MULTIPHYSICS SIMULATION AND EXPERIMENTAL VALIDATION OF ECM DRILLING PROCESS

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Abstract :

Electrochemical Drilling Process (ECD) provides the alternative to traditional or conventional drilling processes without a direct contact between the tool and the workpiece, with high material removal rates, irrespective of diverse mechanical properties of the workpiece. Even though ECD has a great potential, the process is still not fully explored and its research is in process. ECD involves number of phenomena such as electrochemistry, mass transfer, heat transfer and hydrodynamics. Due to this it is very difficult to predict the hole diameter accurately in ECD. This problem is considered for investigation by developing a Multiphysics simulation model for ECD and the effect of tool geometry on generated anode profile is studied to improve the dimensional control and performance of the Electrochemical Machining Process. For development of Multiphysics simulation model for the tool design in ECM hole making process, finite element analysis (FEA) software, COMSOL is used because of its capability to couple various phenomena in ECM process in a single model for better accuracy. The performance characteristics namely; overcut and height of spike generated is predicted by simulation and validated with the experimental results for the accuracy and capability. The predicted and experimental results agreed well and the developed innovative simulation model provides complete visualization and understanding of the ECD process.

IndexTerms - **Electrochemical Drilling, ECD Multiphysics simulation, current density distribution, metal removal rate, dimensional accuracy**

I. INTRODUCTION

Modeling and Simulation of Electrochemical Machining

Partial differential equations (PDEs) are generally used to express the physics laws in space dependent and time dependent problems. Analytical methods are not capable to solve these Partial differential equations in most of the problems. The Finite Element Method (FEM) is an alternative numerical technique where a continuum system is discretized into small elements. [1]–[12][13]

By using numerical model equations, these discretization methods approximate the PDEs, to solve them numerically. The solutions to these numerical model equations are, the approximations of the real solutions to the PDEs. To compute such approximations, the finite element method (FEM) is used. [14]–[22]

Computational simulation has now become necessary tool in engineering and technology. Simulation is transformation of physical and chemical laws of real-world into virtual form for the development, prediction and optimization of the process.

The basic purpose for using simulation model in ECM is to increase the understanding, applicability, accuracy and dimensional control with proper and accurate tool design and prediction of process outcome[1]–[6], [21], [22], [28], [29], [11]–[15].

Model Geometry and meshing:

The geometry used for ECM simulation model is shown in Figure 2. The figure describes the selected problem and helps for problem formulation and finalizing computational domain as shown in model geometry. The model is axisymmetric in nature so 2D geometric model is selected and 2D geometric model is prepared as shown in Figure 2. The tool is insulated with no bare tip length as shown with blue line in the model and remaining surface of tool is conductive. The insulated boundaries are shown by blue lines in the Figure 2. The IEG can be selected as per requirement in model geometry. All the computational domain boundaries are marked for applying boundary conditions.

The Physics controlled mesh in COMSOL has been chosen for meshing of the geometry and free triangular mesh elements are used for discretization. To capture large potential gradients and insight extremely fine element size mesh is applied in inter electrode gap where machining process is to be observed in detail while at the far away region from IEG coarse size mesh is applied.

Computational domain area changes with the changing inter electrode gap and tool shape used. The number of nodes varies accordingly. A mesh used is shown in Figure 3.
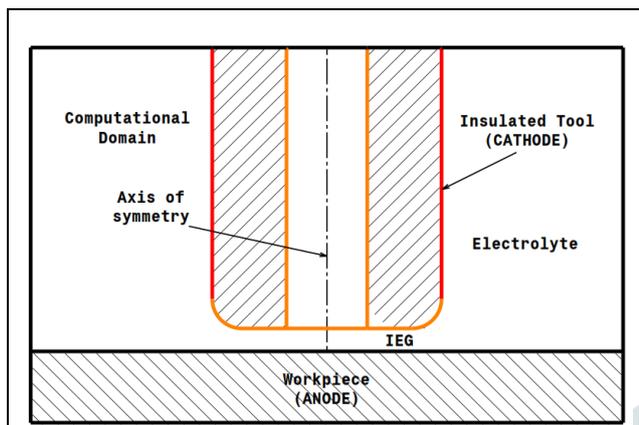

