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Simulation of nano-second pulsed phenomena in electrochemical micromachining processes – Effects of the signal and double layer properties

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ABSTRACT

Pulsed electrochemical micromachining is a metal dissolution process where the capacitive behaviour of the double layer enhances the confinement of the machining profile, when very short voltage pulses are applied. During the pulses, the dissolution is confined to electrode regions where the tool–workpiece gap is the smallest. The model used combines the potential distribution in the electrolyte with the load–unload behaviour of the double layer. The model is solved using the Finite Element Method. The pulse and double layer charging are the main focus and therefore no shape change is included in the model at this point. The influence of the double layer, pulse signal parameters and inter-electrode gap size on the dissolution current density (material removal depth), as a function of time, is investigated. An estimation of the double layer loading time is presented, as well as a quantification method for the metal removal confinement, by comparing the calculated error against an ideal removal profile. The influence of pulse characteristics on the dissolution process has also been studied. It was found that a strongly non-linear polarization in combination with nano-second pulses and a small gap size increases the confinement. All the simulation results were obtained on an axisymmetric case by considering several geometrical set-ups.

1. Introduction

Similar to conventional electrochemical machining [1], pulsed electrochemical micromachining (PECMM) is a controlled anodic dissolution process for removing metal. A high current density (typically in the range of 10^5 A m^{-2} [2]) passes between the tool (cathode) and the workpiece (anode) through an electrolyte solution. By advancing the tool towards the workpiece, the current density is higher at shorter electrode distances and the shape of the tool is copied on the workpiece [3].

Compared with other machining techniques, PECMM is a high precision technology for drilling narrow holes or manufacturing microcomponents with crack-free and stress-free smooth surfaces of the workpiece [4].

The use of ultrashort pulses (usually <100 ns) enhances the precision by confining the faradaic current density, which is responsible for material removal, to the region under the tool [5,6,2]. The confinement is mainly due to the incomplete loading of the double layer (DL) in regions furthest from the tool, which receive a lower current density. To exploit this effect, the shape, length and amplitude of the applied pulses are crucial.

Considerable progress has been published on the experimental research of electrochemical micromachining (ECMM) [2,7–10]. In numerical simulations literature, Kozak et al. [4,11], Burkert et al. [7], and Kenney and Hwang [12,13] presented time accurate computations for predicting the material dissolution rate. Kozak et al. [4] approximated the current density distribution by an analytical formula that relates the potential drop, between the tip of the tool and a point on the workpiece, to the inverse distance. Kenney and Hwang [12] proposed an equivalent network to approximate the current density distribution in the electrolyte solution. This approach can only be applicable to specific geometries. A similar equivalent network was employed by Fafilek et al. [14], for simulating transient signals in micro-galvanic processes. They showed that by using linear polarization, the current density is not confined over the workpiece. Mithu et al. [15] investigated the effect of high frequency and duty cycle on the material dissolution using a model based on the combined use of Faraday's law and an analytical expression relating the potential drop between the electrodes with the inverse distance (like Kozak et al. [4]). In their computational and experimental work, Mithu et al. [15] used an applied potential of 10 V. Filatov [16] used the Finite Difference Method to compute fluid dynamics related quantities (electrolyte velocity and pressure) involved in the ECM process.

In spite of all these efforts, there is still a need to improve the numerical models, such that one can predict the material removal

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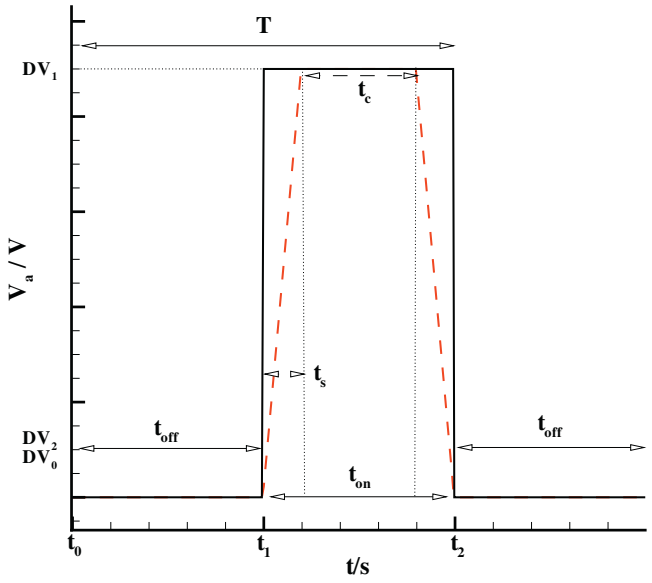

Fig. 1. Signal description. t_{off}, t_{on}, t_s, t_c are the pulse off-time, on-time, slew-time and respectively constant-potential-time. DV_0, DV_2 are the generic off-time values before and after the pulse; DV_1 is the amplitude at pulse t_{on}. T is the pulse period.

rate, represent the change of the workpiece geometry and find the optimal tool shape and pulse signal parameters for machining a desired workpiece shape [17]. A complete model of PECMM should be able to accurately describe the power source, effects of the fluid flow, gas evolution, heat generation, electrochemical processes at the electrodes, transport of the involved species and the changing workpiece geometry [18].

