Simulation study on performance characteristic of electrochemical micro machining process

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Abstract: In recent times, Electro Chemical Micro Machining (ECMM) has been gaining popularity due the advent of micro/nano electro mechanical systems (MEMS/NEMS) in medical and industrial fields. The process can be used to machine miniaturized components with negligible tool wear. ECMM is an advanced mechanical based micro machining process used to remove the material from the workpiece in the form of debris. The principle of material removal is due to ion displacement. The present work is focused on the development of ECMM setup model using CATIA and the material removal rate has analyzed using COMSOL Multiphysics in electro deposition method. The process parameters used for the simulation are voltage, current density, concentration and conductivity of electrolyte. It has been observed that by varying the voltage from 10 V - 30 V (each successive step by 5 V), the rate of material removed over the workpiece surface area was found to be enhanced from 0.00344 mm²/s - 0.01208 mm²/s.

Keywords. Electro Chemical Micro Machining, Electrolyte, Electrode tool, Simulation, Material removal.

1. Introduction

During the past few decades, due to the market demands for miniaturized features and intricate components with high surface quality characteristics and closed dimensional tolerances, industries are focusing on the advanced machining methods. Traditional machining methods are not suitable to achieve the same as they are unreachable to the required size of the machining tool, exhibit high setup cost, tool wear and involve more energy consumption with large unit removal of material. However, the quest for a chemical based advanced micro machining method has become considerably important to overcome the shortcomings of the traditional methods. ECMM method is one such method which can meet the above requirements and able to produce micro-features on various engineering materials used in potential applications. These micro-features include micro holes in nozzles, turbine blades, ink jet printers and micro channels in micro fluidics, nuclear reactors, etc. They can be achieved in an effective and economical way if the influence of ECMM parameters like voltage, current density, concentration and conductivity of electrolyte on the rate of material removal is properly studied through simulation prior experimentation. A critical appraisal of some of the research findings shows Leese and Ivanov [1] reviewed the application of ECMM process and the current development of the process with different machined material and process parameters. Wang et al [2] pointed out that the
current density distribution was influenced by concentration of electrolyte. They found that the machining efficiency was decreased with increase in electrolyte concentration. Ghoshal and Bhattacharyya [3] produced micro channels using ECMM process and they observed that with increase in concentration of electrolyte as the standard deviation of micro channel is decreased. Landolt et al [4] observed that with increase in current material removal rate (MRR) found to be increased. This is due to the more amount of energy reaching electrodes per unit time. Rajurkara et al. [5] experimentally studied the machining of steel, carbide and aluminium using titanium tool via ECMM process. They produced high aspect ratio micro-features by considering the input parameters like NaCl as electrolyte (15%) with water, voltage as 10-25V, current 20-200A and flow velocity 10-50m/s. These micro-features are suggested to be used particularly in bio medical field. Michael Kowalick et al. [6] observed that with increase in concentration over cut increased and this is attributed to the increase in current density. Matthias Hackert-Oschatzchen [7] suggested that at higher concentration the surface property of the machined material found to be increased. Loutrel [8] studied that at higher concentration (20 wt%), the temperature of the electrolyte increased. This results in the formation of enormous bubbles within the inter electrode gap and thus the electrodes get damaged. Bannard [9] observed that at higher current density the rate of material removal enhanced. Also, in ECM process where micro tools are involved, it is important to have an optimal design of the setup and realize the material removal characteristics of the process.

Based on the extensive literature review, it has been found that simulation of ECMM process through a structured simulation is very limited. Therefore, in the present paper, an ECMM setup has modeled using CATIA and the rate of material removal has analyzed using COMSOL Multiphysics. Electro Chemical Micro Machining (ECM) is one of the advanced machining processes where material removal takes place through electrolysis phenomena. It is best suited for materials which are difficult to be machined by mechanical machining process. Figure 1 shows the schematic diagram of ECMM setup.

