable effort. Sequential simulation of the influencing quantities is also a possibility for reducing the calculation effort. After meshing the model and a successful calculation, a simulation result shows values for the target quantities. For the validation of the output data, integrative quantities should be used, such as electrical currents or charges. Especially in ECM processes the measurement of these values is comparatively easily ascertainable. Depending on the correlation to the real process to the simulated one, the simulation is adapted or refined.

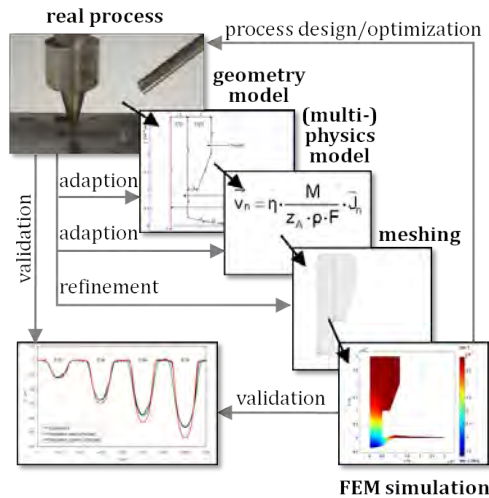


Figure 2: Flow chart for FEM simulation of ECM processes.

The FEM simulation of ECM processes will be exemplarily discussed on the Jet-ECM process.

2 FEM Simulation of Jet-ECM

Jet-ECM is an electrochemical process where the anodic dissolution is localized by a closed electrolyte jet impinging onto the workpiece' surface [8]. Goals of the simulation are the visualization of current densities and the thereof resulting eroded geometry in dependency of the process time. The process of erosion localisation should be understood. The FEM simulation will be validated with experimentally gained results.

2.1 Geometry Model

As geometry, a nozzle with a diameter of 100 μm was chosen which ejects a jet onto a flat substrate placed in a distance of 100 μm (Figure 3). The workpiece' surface at time zero is the abscissa. The jet diameter d_{jet} is equal with the nozzle diameter. Assuming a constant total velocity of flow, the height of the electrolyte film on the surface decreases progressively starting from $0.25 d_{jet}$. This shape was implemented as static geometry which was already applied in simulations by Yoneda and Kunieda [9]. The assumption of an axisymmetric jet shape allows the reduction of the model to a 2D axial-symmetric model.

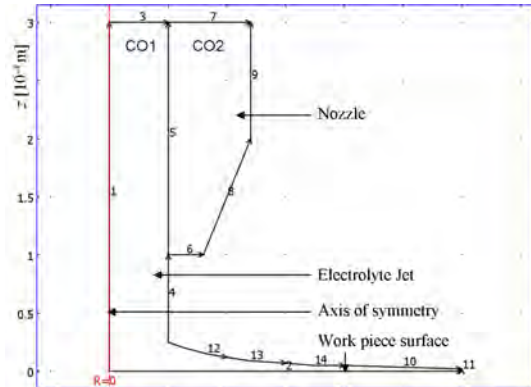


Figure 3: Jet-ECM model 2D axial-symmetric.

2.2 (Multi-)Physics Model

Main driver of EC erosion is the anodic dissolution of metal bonds due to an electric charge transport Q following Faraday's law. The removed material volume V is calculated by:

$$V = \eta \cdot \frac{M}{\rho \cdot z \cdot F} \cdot Q \quad (1)$$

M is the molar mass, ρ the density, z the electrochemical valence of the material, F the Faraday constant, and η is the current efficiency. The velocity of material removal in normal direction \vec{v}_n depends on the current density in normal direction \vec{J}_n :

$$\vec{v}_n = \eta \cdot \frac{M}{\rho \cdot z \cdot F} \cdot \vec{J}_n \quad (2)$$

Most influencing parameter for the material erosion is the electric field \vec{E} since it affects the current density proportionately:

$$\vec{J} = \sigma \cdot \vec{E} \quad (3)$$

The Jet-ECM process was set as transient model into the COMSOL application modes "Moving Mesh" and "Conductive Media DC". Due to the permanent flow of "fresh" electrolyte, thermal effects, concentration variations, as well as material transport phenomena and fluid dynamics were neglected. The conductivity of the electrolyte (subdomain CO1) was set to 16 S/m and as material steel AISI 4340 (stainless steel 1.4541, subdomain CO2) was chosen. Necessary parameters for the erosion calculation following equations 2 and 3 are listed in table 1. A voltage of +56 V was applied onto boundary 2. A mesh displacement for boundary 2 was implemented following equations 2 and 3.

