Time-dependent simulation of electrochemical machining under non-ideal conditions

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Abstract

Electrochemical machining (ECM) is a manufacturing process based on the principles of electrolysis. It machines irrespective of workpiece hardness and, as a result, it is used in the manufacture of parts requiring the use of hard alloys such as airfoil blades. Die-sinking ECM involves a shaped tool being moved closer towards the workpiece. Material removal takes place under the influence of an electric field. Once material removal rates are equal to the tool feed rate the process is said to have reached equilibrium. At equilibrium the workpiece is an approximate inverse of the tool shape. Under ideal ECM conditions, a number of process parameters are assumed to be constant. Industrially however, conditions are rarely ideal, and it may not be desirable to machine until equilibrium. This paper presents a time-dependent simulation that includes a model of one of the changing parameters, the overpotential, which is the voltage required to drive the electrochemical reactions at the workpiece and the tool. Previous work has shown that this condition varies throughout the course of machining. Validation is performed against experimental results, and comparisons are made against simulation under ideal conditions.

Keywords: electrochemical machining (ECM), simulation, time-dependent, finite-element analysis, overpotential, non-ideal, non-equilibrium.

1 List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_0$</td>
<td>Overpotential</td>
</tr>
<tr>
<td>$n$</td>
<td>Valency</td>
</tr>
<tr>
<td>$V_t$</td>
<td>Applied voltage</td>
</tr>
<tr>
<td>$A$</td>
<td>Area of workpiece electrode</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Conductivity</td>
</tr>
<tr>
<td>$I$</td>
<td>Current</td>
</tr>
<tr>
<td>$z$</td>
<td>Gap</td>
</tr>
<tr>
<td>$\overline{dh}$</td>
<td>Material removed</td>
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</tbody>
</table>
2 Introduction

2.1 Background

Electrochemical Machining (ECM) is a manufacturing technique capable of shaping complex parts through anodic dissolution. It is most effectively applied when the material to be shaped is prohibitively hard for efficient machining using conventional contact techniques. It has been adopted in many areas of the manufacturing sector, including the aerospace industry where super-alloys are regularly used. It is a non-contact method that results in little or no tool wear, and ensures that there is no introduction of undesirable sheer stresses in the workpiece material [1, 2]. A variety of products are manufactured using this technique, from turbine blades and blisks in the aerospace industry to microelectronics [3].

This paper discusses die-sinking ECM where the electrolyte is pumped through a gap between the tool (cathode) and the workpiece (anode), removing the products created by dissolution. During the process the two electrodes are fed closer together. After a period of machining, the material removal at the workpiece is equal to the feed rate and an equilibrium-state is reached. At this stage the workpiece is an approximate inverse to the tool shape [1].

2.2 Non-ideal conditions during ECM

Under ideal conditions, a number of process parameters are considered to be constant [1]. Industrially, however, the ECM process often cannot be considered ideal, with variations in process parameters and non-equilibrium machining requirements apparent. In non-equilibrium machining the workpiece is not machined to an equilibrium shape. The tool needs to be designed to produce the correct shape prior to reaching the equilibrium state. An example of such a process is the ECM of the trailing edge of aerofoil blades that are used in turbine engines. Consequently, tool design becomes increasingly complicated, often resulting in the adoption of a costly trial-and-error approach [4]. In an effort to reduce these costs, approaches have been developed to aid the tool design process and simulate machining. Additional work has taken place to include models of varying parameters during machining.

In the area of tool design, analytical approaches have been developed that utilise process parameters to predict a tool-shape from a desired workpiece shape. Methods include simplistic shape projection techniques [1], to more complex conformal mapping techniques [5, 6]. These methods lend themselves to computational efficiency, however they assume equilibrium is reached and can produce unrealistic tool profiles [6].
Time dependent, numerical approaches to simulating the ECM process have also been devised. The finite-element approach has been shown to be a valid way of simulating the process and is capable of producing accurate results [7, 8, 9]. These simulations can offer workpiece shape-solutions during machining, not just at equilibrium, as well as allowing experimental parameters to be monitored over time.

Variations in process parameters can result in the deviation from predicted workpiece shapes calculated assuming ideal conditions. The conductivity (κ) of the electrolyte can vary under the influence of phenomena such as temperature change, flow path variation and hydrogen bubble generation. This variation of κ will alter the rate at which material is removed along the workpiece. Further developments have led to the inclusion of additional mathematical models to simulate some of the process phenomena that are taking place during the ECM process [10]. These include temperature and gas generation within the inter-electrode gap during machining as well as some modelling of the electrolyte flow.