Figure 1. Problem Definition- Two dimensional Computational Domain –Tool, Workpiece and Electrolyte.
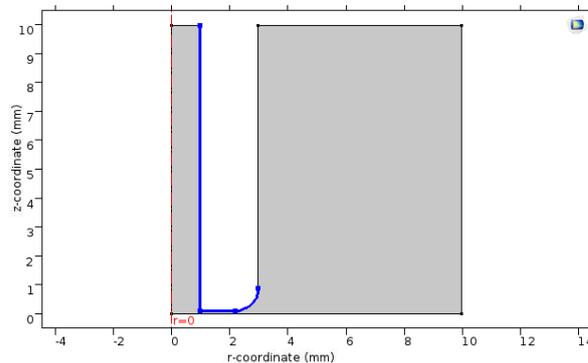

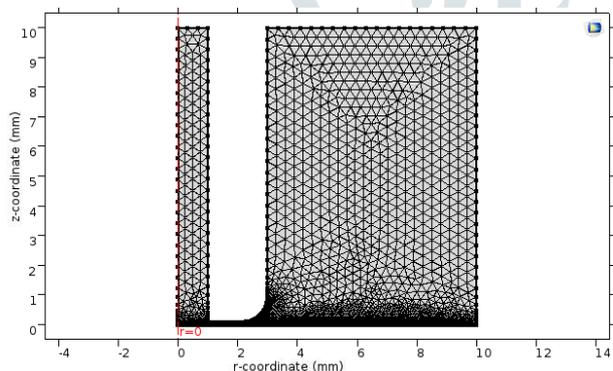Figure 2. Problem Definition-Model Geometry- 2D axisymmetric model

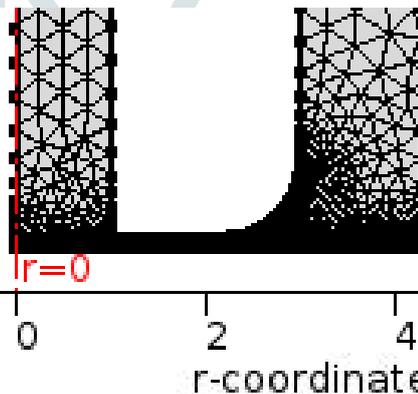Figure 3. Problem Definition-Meshing- Physics controlled mesh with free triangular elements.

Figure 4. Problem Definition-Meshing- Physics controlled extremely fine mesh in IEG.

Boundary conditions in the Simulation Model

As discussed earlier Laplace's equation gives the potential distribution in the inter electrode gap at any time in the computational domain.

$$\nabla^2 \phi = 0 \qquad\qquad\qquad 1$$

The current density i_l at any point in space in the domain is given by Ohm's law.

$$i_l = -\sigma_l \nabla \phi_l \qquad\qquad\qquad 2$$

The material dissolution rate v_{normal} at the anode is given by Faraday's law

$$v_{normal} = v_{eff} \frac{M}{\rho z F} i_l = (k) i_l \qquad\qquad 3$$

Boundary conditions used in simulation are given in the Table 1 which are used for solving charge conservation and moving boundary problem due to the constant dissolution of material from the anode workpiece. This boundary condition is also applicable at symmetry boundaries where the potential is known to be symmetric with respect to the boundary.[13]

The distance of the cathode tool conductive surface which is not insulated is not equal at each point from the anode workpiece as shown in model geometry (Figure 2). The effect of sludge formation and gas bubble formation is assumed insignificant as continuous fresh electrolyte is supplied.

The insulation is applied on the outer surface of cathode tool as shown in model geometry (Figure 2).

Table 1 Charge conservation boundary conditions

Boundary	Mathematical cond.	Boundary condition
Non Metallic side boundaries	$\dfrac{d\varphi}{dn} = 0$	Insulation
Cathode Tool insulated boundaries	$\dfrac{d\varphi}{dn} = 0$	Insulation
Tool conductive boundaries	$\varphi = 0$	Ground boundary condition, Tool (Cathode) surface
Workpiece conductive boundaries	$\varphi = V$	The electric-potential boundary condition, Workpiece (Anode) surface.

The fixed parameter values for the machining process are given below

Table 2 Parameters of the machining process

Parameter	Value
Applied Voltage	9 V
Inter electrode gap IEG	0.1 mm
Tool Feed Rate	0.5 mm/min
Electrolyte conductivity	7 S/m

Current density distribution, profile generation and spike height is analyzed through a set of numerical experimentation.