Name	Value
η Current efficiency	100 %
M Molar mass	55.06 g/mol
z_A Valency	3.436
ρ Mass density	7.76 g/cm ³
F Faraday constant	9.65·10 ⁴ C/mol

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

2.3 Meshing

The mesh was generated using the automatic mesh creator with the option "Extra fine".

2.4 Results of the FEM Simulation

As first main result, Figure 4 plots the normal current density of the workpiece boundary 2 over the radial distance r from the nozzle axis. Several important process characteristics

can be derived from this. The maximum of 660 A/cm² is at $r=0$. The current density decreases to nearly 0 A/cm² within a distance of 100 μ m. That implies that the current density, and as well the erosion, is strongly localized in a circumference of 100 μ m around the nozzle axis.

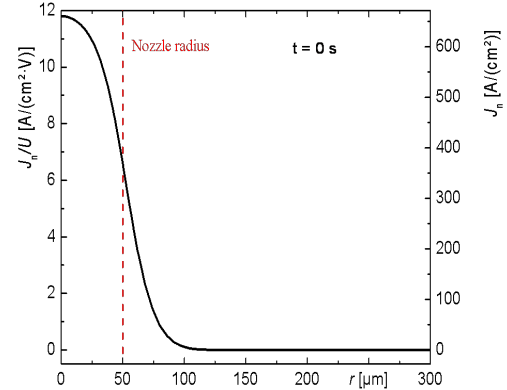


Figure 4: Normal current density at boundary 2 at $t = 0$ s.

Figure 5 depicts the z -displacement after a simulation time of 0.4 s. A calotte-shaped pit geometry is the result of the simulation.

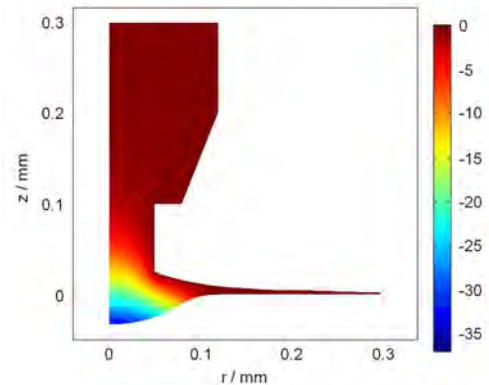


Figure 5: Surface plot of z -displacement in μ m at $t = 0.4$ s.

2.5 Validation and Model Adaption

Using boundary integration, the simulated total electric current I was calculated in a time frame from 0 to 2 s. Figure 6 compares the calculated regime of I with four measured signals at different processing times. The model conforms very well the experimental current signals, especially below 0.5 s time. Not at least the simulated currents are systematically

about 10% to 20% higher than the real current signals.

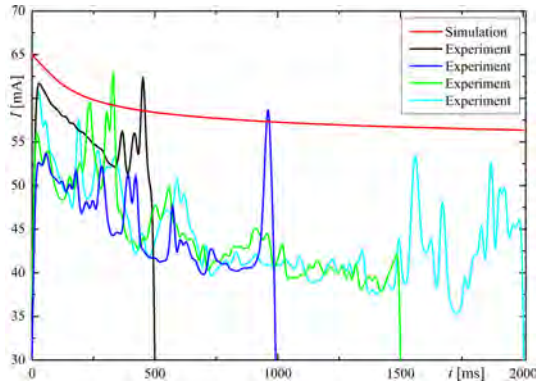


Figure 6: Surface plot of z-displacement at $t = 0.5$ s.

The shape of the simulated eroded surface corresponds very well to the geometries generated in the experiments. Figure 7 shows a scanning microscope image of typical point erosions, generated by Jet-ECM. The localization of the current density was predicted by the simulation and affects the characteristic shape and the localization of the erosion process.

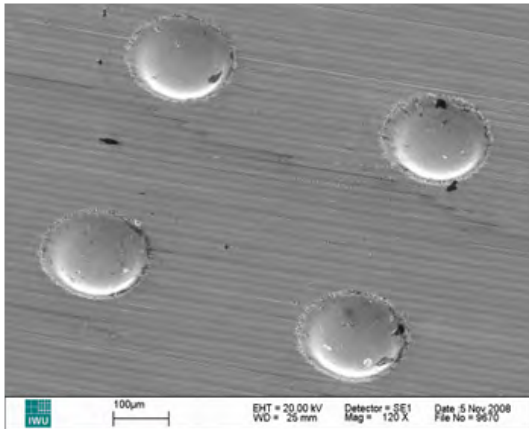


Figure 7: SEM image of four calottes generated with Jet-ECM.