![Figure 1. Schematic of ECMM setup](image)

In ECMM is the removal of material from the work piece by ion displacement. The tool and workpiece are close to each other with a very small gap between them by using servo motor. D.C voltage is applied between tool and workpiece and then electrolysis is pumped at high pressure. When electrolyte flows between the electrodes, positive charged ions move towards the tool (cathode) and negative charged ions move towards workpiece (Anode). As a result, electrochemical reaction takes place and thus material is removed from the workpiece.

2. Modeling and simulation of ECMM process

2.1. Introduction
The ECMM setup is designed and modeled using CATIA V5 as shown in figure 2, and analyzed using COMSOL Multiphysics. The model consists of tool, workpiece, lead screw, vertical axel, base, and other accessories.

![ECMM CATIA model](image)

**Figure 2.** ECMM CATIA model

The tool and workpiece modeling has carried out with COMSOL Multiphysics. In that model wizard, the 2D geometry is considered as deformed geometry and physics is electro deposition principle. The result of 2D geometry is shown in Figure 3. This geometry consists of 3 domains of electrolyte, tool and workpiece. The diameter of tool is 0.4 mm and length is 20 mm. The gap between tool and workpiece is 0.5 mm.

![ECMM 2D geometry](image)

**Figure 3.** ECMM 2D geometry
2.2. Meshing

The FEM mesh for ECMM simulation using COMSOL Multiphysics is shown in figure 4. The quality of mesh depends on geometrical model and accuracy of result. The FEM meshes were created using the automatic mesh creator and are used in the simulation for calculation of the local current density and the material dissolution. To generate this mesh, a user-defined mesh was chosen. The setting includes triangular mesh having minimum element size of 0.01 mm and maximum size of 0.005 mm. The complete mesh consists of 49260 domain elements and 2964 boundary elements.

1. Tool (Cathode):
   Tool top - Top face of the tool
   Tool bottom - Bottom face of the tool
   Tool inner - Inner side of the tool
2. Electrolyte:
   Velocity inlet - Inlet of electrolyte flow
   Pressure outlet - Electrolyte flowing out
   Brine inner
   Brine bottom
3. Workpiece (Anode):
   Work top - Top face surface of workpiece
   Work bottom - Bottom face surface of workpiece
   Work outer - Outer surfaces of workpiece

![Figure 4. FEM Mesh for ECMM simulation](image)

The simulation of ECMM was performed by using the mode of electric currents and deformed geometry. The material removal depends on time study during simulation. Stainless steel was chosen from the material library of COMSOL for the domain of the tool (cathode) and workpiece (anode) as aluminium. The boundary conditions of ECMM process according to figure 3 is provided in Table 1.
Table 1. Boundary conditions in the mode electric currents

| Boundary | Definition |
|----------|------------|
| 4,9      | $n \cdot j = 0$ |
| 5        | Continuity  |
| 6,11     | $n \cdot j = 0$ |
| 7        | Continuity  |
| 8        | 0V          |
| 2,3,10   | 20V         |
| 1,12     | $n \cdot j = 0$ |

The time-dependent simulation of the material removing was carried out by coupling the mode electric currents with deformed geometry. The functional principle of ECM is the anodic dissolution of metal due to the Faraday's law of electrolysis. The rate of material removal is proportional to the electrochemical equivalent of the material.

Assuming that all the current flowing through the electrolyte cell is used to describe the metal removal process (i.e. 100% current efficiency).

$$ V = \frac{M}{z \rho F} J \cdot \eta $$

Where, $M$ is the molar mass, $\rho$ the density, $z$ the electrochemical valence of the material, $F$ the Faraday constant, and $\eta$ is the current efficiency. The velocity of material removal in normal direction $v$ depends on the current density in normal direction $J$.

Table 2. ECMM Properties

| Symbol | Name                  | Value       |
|--------|-----------------------|-------------|
| $M$    | Molar mass            | 54.94 g/mol |
| $z$    | Valence               | 2           |
| $F$    | Faraday constant      | $9.65 \times 10^4$ C/mol |
| $\rho$ | Mass density          | 7.77 g/cm3  |
| $\eta$ | Current efficiency    | 100%        |

3. Results and discussion

In this section, the current density, shape of workpiece and material removal rate are discussed with the help of the model created using COMSOL Multiphysics.