Simulation with Designed Tool:

Figure 5 shows surface plot of electric potential and current density stream lines at initial condition i.e. t = 0 s and it gives the potential at each and every point in the computation domain. It shows that it is not uniform in the domain. Electrolyte potential is affecting the current flowing through the electrolyte and the current density is shown by the stream lines. Denser stream lines indicates higher current density region in the domain.
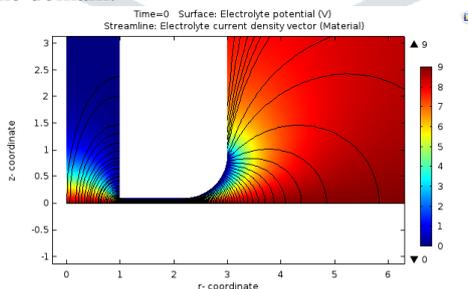

Figure 5. Surface plot of electric potential and current density stream lines at t=0 s.
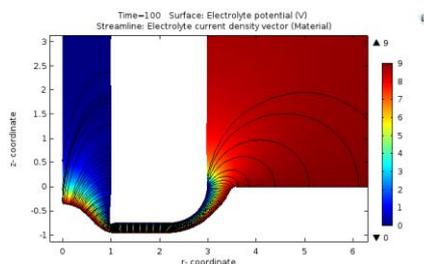
Figure 6. Surface plot of electric potential and current density stream lines at t=100 s.

Figure 6 shows surface plot of electric potential and current density stream lines at final condition i.e. t = 100 s and it gives the potential at each and every point in the computation domain. It shows that Electrolyte potential is affecting the current flowing through the electrolyte and the current density. It also shows that maximum material is removed from the region where the current density stream lines are maximum.
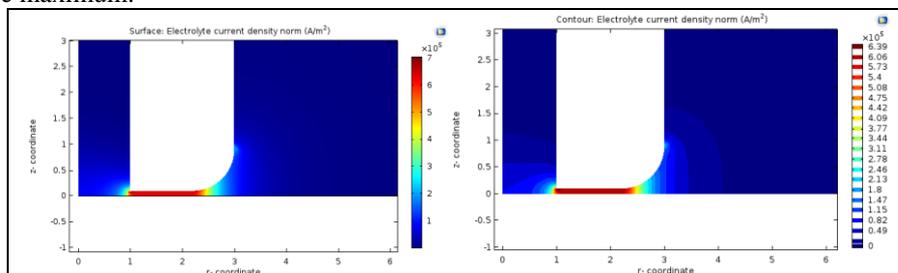

Figure 7. Surface plot and contour plot of current density at t=0 s.
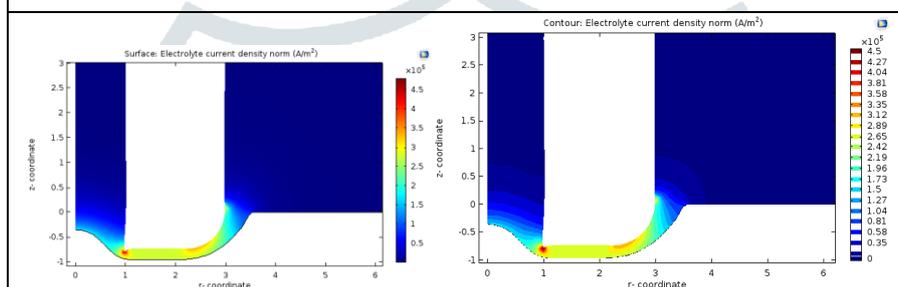

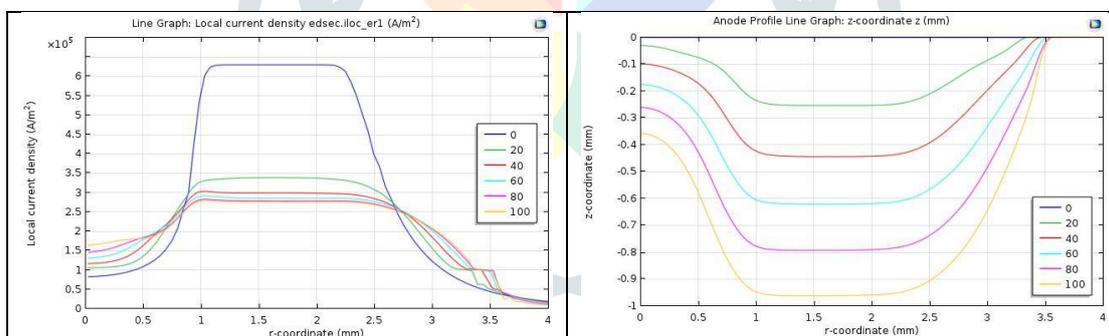*Figure 8. Surface plot and contour plot of current density at t=100 s.*

