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A temperature dependent multi-ion model for time accurate numerical simulation of the electrochemical machining process. Part III: Experimental validation

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ABSTRACT

The temperature distribution and shape evolution during electrochemical machining (ECM) are the result of a large number of interacting physical processes. Electrolyte flow, electrical conduction, ion transport, electrochemical reactions, heat generation and heat transfer strongly influence one another, making modeling and numerical simulation of ECM a very challenging procedure. In part I [1], a temperature dependent multi-ion transport and reaction model (MITReM) is put forward which considers mass transfer as a consequence of diffusion, convection and migration, combined with the electroneutrality condition and linearized temperature dependent polarization relations at the electrode–electrolyte interface. The flow field is calculated using the incompressible laminar Navier–Stokes equations for viscous flow. The local temperature is obtained by solving internal energy balance, enabling the use of temperature dependent expressions for several physical properties such as the ion diffusion coefficients and electrolyte viscosity. In part II [2], the temperature dependent MITReM is used to simulate ECM of stainless steel in aqueous $NaNO_3$ electrolyte solution. The effects of temperature, electrode thermal conduction, reaction heat generation, electrolyte flow and water depletion are investigated and a comparison is made between the temperature dependent potential model and MITReM. In this third part, the theoretical model is validated against ECM experiments in a flow-channel cell. The model is further optimized by including the effect of metal hydration and non-linear polarization relations. A close match is obtained between experiment and simulation.

1. Introduction

Metal removal using electrochemical machining is achieved by the controlled electrochemical dissolution of an anodically polarized workpiece. A cathode tool and anode workpiece are immersed into an electrolyte solution and subjected to a potential difference, causing electrochemical reactions to occur at the electrode–electrolyte interfaces. In particular, at the anode–electrolyte interface, metal is dissolved into metal ions.

With the aim of improving the reliability of industrial simulations, new approaches and numerical techniques for accurate prediction of the workpiece shape evolution are introduced. This requires a complex combination of models that should be adequately capable to handle electrochemistry (species convection and diffusion, ion migration in an electric field, electrochemical reactions and heat generation) as well as fluid flow, heat transfer and thermal influences on a geometry that changes over time. This multi-physics aspect makes the numerical simulation of electrochemical machining an extremely challenging procedure.

Part I of this article presents an advanced model for dealing with ECM simulations [1]. The multi-ion transport and reaction model (MITReM) [3] is solved, which considers mass transfer as a consequence of diffusion, convection and migration, combined with the electroneutrality condition and linearized polarization relations at the electrode–electrolyte interface. The MITReM is able to deal with concurrent electrode reactions (*e.g.* metal dissolution vs. oxygen evolution at the anode), such that the current efficiency is inherently part of the model. The model is further extended with temperature and concentration dependent density, viscosity, species diffusion and electrical conductivity correlations. In addition, boundary conditions dealing with cooling of the electrodes by natural convection are added. Temperature and concentration dependent polarization behavior is included, such that the effects of water depletion [4,5] can be accounted for. To obtain the temperature field, the internal energy balance is added to the set of equations. Heat is generated in the electrolyte bulk (Joule heating) and by the electrode reactions in the double layer.