Additionally, variations occur in the chemical parameters that determine the dissolution rate of the workpiece material [11]. These include the valency of the workpiece material and the overpotential required to drive the reactions at each electrode. These parameters have previously been assumed to remain constant during machining.

This paper proposes the inclusion of a parametric model of the changing overpotential into a numerical, time-dependent ECM simulation. It is believed that with the inclusion of this model a more accurate simulation can be produced. The approach demonstrated uses repeated finite-element analysis over a series of time steps allowing geometric solutions at any stage of the machining, not just at the equilibrium state.

3 Overpotential variation during ECM

3.1 Overpotential

During electrolysis two reactions occur: an oxidation process at the workpiece and a reduction process at the tool. The oxidation process results in metal ions being displaced from the workpiece, through an oxide layer, and into the electrolyte solution. The displacement of these metal ions creates vacancies in the oxide layer, which are filled by more ions from the workpiece. The oxide layer is produced by a reaction between the workpiece material and oxygen. At the tool, a reduction process takes place, which releases an hydroxide ion. In ECM, the electrolyte is pumped between the tool and the workpiece in order to remove these ions from the system. In order to drive these electrochemical reactions at tool and workpiece, an overpotential ($V_0$) is required.

3.2 Characterisation of overpotential

Research has been undertaken to characterise $V_0$ against measurable machining parameters for a variety of workpiece materials typical to those used industrial
ECM. Typical materials include Inconel, Stainless steel and Titanium. Eqn (1) defines the relationship between $V_0$ and the current ($I$) during machining.

$$I = \frac{(V_t - V_0)A\kappa}{z}$$

Ultrasound techniques have been implemented to produce real-time measurement of the inter-electrode gap ($z$) during machining [12]. This, combined with measurement of $I$, and knowledge of the tool voltage ($V_t$), electrode area ($A$) and electrolyte conductivity ($\kappa$), allows the calculation of changes in $V_0$ during machining.

![Figure 1: A typical graph showing changes in overpotential against current density. Region A shows the measurements taken before the breakdown of the oxide layer. Region B shows measurements taken once machining through the broken oxide layer.](image)

Whilst machining in region A, shown in Figure 1, the oxide layer is of a constant thickness. The resistance is constant and the layer behaves in an ohmic fashion, producing a linear relationship [13, 14] between $V_0$ and $J$. At higher $J$ values, as seen in region B, the rate of dissolution is increased and more ions and electrons are released. The number of vacancies produced increases and they start to coalesce. Consequently, the oxide film begins to breakdown, producing a drop in the resistance, and a reduction in $V_0$. Experimentally, the tool and the workpiece are moved closer together, reducing the resistance across the inter-electrode gap. Subsequently, $J$ increases and results in an increase of $V_0$ at the workpiece.

It is the $V_0$ increase in region A that this paper will introduce as a parametric model into a simulation of the ECM process. Models are still being developed to describe the variations in $V_0$ seen in region B as well as the transition between the two regions.
4 Simulation overview

The software used for this simulation is MATLAB used in conjunction with the finite-element package FEMLAB. The geometry used represents the electrolyte gap with the upper and lower boundaries defining the profile of the tool and the workpiece. The workpiece boundary is broken down into a number of points, evenly distributed along its length. Figure 2 shows the boundary conditions applied in the model.

![Diagram of boundary conditions](image)

Figure 2: An example of a possible geometry with boundary conditions used in simulation.

The tool boundary is assigned \( V_t \). The side boundaries are constrained so that the normal of the current density \( (nJ) \) equals zero. \( V_0 \) is applied as the workpiece boundary condition and varies in magnitude in the simulation in accordance with \( J \) as discussed in Section 3.2.

The simulation feed rate \( (f) \) and \( V_t \) are assigned constant values based on typical experimental settings. \( \kappa \), determined through analysis of experimental electrolyte concentrations, is defined in \( \Omega \) and the electric field is evaluated through solution of the Laplace field equation,

\[
\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} = 0 .
\]  

Analysis takes place during each time step \( (dt) \), after which the current density \( (J) \) data is extracted from points along the workpiece boundary. The material removal at each of these points \( (\Delta h) \) takes place normal to the workpiece, and is calculated using,

\[
\frac{\Delta h}{dt} = \frac{Jtn}{FM\rho} ,
\]  

where \( n \) is the valency, \( M \) is the molecular mass, \( \rho \) is the density of the workpiece, and \( F \) is Faraday’s constant. A spline representation is used to calculate the normals at each of the points distributed along the boundary.
\(\overrightarrow{dh}\) is combined with the tool movement and the points are displaced. A spline is interpolated through the new coordinates, and a new set of evenly distributed points are defined. The geometry is re-formed and re-meshed, \(V_0\) is re-evaluated, the new boundary condition is applied, and solution of the electric field is repeated.