3.1. Effect of current density

The current distribution of ECMM model is shown in figure 5. In the ECMM process, the current density distribution is of immense importance because MRR is purely dependant on the current density within the Inter electrode gap. Conservation of species $n$-1 species, $n$th through current and charge conservation (electro neutrality)

$$ \frac{\partial c_i}{\partial t} = -\nabla(-D_i \Delta c_i + c_i u - z_i m_i F c_i \nabla \phi_i) + R_i $$

For primary and secondary case
The Electro deposition Module: The Electrode position module is able to model arbitrary reaction mechanisms by using the transport of charged and neutral Species. In $D_i$ is the diffusivity, $c_i$ is the concentration, $u$ is the flow velocity, $z_i$ is the charge, $m_i$ is the mobility and $\Phi_l$ is the electric potential.

The flux is,

$$N_i = -D_i \Delta c_i + c_i u - z_i m_i F c_i \nabla \Phi_l$$

Conservation of Species, Current, and Charge

Current density

$$j = F \sum z_i N_i$$

$$j = F \left( \sum -z_i D_i \nabla c_i + u \sum z_i c_i - \nabla \Phi_l \sum (z_i)^2 m_i F c_i \right)$$

Electro neutrality, charge conservation sum of charges = 0

$$j = F \left( \sum -z_i D_i \nabla c_i - \nabla \Phi_l \sum (z_i)^2 m_i F c_i \right)$$

Perfectly mixed primary and secondary current distribution

$$j = - \left( F \sum (z_i)^2 m_i F c_i \right) \nabla \Phi_l$$

$k$ = conductivity
The current density ($J$) was set to 10 A/cm² as per the available technical literature.

### 3.2. Influence on material removal rate

In the domain of current density distribution the charge transport is involved. When the current flows through the working gap, these charge carriers move through the electrolyte towards the anode and due to reverse electroplating phenomena the dissolution of the workpiece occurs as shown in figure 6. The variation of material removal rate (MRR) with voltage is presented in Table 3. At the voltage varies from 10 V-30 V, the material removal rate increases from 0.00344 mm²/s to 0.01208 mm²/s figure 7.
Figure 6. Material removal rate at different voltage ad constant current: (a) Voltage varying from 0 to 10 V, (b) Voltage varying from 0 to 20 V, (c) Voltage varying from 0 to 25 V, (d) Voltage varying from 0 to 30 V

Table 3: Variation of MRR with voltage

| Voltage | RMS value | MRR(mm²/s) |
|---------|-----------|-------------|
| 10      | 0.0086    | 0.00344     |
| 15      | 0.0122    | 0.00488     |
| 20      | 0.0189    | 0.00756     |
| 25      | 0.0253    | 0.01012     |
| 30      | 0.0302    | 0.01208     |

The profile of the current density reflected in the simulated erosion geometry shows the initial geometry of the workpiece at time $t_0 = 0$ s and the machined contour after a processing time of $t_1 = 1$ s. It can be assumed that the material removal takes place over the area of the workpiece.
4. Conclusions
In this work an ECMM setup was modeled using CATIA and the material removal rate has analyzed using COMSOL Multiphysics. The process parameters like voltage, current density, concentration and conductivity of electrolyte are used for the simulation of the process. It has been observed that by varying the voltage from 10 V - 30 V (each successive step by 5 V), the rate of material removed over the workpiece surface area was found to be enhanced from 0.00344 mm$^2$/s - 0.01208 mm$^2$/s. The simulation study on the performance characteristic of ECMM process helps to select the optimal process parameters that can be exploited to study the performance characteristics of ECMM process experimentally. Accordingly the process can be cost-effective.

5. References

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Figure 7. Voltage vs MRR