The Effect of Electrolyte Flow Slots in Tooling Electrodes on Final Anode Surface in Electrochemical Machining

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Abstract: Electrochemical machining (ECM) is a non-conventional machining process that uses electrolysis to precisely remove material at high rates. ECM has many advantages over conventional machining: virtually no tool wear, no induced mechanical or thermal stresses, and excellent surface finishes. However, challenges can arise during the design of the electrode tool when considering the influence of electrolyte flow slots on the formation of ridges on the workpiece. A model to predict the final machining surface in the presence of electrolyte flow slots in the electrode tool is created using COMSOL finite element software. The anode recession rate was modeled as a function of the resulting normal current density in accordance with Faraday's law of electrolysis. Good agreement was shown between the theoretical and experimental ridge widths under specific machining conditions.

Keywords: Electrochemical machining, ECM, modeling, flow slots, ridge

1. Introduction

Electrochemical machining operates on the principal of electrolysis and can be thought of as highly accelerated and controlled corrosion. The main advantages of this process are the complex 3D geometries obtainable, high rates of machining which are virtually independent of material hardness, and precise surface finish because material is removed at an atomic level.

Electrolyte can be supplied across the work surface either by flow slots on the cathode, or from the side of the too through the use of back pressure dams. Flow slots in tooling are generally less complex to design, but will leave ridges in the areas directly underneath the slot due to the increased electrical resistance (and hence decreased current). The ridges predominately must be removed by a secondary machining process after the ECM operation depending on the depth of cut. Many research papers have been dedicated to investigating the effect of process inputs on material removal rates, surface finishes, and overcut [1-3]. However, little research has been dedicated to prediction of flow slot ridges after an ECM operation. Westley et. al. documented their work designing and testing a tool electrode for the ECM of a turbine blade [4]. They experimentally showed various ridge formations from different sizes of flow slots, but no analytical model was presented. This paper presents a COMSOL model and experimental results for prediction of ridge geometry on the final workpiece surface under ECM conditions. This model can be used to determine estimates of ridge formation during the machining process to help further understand the challenging problem of tooling electrode design.

2. Methods

2.1 Equipment and materials

A laboratory electrochemical test apparatus was used to conduct the machining experiments; the machining cell is shown in Figure 1. Detailed information about the design and construction of the apparatus is available [5].

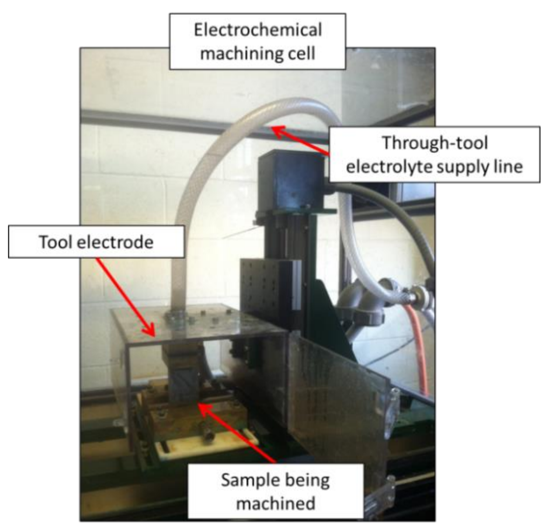

Figure 1: Electrochemical machining cell used in experimentation

The power supply used is variable voltage, DC 20V/250A. Process variables were set to the following values shown in Table 1 below.

Voltage	20V
Flow Rate	5 gpm
Electrolyte	NaCl
Concentration	15 % w/w
Feed Rate	0.1 mm/min
Gap	0.5 mm

Table 1: ECM process parameters used

Electrolyte was filtered through a 74 µm filter prior to being delivered to the tool flow slot by a high pressure centrifugal chemical pump. The tooling was designed as a two–part assembly to allow for the machining of a tapered flow slot to reduce turbulence of the electrolyte. The tool was made of machinable brass and had a bottom surface area of 1.05" x 1.05". This is shown in Figure 2 below.

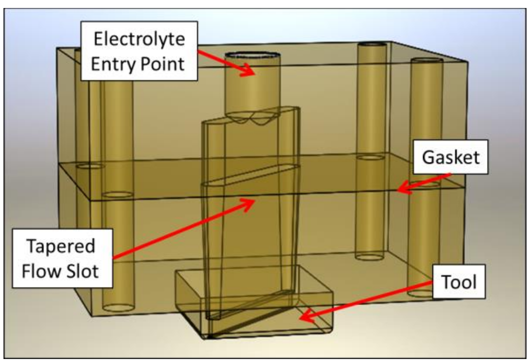

Figure 2: CAD model of tooling design with internal tapered flow slot

High strength 1045 carbon steel samples 0.75in^2 were used for experimentation. Tests were run for ten minutes, and ridge height and width was measured using digital calipers and a digital height gauge.