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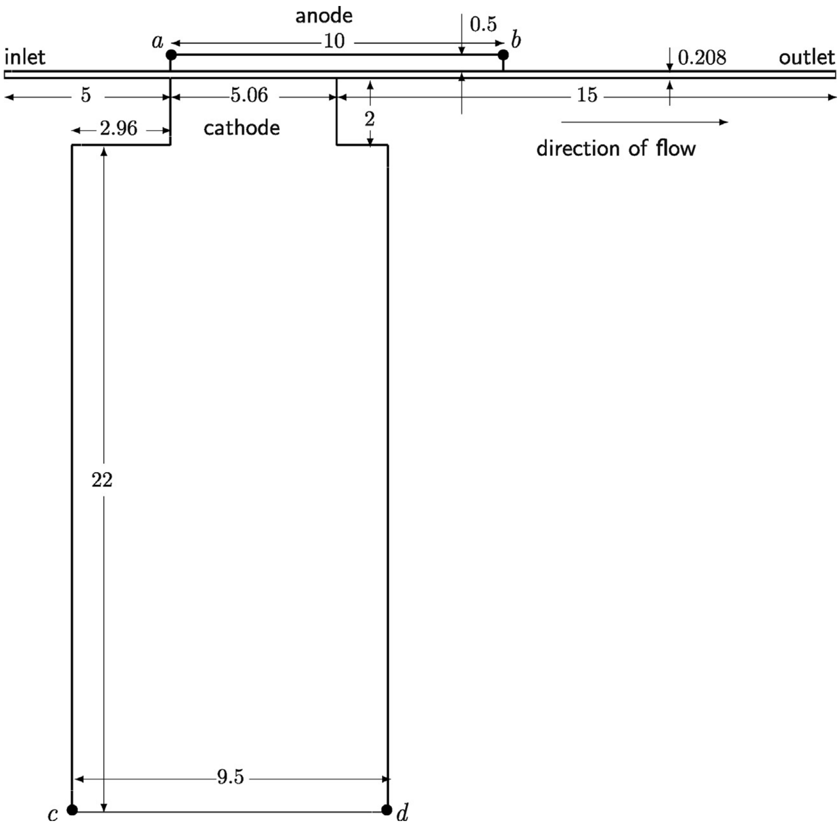

Fig. 1. Geometrical model of a cross section of the flow-channel cell along the channel center in the flow direction, used for numerical simulation. Dimensions are given in mm.

In part II of this article, the temperature dependent MITReM is used to simulate ECM of steel in aqueous $NaNO_3$ electrolyte solution [2]. Additionally, the effects of temperature, electrode thermal conduction, reaction heat generation, electrolyte flow and water depletion are investigated. Since the model is computationally very heavy, it is important to be able to simplify where possible. Such is for instance the case with the potential model which assumes constant concentrations in the electrolyte, making the simulation substantially more manageable in terms of equations and computation speed compared to the MITReM. This is all the more desirable when considering the three-dimensional problem. In order to know whether simplifications are possible and justified, a parameter sensitivity study is performed on the full model. The importance of parameters and their temperature dependence with respect to ECM is studied. In addition, a comparison is made between the temperature dependent PM and MITReM.

In this subsequent part III, the temperature dependent MITReM presented in parts I and II is used to compare the results of several simulations to experimental data. Experiments are conducted by Hoogsteen and Kuindersma [6]. They were so kind as to provide the necessary technical details and experimental data for the numerical study at hand. The study is performed on a so-called flow-channel cell, specifically designed to characterize electrochemical systems and material properties and behavior with regard to ECM.

First the setup on which the measurements are performed is presented. Consequently, the experimental procedure is explained, followed by numerical simulations. A comparison is made between experiment and simulation in which similarities and differences are discussed. Finally, model optimizations are implemented to obtain a close match between simulation and experiment.

2. Experimental procedures

The complete experimental procedure and measurement apparatus are detailed by Hoogsteen et al. [7]. In this section, the aspects of the experimental procedure which are relevant to the simulations are detailed.

2.1. Setup

The experiments are conducted in the *flow-channel cell*. The design of the cell is similar to the one used by Landolt and Datta [8,9]. The width of the flow channel is 1.0 cm. A schematic of a cut-section of the flow-channel cell in the vicinity of the electrodes, is shown in Fig. 1.

The length of the bronze cathode is 0.506 cm and its width 0.710 cm, as shown in Fig. 2. The anode samples are much larger, 1 cm by 3 cm, and aligned with its leading edge exactly parallel to the leading edge of the cathode. Fig. 3 shows two anode samples after electrochemical machining in the flow-channel cell.

In order to guarantee a fully developed velocity profile at the electrodes, the leading edge of each electrode is positioned 3.1 cm downstream from the inlet of the flow channel. The initial inter-electrode distance is $208 \pm 10\,\mu m$.

The anode material is 6C27 martensitic stainless chromium steel, produced by Sandvik. The composition of this type of steel is given in Table 1. The samples have been hardened at standard conditions prior to the experiment at a temperature of 980 °C. During the hardening process, most of the carbides are dissolved in the steel, increasing its hardness to about 525 HV.

High-rate electrochemical dissolution experiments are carried out in aqueous $230\,g\,l^{-1}$ technical grade $NaNO_3$ solution (BASF) at 25 °C. The electrolyte is pumped through the flow-channel at a