Efficient modeling of material dissolution in electrochemical machining

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The manufacturing process of electrochemical machining (ECM) allows for the precise machining of high-strength materials. In order to save time and reduce experimental costs, one depends on efficient simulation tools. Numerous modeling approaches consider the anodic material dissolution in ECM based on a high resolution of the material (see e.g. [2], [3]). However, these models require computationally expensive remeshing after every time step. Therefore, we propose a novel approach that describes the dissolution process based on effective material parameters (see [5]). Faraday’s law of electrolysis provides the evolution of the dissolution level which is described by an internal variable that relates the dissolved volume to a reference volume. The dissolution level in turn controls the effective material parameters. This procedure allows for the simulation of the entire process with a fixed finite element mesh. Moreover, the model considers the full coupling of the thermoelectric boundary value problem to accurately account for the electric current density distribution. The comparison of the model with analytical and experimental reference solutions yields realistic results and, hence, motivates the model’s application to predict the surface roughness evolution in a pulsed electrochemical machining process.

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1 Material modeling

The dissolved volume due to electrochemical machining depends via Faraday’s law on the experimentally determined material parameter $V_{\text{eff}}$, the electric current $I$ and the machining time $t$

$$V_{\text{dis}} = V_{\text{eff}} I t.$$  \hspace{1cm} (1)

The model strives for a smooth description of the anodic dissolution by introducing the dissolution level

$$d \in [0, 1]$$

analogously to classical damage modeling approaches - the ratio of the dissolved volume $V_{\text{dis}}$ to the incremental reference volume $d V_{\text{ref}}$ (see [5]). This yields the evolution equation for the dissolution level according to

$$\dot{d} = \frac{1}{d V_{\text{ref}}} \frac{d V_{\text{dis}}}{d V_{\text{ref}}} = \frac{1}{d V_{\text{ref}}} V_{\text{eff}} I.$$  \hspace{1cm} (2)

Next, the dissolution level $d$ serves to formulate the effective material parameters $(\bullet)$ which are defined by the mixture of the metal and the electrolyte

$$(\bullet) = (1 - d) \sum_a \lambda_a (\bullet)^a + d (\bullet)^{\text{EL}}$$  \hspace{1cm} (3)

where $(\bullet)^a$ is a material parameter of metal phase $a$ with the volume fraction $\lambda_a$ and $(\bullet)^{\text{EL}}$ the corresponding material parameter of the electrolyte. The mandatory localization requirement that dissolution may only occur on the metal surface where the metal is in contact with the electrolyte is modeled with an activation function that is only active for metal with contact to the electrolyte. Afterwards, we incorporate the effective material parameters into the coupled problem of thermoelectricity and obtain the following weak forms $g_v$ and $g_\theta$ (cf. [4] for the non-transient case):

$$g_v := -\int_{\Omega} (\dot{\theta} + j \cdot \dot{j}) \cdot \nabla \delta v \, dV + g_{\delta v} = 0$$  \hspace{1cm} (4)

$$g_\theta := \int_{\Omega} (\tilde{\rho}_c \cdot \delta \dot{\theta} - j \cdot E - q^* \cdot \delta \theta) \, dV - \int_{\Omega} q \cdot \nabla \delta \theta \, dV + g_{\delta \theta} = 0$$  \hspace{1cm} (5)

Here, $\delta v$ and $\delta \theta$ denote the variations of the primary variables, the electric potential $\nu$ and the temperature $\theta$. Moreover, $\dot{j}$, $j$, $q$, $\tilde{\rho}_c$, $E$, $q^*$, and $c_0$ denote the constitutively dependent variables, namely the electric current density, the displacement current density and the heat flux. Additionally, $\dot{\theta}$, $E$, $q^*$, $\tilde{\rho}_c$ and $c_0$ denote the rate of the temperature, the electric field strength, additional heat sources and the effective material parameters of the volume density and the specific heat capacity. Prescribed current densities and fluxes are considered by $g_{\delta v}$ and $g_{\delta \theta}$.

For further information on the linearization and the finite element implementation of the problem, the interested reader is kindly referred to [5]. Furthermore, analytical and experimental validations of the model with [1] are conducted in the aforementioned literature and, thus, omitted for brevity.

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2 Numerical example

In this contribution, the authors would like to further investigate the numerical example of a pulsed ECM process (PECM) which is presented in [5], where also the geometrical dimensions and the functions of the material parameters may be found. In PECM, the electrodes are stationary or move with a low feed of the cathode. Additionally, the electric potential difference $\Delta v$ between cathode and anode is varied in a pulse pattern that allows a precise machining of the surface. Here, we focus on the distribution of the electric current density in the first load pulse.

In Fig. 1, the machining process of an initially rough surface is presented. For a low voltage, in Fig. 1 (a), the electric field lines concentrate on the peaks of the surface profile and initiate the material dissolution at these peaks. When increasing the applied voltage up to the maximum value, see Figs. 1 (b) and (c), the density of the electric field lines increases at the peaks and, thus, yields the maximum electric current density at these positions. Moreover, a pronounced material removal and a high electric current density at the peaks can also be observed for a high voltage, whereas the dissolution in the valleys of the surface profile proceeds slower due to the smaller electric current density. Therefore, also a smaller number of electric charges, which induce the material removal, pass the corresponding regions of the metal surface.

Fig. 1: Simulation of the machining of a rough surface in a pulsed ECM process, see also [5]. The figure shows the distribution of the norm of the electric current density $\|j\|$ with the electric field lines and the evolution of dissolution level $d$ during the first pulse. The electric potential difference $\Delta v$ is increased from (a) a low voltage, to (b) an intermediate voltage, to (c) the maximum voltage.

When considering the path of least electrical resistance, it becomes evident that this path leads from the cathode through the electrolyte to the peaks of the surface profile. Hence, the leveling of the surface occurs with advancing machining time. This phenomenon is studied in detail in [5], where the evolution of the surface profile from an initially rough surface to an even surface is investigated and, thereby, conforms to the conclusion of the present study.

The proposed model is, thus, able to successfully perform simulations of a dissolution process in electrochemical machining where special attention is paid to the evolution of the surface profile.

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