2.2 Assumptions

Several assumptions were made about the ECM process for this model:

1. Constant electrolyte conductivity
2. No gaseous generation (hydrogen)
3. Fully laminar electrolyte flow
4. 100% machining efficiency

A combination of gap size (0.5mm) and electrolyte flow rate (5gpm) was chosen to ensure evenly distributed and non-tubulent flow over the anode surface. Fresh electrolyte was used to reduce the effect of dissolved material on electrolyte properties. The effect of hydrogen generation on conductivity was neglected in this study for the purpose of simplicity. However, the short flow paths and high flow rates used minimized this effect. The sample surface was inspected post-test and no evidence of differential machining or increased surface roughness was seen near the edge of the sample. This indicates that hydrogen generation and concentration gradients from dissolved material had a negligible effect. Machining efficiency was taken to be 100% as it has been shown that the efficiency of steel dissolved with NaCl electrolytes is not dependent on current density like with $NaNO_3$ electrolytes [6].

2.3 Modeling

A 2D model of the process was created in COMSOL multiphysics software. A cross section of the tool, workpiece, and electrolyte geometry was taken and drawn in COMSOL. The pink and green lines represent the cathode and anode boundaries respectively. The electrolyte was assumed to be the space in between these boundaries.

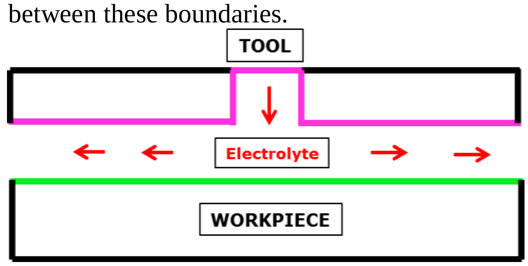

Figure 3: Drawing of cross section modeled in COMSOL

A potential of 20V was applied to the anode boundary layers, and the cathode boundary layers were grounded. The side boundaries were insulated. This is shown in Figure 3.

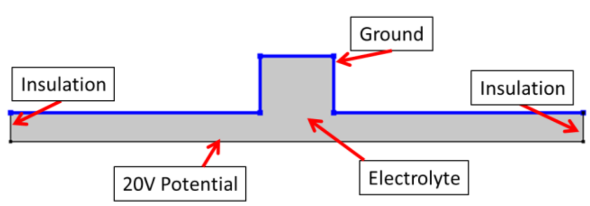

Figure 4: Boundary conditions used in the model

The electrolyte, the space separating the two electrodes, was given a constant conductivity value. This was measured with a conductivity meter after diluting the solution 1:100 and then back calculating the conductivity at full concentration. NaCl was seen to fully disassociate in water at 10% weight by weight (w/w) concentrations; thus, conductivity was assumed to be a linear function of concentration. Permittivity values for the solution were taken as $\varepsilon_r = 1$. The electric field in the electrolyte was calculated by $E = -\Delta V$, where E is the electric field and V is the applied voltage. The resulting current density (J) was calculated from the electrolyte conductivity (σ) and electric field: $J = \sigma E$. Finally, the workpiece recession rate was determined from the normal current density and Faraday's law of electrolysis.

$$\vec{v} = \alpha \cdot \frac{M}{p \cdot z \cdot F} \cdot \overrightarrow{J_n}$$

$\vec{v}$ is the velocity of the anode boundary layer, $\overrightarrow{J_n}$ is the normal current density distributed along the workpiece surface, α is the machining efficiency, ρ is material density, z and F are electrochemical constants, and M is the molar mass of the sample. The values used in this model are shown in Table 2 below.

	Name	Value
α	Current efficiency	1.0
p	Density	7.87 g/cm^3
z	Valence	3
F	Faradays constant	95600 C/mol
M	Molar mass	55.8 g/mol

Table 2: Values used in the COMSOL model

The cathode boundary layer was set to the user specified feed rate, in this case 0.1 mm/s, and the anode was set to recede at the rate of $\vec{v}$. An incremental mesh refinement was performed to identify the region of mesh convergence. Built-in adaptive meshing tools were used to address the deforming geometry of the workpiece surface.

5. Results

Figure 5 shows the solved current density distribution along the anode surface that was used to determine the boundary recession rate. This was solved for with the AC/DC and deformed geometry modules.

