Abstract: The machining of materials on micrometer and sub-micrometer scale is considered the technology of the future. The current techniques for micro manufacturing mostly are silicon based. Micro electrochemical machining (µECM) removes material while holding micron tolerances and µECM can machine hard metals and alloys. This study aims at developing a novel µECM utilizing high frequency voltage ultrasonic vibration pulses and closed loop control. Stainless steel and copper alloy were chosen as the workpiece materials. A model was developed for material removal rate. Experimental setup was created of small drilled holes agreed with theoretical models within 10%. Micro burrs can be effectively removed by optimal Ultrasonic Vibration polishing in µECM. A sacrificial layer helped to improve the hole profile since it reduced 43% of corner rounding.

I. ELECTROLYSIS

Electrolysis is the chemical reaction that occurs when an electric current is passed between two conductors dipped in a liquid solution. The completeness of this electric circuit is found by attaching an ammeter to the system and ammeter displays a reading. A schematic design of an electrolytic cell utilizing copper sulphate as an electrolyte and copper wire as electrodes appears in Figure 1.

The chemical reactions are named cathodic reactions depending on where they happen at the cathode, respectively. The basic difference between electrolytes and metallic conductors of electricity are:
- Current is carried by electrons in metals
- Current is carried by ions in electrolytes.

Ions are atoms that have lost or gained electrons and they acquired a positive or negative charge. The positively charged ions travel towards the cathode and the negatively charged ions travel towards the anode. Thus the electrolyte must be neutral, there must be a balance between the total positive charge and the negative charge. At the completion of the reaction, the amount of material lost by one of the electrodes is equivalent to the amount of material gained by the other. Hence, this process can be used for both material removal and addition. The applications of electrochemical reaction is electrolysis are electroplating and electro-polishing.

II. ELECTROCHEMICAL MACHINING

Micro Electrochemical machining is a material removal process equal to electro polishing. In this process the work piece to be machined is made the cathode and the tool is made the anode of an electrolytic cell with a Nacl solution is used as an electrolyte. The tool is normally made of copper, brass, or stainless steel. The tool and the machined piece are placed so there is a gap between 0.1mm to 0.6mm between them (Rajurkar et al. 1999). The tool is designed so that it is the exact inverse of the feature to be machined. On connection a potential difference between the electrodes and subsequently when adequate potential difference energy is available between the tool and the machined piece, positive metal ions leave the machined piece. Since electrons are removed from the machined piece, oxidation reaction occurs at the anode which can be represented as

\[ M \rightarrow Mn^{n+} + ne^- \]

where n is the valence of the workpiece metal. The electrolyte accepts these electrons resulting in a reduction reaction which can be represented as,

\[ nH_2O + ne^- \rightarrow n/2H_2 + nOH^- \]

Hence the positive ions from the metal react with the negative ions in the electrolyte forming hydroxides and thus the metal is dissolved forming a precipitate. The electrolyte is constantly flushed in the gap between the tool and the workpiece to remove the unwanted machining products which otherwise would grow to create a short circuit between the electrodes. The electrolyte also carries away heat and hydrogen bubbles. The tool is advanced into the workpiece to aid in material removal (McGeough 2005).
schematic of a cell used for electrochemical machining is shown in Figure 2.

![Schematic of ECM](image)

Figure 2

Schematic of ECM

3. MODELING

The existing formulae for material removal rate are for electrochemical machining using direct current. A model was developed for the calculation of material removal rate while using pulsed current.

III. MODEL FOR MATERIAL REMOVAL RATE

The developed model gives the volume of material removed for each pulse of current. The model was derived under the assumption that material is removed only during the pulse ON duration and flow rate is adequate to flush away the reaction products. Equation (15) gives the volume of material removed for each pulse.

IV. CALCULATION OF ELECTROCHEMICAL CONSTANT

The formula for calculating electrochemical constant for single material elements was given in Equation (4).

\[ c = \frac{A_w}{ZF \rho} \]

where \( \rho \) is the density of the alloy, \( F \) is the Faraday’s constant, \( x_i \) is the percentage of \( i \)th element in the alloy, \( z_i \) is the valence of \( i \)th element in the alloy, \( A_i \) is the atomic weight of \( i \)th element in the alloy, and \( \rho_i \) is the density of the \( i \)th element in the alloy.

Calculation of Electrochemical Constant for CA-173:

The composition of CA-173 alloy is given in Table 2 (ASTM B196, 2007).