For a quantitative validation, the profiles of eroded geometries were extracted from the simulation and compared to profiles of jetted geometries which were determined by a tactile profilometer (Figure 8). For the geometry of $t = 0.5$ s simulation and experiment show a good coincidence. But for longer process times the simulated pit diameters are larger

and the pit depths are smaller than the experimentally generated geometries. That means with increasing time the model contains a systematic deviation from the real process. Probably, the shape of the electrolyte film cannot be assumed to be static during the process. A solution would be the consideration of the impinging jet as a flowing media, which would comprise the expansion of the simulation to fluid dynamics. This would lead to a very complex model and requires knowledge of the relevant fluid parameters such as viscosity, surface tension and pressure. Additionally, the solving time would increase drastically.

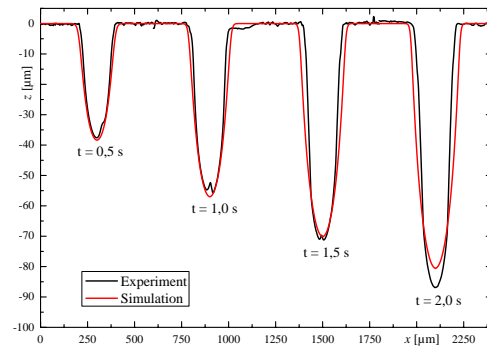


Figure 8: Profiles of simulated and experimentally generated Jet-ECM point erosions.

A more simple approach is to set the electrolyte shape (boundaries 10, 12, 13, 14) concerning its movement as "free" in boundary conditions. Figure 9 shows the deviation of the dynamic jet shape in comparison the static one in Figure 5.

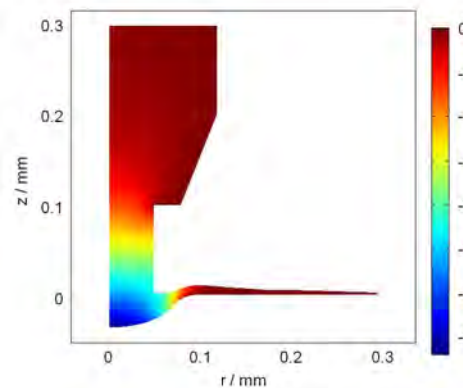


Figure 9: Surface plot of z-displacement in μm at $t = 0.4$ s.

Figure 10 plots the depths and diameters gained by experiments, by a simulation with a static electrolyte film, and by a simulation with a dynamic electrolyte film. The values resulting from the model with the dynamic electrolyte boundary are closer to the measured values than the model with static boundary. It is shown that this small adaption of the model leads to an extension of the valid time scale. The model of the Jet-ECM process can now be used for the design of the machining process.

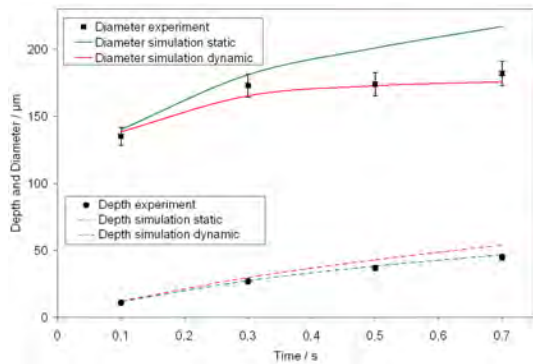


Figure 10: Comparison of pit depth and diameter of simulated and experimentally generated Jet-ECM point erosions.

3 Conclusions

Multiphysics FEM simulation is a powerful tool for the design and improvement of electrochemical processes. It provides information for an optimization of the electrode design for achieving the intended workpiece geometry and it can propose process parameters, such as voltage, electrode velocity, or electrolyte pressure. Instead of an iterative tool and process design an FEM simulation can be an effective shortcut which reduces time and financial effort. Additionally, it visualizes the ECM process.

The simulation of ECM processes with a consideration of all influencing parameters is very complex. By the definition of goal quantities and a smart model design, the simulation effort can be drastically reduced. Depending on the objective, the geometric and physical model should only respect relevant parameters. By a validation with experimental results, the model can be adapted and refined in iterative steps. The validation, especially with integrative quantities, is necessary due to the strong reduction of the real process.

4 Acknowledgements

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