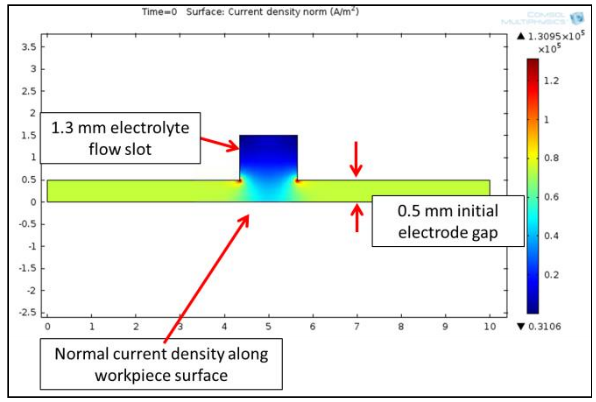

Figure 5: COMSOL 2D model current density distribution along anode

The theoretical ridge for the finest mesh after 1.0 mm of cutting can be seen in Figure 6 below.

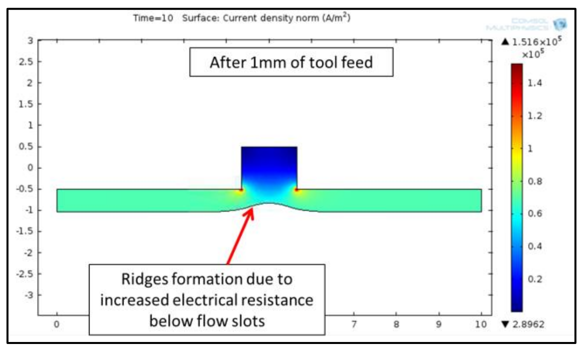

Figure 6: Final anode surface prediction after 10 minutes of machining (finest mesh)

The resulting ridge heights and widths for both the theoretical and experimental cases are shown in Table 3 below. Ridge heights and widths at various mesh densities are also shown.

	Number of Elements	Ridge Width (mm)	Ridge Height (mm)
Experimental	-	1.9	0.45
Mesh: Courser	41	2.0	0.15
Mesh: Normal	52	2.0	0.20
Mesh: Finer	166	2.2	0.20
Mesh: Ex. Fine	1725	2.2	0.20

Table 3: Ridge heights and widths for theoretical and experimental cases

6. Discussion

The theoretical ridge widths show good agreement (~10%) with the experimental results. Figure 7 shows a typical ridge that was seen on the workpiece after an ECM operation. Flow lines are also visible along the top surface where the electrolyte flow is diverging away from areas of higher pressure.

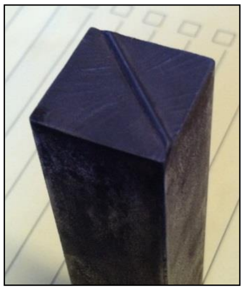

Figure 7: Ridges and flow lines seen post-ECM

However, the height of the ridges was under-predicted by the theoretical model. This could be caused by a variety of reasons, but electrolyte turbulence due to impingement on the ridge surface could cause a significant reduction in effective conductivity. This would in turn decrease the rate of machining along the top of the ridges. In other testing to investigate this discrepancy, high electrolyte turbulence was induced by increasing flow rates and decreasing gap size. Machining was noted to only occur directly underneath the flow slot, and poor surface finish and dimensional control was seen. An example of one of these tests is shown in Figure 8 below.

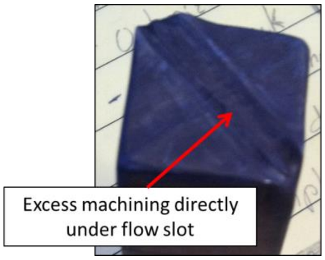

Figure 8: High flow rate (10 gpm) and low gap size (0.25 mm) causing unstable electrolyte flow

Care should be taken when designing flow slots as to eliminate as much electrolyte turbulence as possible. It has been recommended that a 5mm radius be added to the exit point of the tool flow slot to help; however, this will lead to increased ridge size on the final workpiece [4].

7. Conclusions

A COMSOL model was created to predict the ridges formed underneath electrode flow slots in electrochemical machining. Good agreement was seen between theoretical and experimental ridge widths; however, the model was shown to under predict ridge height. This model can be used to help predict estimates of residual flow ridges based solely on the geometry of the tooling. Future work should investigate the effect of turbulent fluid dynamics, concentration gradients, and gas generation on final ridge geometry.

8. References:

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