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>PERCENTAGE (%)</th>
<th>VALENCY</th>
<th>ATOMIC MASS (g/mol)</th>
<th>DENSITY (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper (Cu)</td>
<td>97.7</td>
<td>2</td>
<td>63.57</td>
<td>8.96</td>
</tr>
<tr>
<td>Beryllium (Be)</td>
<td>1.9</td>
<td>2</td>
<td>9.012</td>
<td>1,848</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>0.4</td>
<td>2</td>
<td>207.2</td>
<td>11.34</td>
</tr>
</tbody>
</table>

Table 2

Composition of CA-173 alloy (ASTM B196, 2007)

V. CALCULATION OF ELECTROLYTE RESISTIVITY

The electrolyte resistivity was measured in an indirect way. The conductance of the electrolyte was found using Thermo Orion micro electrodes conductivity probe. The conductance measured was 29.9 millisiemens. The conductivity was calculated using Equation (19).

Cell Conductance * Cell Constant = Conductivity

Equation (19)

The cell constant value was obtained from equipment manual to be 1 cm⁻¹. The conductivity obtained using Equation (19) is 0.0299/Ω-cm. The resistivity was measured as,

\[ \text{resistivity} = \frac{1}{\text{conductivity}} = 33.44 \Omega \]

VI. MODEL FOR DEBURRING

A model was developed which enabled to calculate the time and speed of electrode necessary to deburr a flat component. The burrs on the surface after micro electrochemical machining (µECM) were in the form of small hemispheres as shown in Figure 3.

![Distorted burr along edges of a machined piece after µECM](image)

Figure

Distorted burr along edges of a machined piece after µECM

Assumptions:

1. Workpiece continuous distorted burrs as half of sine wave.
2. Smoothing burr in work mode that is removing burrs just under the electrode.
3. Smoothing the burr one edge at a time.

Consider the case as shown in Figure (a) where burrs are modeled as an absolute sine wave of magnitude \( h \) and period \( P \). A top view of the burrs along the edge of the workpiece and position of the tool is shown in Figure (b).
VII. RESULTS AND DISCUSSION

ANALYSIS OF HOLES DRILLED IN COPPER

Figure shows some kind of layer formed on the surface of CA-173 after machining. It was suspected that this layer impeded machining and further tests were performed to obtain the composition of the layer.

Surface of CA-173 workpiece after µECM at 0.5 KHz and 16 VPP

Figure shows images of stainless steel electrode that was used to machine a holes in CA-173. There was a clear indication of deposition on the electrode. (a) shows the bottom of the electrode whereas (b) shows a side view of the electrode.

Stainless steel electrode after machining CA-173 workpiece at 0.5 KHz and 16 Vpp

Ultra sonic Vibration Polishing

RESULTS

µECM was successfully applied to deburr micro components. Figure shows the component with burrs along the edges.

Micro electronic component with burrs

Component Ultrasonic polishing with µECM at along edges 50 KHz, 16 Vpp and ø500 µm tool

Parameters for deburring calculated by model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pulses</td>
<td>684000</td>
</tr>
<tr>
<td>Speed (µm/s)</td>
<td>137</td>
</tr>
<tr>
<td>Time (s)</td>
<td>14.62</td>
</tr>
</tbody>
</table>

The plot obtained from EDS on a stainless steel electrode that was used to drill 8 holes in CA-173 is shown in Figure. The composition of each element and their source are tabulated in Table

Results of quantitative analysis on stainless steel electrode

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel (Ni)</td>
<td>41.04</td>
<td>Coating on electrode</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>19.07</td>
<td>Tool material</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>18.79</td>
<td>Workpiece material</td>
</tr>
<tr>
<td>Oxygen (O)</td>
<td>9.42</td>
<td>Oxidation</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>6.9</td>
<td>Electrolyte</td>
</tr>
</tbody>
</table>

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

A novel µECM with vibration polishing system was developed:

- Using high frequency pulses.
A model was developed for material removal rate using pulsed current.

The system was used to successfully form micro holes and for profile refinement.

Experimental data on small drilled holes agreed with theoretical data within 10%.

Micro burrs can be effectively removed by optimal µECM setup.

**RECOMMENDATIONS**

Future work includes using pulsed laser to enhance the process. It is assumed that the pulsed laser would enhance the rate at which the reaction products are flushed out of the machining zone resulting in a higher material removal rate. The pulsed laser would heat up the machining zone locally increasing the rate of anodic dissolution.

The model for material removal rate can include the effect of pulse OFF duration and flow rate to accurately predict the material removal rate.

**REFERENCES**