A computational model to calculate the potential distribution in the electrolyte solution by solving the Laplace equation, is proposed in this work. The effects of double layer loading and non-linear polarization due to the electrochemical reactions are considered at the electrode surfaces. The model is solved time accurately by using our own multi-physics numerical solver [19], named MuPhyS, based on the Finite Element Method (FEM) [20,21].

Based on an axisymmetric configuration, the influence of the double layer capacitance, the gap size and pulse characteristics on the machining precision has been investigated. A full understanding of these interactions is vital for practical applications and for real electrode shape change under PECMM conditions.

2. The pulse signal

The applied signal is an essential aspect of the PECMM and is directly related to the accuracy of the process [22]. The potential pulse imposed at the workpiece $V_a(t)$, is shown in Fig. 1. The tool is grounded and thus the potential V_c is constant and set to zero.

The impedance of the wires and the electrodes are not taken into account.

Since in reality the applied potential is not a perfect rectangular wave, the slew rate $SR = dV_a/dt$ [V s^{-1}] being the potential change rate at rising and falling pulse had to be introduced. The duty cycle $D = t_{on}/T$ is the fraction of active state within a pulse period $T = t_{on} + t_{off}$.

In the following simulations, the pulsing starts with an off-time of 100 ns.

3. Mathematical model

This work focuses on the effects of pulse characteristics and double layer on the machining precision. For that reason, the changes in ion concentrations, temperature and shape change may be neglected. Therefore the local concentrations of species, involved in the electrochemical reactions are considered to be constant and equal to bulk concentrations. Also, the temperature is kept constant and no anodic displacement is taken into account.

In the electrolyte, the potential distribution U [V] is computed which, based on the local form of the charge conservation, reads [23]:

$$\vec{\nabla} \cdot \vec{j} = \vec{\nabla} \cdot (-\kappa \vec{\nabla} U) = 0 \tag{1}$$

where κ [S m^{-1}] is the specific electrical conductivity of the electrolyte, considered constant.

When a potential difference is applied, the current density passing through the interfaces [24], normal to the electrode surface, is equal to the sum of a faradaic and a capacitive current density:

$$\vec{j}_n = -(\kappa \vec{\nabla} U) \cdot \vec{1}_n = j_f + j_c \tag{2}$$

where $\vec{1}_n$ is the external unit normal to the electrode surface.

The faradaic current density, related to the electrochemical reactions taking place at the electrode, is driven by the overpotential $V - U$ (without loss of generality the cell potential E_0 at zero current has been omitted) and is given by the Bulter–Volmer (BV) equation [25]:

$$j_f = nF \left\{ k_F \exp\left[\frac{\alpha_F nF}{RT}(V-U)\right] c_{red} - k_B \exp\left[\frac{-\alpha_B nF}{RT}(V-U)\right] c_{ox} \right\} \tag{3}$$

where n is the charge number, F [C mol^{-1}] is the Faraday constant, k_F and k_B [mol m^{-2} s^{-1}] are the forward and backward reaction rate coefficients, α_F and α_B are the forward and backward charge transfer coefficients, R [J mol^{-1} K^{-1}] is the ideal gas constant, T [K] is the temperature and V [V] is the electrode potential. c_{red}, c_{ox} in [mol m^{-3}] are the local concentrations involved in the anodic and cathodic reactions.

The capacitive current density is described by the following expression:

$$j_c = \frac{\epsilon}{d} \frac{d(V-U)}{dt} \tag{4}$$

with ϵ/d [F m^{-2}] being the specific DL capacity. Although the DL capacity may depend on the polarization, ϵ/d is considered to be constant.

The local machining depth at a given time $d_a(\vec{r}, t)$ [m] is proportional to the local faradaic charge passed per unit surface. The local charge distribution $q_f(\vec{r}, t)$ is calculated at each time step and every node of the workpiece by integrating the faradaic current density in time. Based on Faraday's law the local machining depth becomes:

$$d_a(\vec{r}, t) = \frac{M}{nF\rho} \int_t eff(j_f) j_f(\vec{r}, t') dt' \tag{5}$$

where $eff(j_f)$ is the current efficiency taken to be 100%, M [kg mol^{-1}] is the molar mass of the workpiece metal, ρ [kg m^{-3}] is the mass density and t [s] is the total pulsing time.

Summarizing, the resulting mathematical model is a Laplace equation with non-linear time dependent boundary conditions.

4. Simulation prerequisites

The geometry is a typical set-up used to drill a micro hole in a flat plate, as shown in Fig. 2. The tool is a small cylindrical rod of radius $r_t = 50$ μm and height $h = 100$ μm. The side walls can be active or insulated. On the opposite side, there is the initially flat