Figure 9. Anode local current density at t=0 s, 20 s, 40 s, 60 s, 80 s and 100 s.	*Figure 10. Anode Geometry deformation and profile generated at t=0 s, 20 s, 40 s, 60 s, 80 s and 100 s.*

In electrochemical machining profile generation can be predicted by analyzing the distribution of current density between the cathode tool and workpiece anode electrode. Figure 9 shows anode local current density at t=0 s, 20 s, 40 s, 60 s, 80 s and 100 s. and Figure 10 shows the corresponding anode profile which shows that material removal is directly proportional to current density. Figure 11 shows three dimensional anode profile generated and Figure 12 shows the cross section of generated hole for Square and Round TIP Tool.
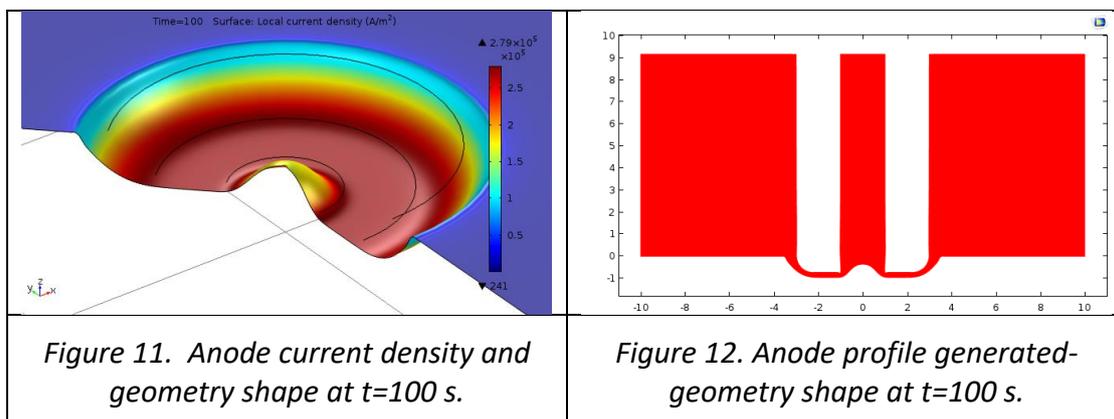
Figure 11. Anode current density and geometry shape at t=100 s.	*Figure 12. Anode profile generated-geometry shape at t=100 s.*

Figure 8 shows, current density Surface plot and contour plot at t=0. It was observed that the nature of current density is not uniform along the radial direction. The tool is insulated from outer surface so current density in side zone (Tool Radius more than 3mm) is minimum shown in blue color in outer zone. Current density is the maximum at the frontal zone.

The predicted results of the simulation run are reported in Table 3.

Table 3 Predicted results by Simulation for Tool at t=100s

Square and round TIP Tool	
Response	**Predicted hole contour**
Hole Diameter (mm)	7.108
Spike Height (mm)	0.589
Spike diameter at bottom surface (mm)	2.194

EXPERIMENTAL VALIDATION AND DISCUSSION

An essential and ultimate step in the development of a simulation model of the ECM process is the validation and implementation of the results in the real world. Even if much efforts are taken in model development to avoid the errors some variation is observed in results. As simulation model is translation of real machine to virtual machine with some assumptions and simplifications, prediction results are to be verified to ensure that they are reasonable or not. This can be verified mathematically in simple problems for some of the cases but if the problem is complex such as ECM, by comparing the predicted simulation results with experimental results. The experiments were conducted with the same parameters which were used as the input parameter in the simulation model, i.e. applied voltage, IEG, electrolyte conductivity, machining time and tool feed rate to validate the simulation model.