The simulation can be terminated automatically based on either user defined conditions such as elapsed time, or can be dependent upon process parameters being monitored for example current values, or depth of material removed.

5 Validation

5.1 Experimental set-up

A flat-segmented tool was positioned in the base of the machining rig and a 40x15mm Titanium 6/4 workpiece was fed towards it at a rate of 0.5mm/min whilst \(V_t\) was set at 16V. Throughout machining a 15% Chloride electrolyte (\(\kappa = 20\)Sm\(^{-1}\)) was pumped between the two electrodes at 16 litres/min and recycled through a tank. This flow rate is considered to be sufficiently high to minimise conductivity changes due to electrical heating and products generated during electrolysis. Machining was allowed to take place until equilibrium had been reached. An ultrasound probe is positioned behind the workpiece to measure the workpiece thickness during machining and subsequently allows for calculation of \(z\). Real-time data was collected and stored for later comparison.

\[\text{Figure 3: Overview of the machining set-up.}\]

5.2 Simulation set-up

The simulations were performed on a PC with Dual Pentium 4 3.06GHz processor and 2Gb RAM. \(f\) and \(V_t\) were set to 0.5mm/min and 16V respectively; \(n\) was set to experimentally obtained values. Figure 3 shows the \(V_0\) model used for Titanium 6/4 in a 15% Chloride electrolyte. It has been calculated using a
least-squares fit through experimental data collected whilst machining in region A.

The simulated machining time was 580 seconds. For further comparison, the same simulation was performed with $V_0 = 5.3\,\text{V}$, the mean of the measured experimental $V_0$. This provides a set of results for simulation under ideal conditions.

Figure 4: The model (▬) used to calculate $V_0$ during non-equilibrium machining.

5.3 Results

Figure 5: Comparison of $I$ against $t$ for experimental (---), non-ideal simulation (▬) and ideal simulation (•••).
6 Discussion

The experimental, non-ideal simulation and ideal simulation results are shown in Figures 5, 6 and 7. Figure 5 and 6 show the current transient and the gap between
the tool and the workpiece surface during the machining respectively. Figure 7 shows the absolute error between experimental $z$ and the simulated $z$ for ideal and non-ideal conditions. The figures also show the two $V_0$ regions, discussed in section 3.2. Region A is defined from experimental data and its duration is the first 270 seconds of machining. After this point, machining is taking place according to region B and the oxide layer is breaking down, resulting in a decrease in $V_0$.

The current transient, shown in Figure 5, demonstrates that both the ideal and the non-ideal simulations produced similar $I$ values whilst machining in region A. The ideal simulation $I$ becomes constant and the non-ideal simulation $I$ continues to increase. This is due to the continued application of the $V_0$ model defined for region A throughout the simulation of machining in region B.

The $z$ vs. $t$ graph, shown in Figure 6, shows that the non-ideal simulation closely follows the experimental data whilst machining in region A. Beyond this stage the model used is no longer an accurate representation of the changes in $V_0$. The ideal simulation $z$ initially matches the experimental data. After 100 seconds however, it indicates that $z$ is wider than that measured experimentally, with deviations of up to 0.5mm, shown in Figure 7.

Once machining in region B, the experimental gap begins to increase as $V_0$ begins to decrease. Since this region is not modelled in the non-ideal simulation, $z$ continues to decrease. The effect of this can be seen in Figure 7 where the error between experimental and non-ideal simulation $z$ increases. The ideal simulation remains constant throughout region B.

### 7 Conclusions

A two-dimensional simulation of ECM using finite-element methods has been created that implements a parametric model for overpotential. The simulation is time-dependent, allowing for non-equilibrium machining to be evaluated.

The non-ideal simulation has been demonstrated and the results for simulation of machining using a Titanium 6/4 workpiece has been compared against both experimental data and results from a simulation using ideal conditions. The results for these tests show that the addition of these parameterised values produced a more accurate predication for the current and gap width during non-equilibrium machining states when the oxide layer is of a constant thickness.

Further work is required to develop the overpotential model to include the behaviour of the oxide layer as it breaks down at high current densities, as well as the application of the model to non-flat geometries.

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References