A series of experiments were performed on SS304 plate with 2 mm thickness by copper cylindrical hollow tools of outer diameter 6 mm and inner diameter 2 mm with similar shape as in simulation. Machining time experiment was 100s and fresh electrolyte with conductivity 7 S/m is pumped from a storage tank through cathode tool in inter electrode gap which acts as conducting medium between anode workpiece and cathode tool.

ECM setup used for experiments

Figure 13 shows experimental set-up fabricated for hole drilling by ECM. The different components of ECM includes a cathode tool feed mechanism, a work-piece and tool holder, an electrolyte feed system, and a power supply. The work piece acts as anode and the copper tool acts as cathode. The electrolyte is continuously discharged through the tubular copper tool between the workpiece and the tool. The workpiece is mounted on the work holder fixture. The cathode tool is mounted on a tool feed drive. The experiments have been conducted with sodium chloride solution with conductivity 7 S/m.
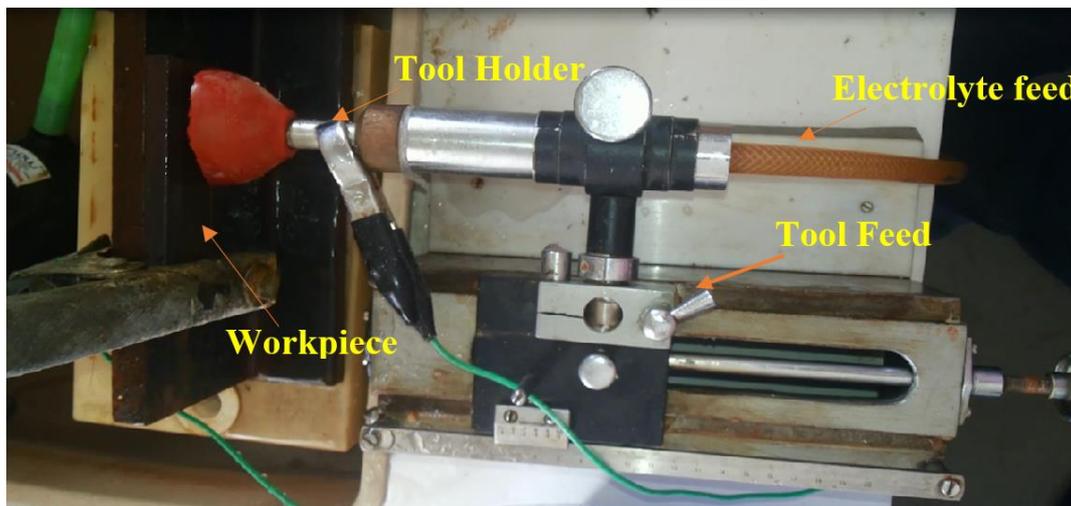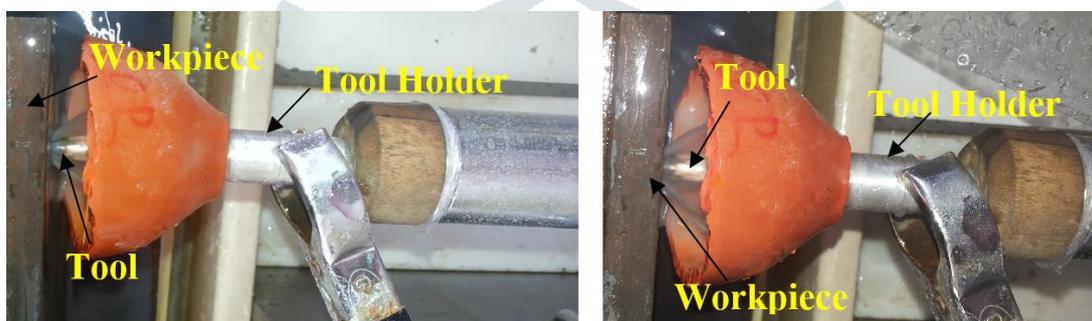
Figure 13. ECM setup

Figure 14. ECM Machining

Experimental Validation

In order to determine the accuracy of the simulation model, experimentally obtained hole contour results are compared with the hole contour results predicted by simulation model at same process parameter as discussed earlier. The parameters for comparison are given in the comparison Table 4.

Table 4 Quantitative analysis of Square and Round TIP Prediction Model

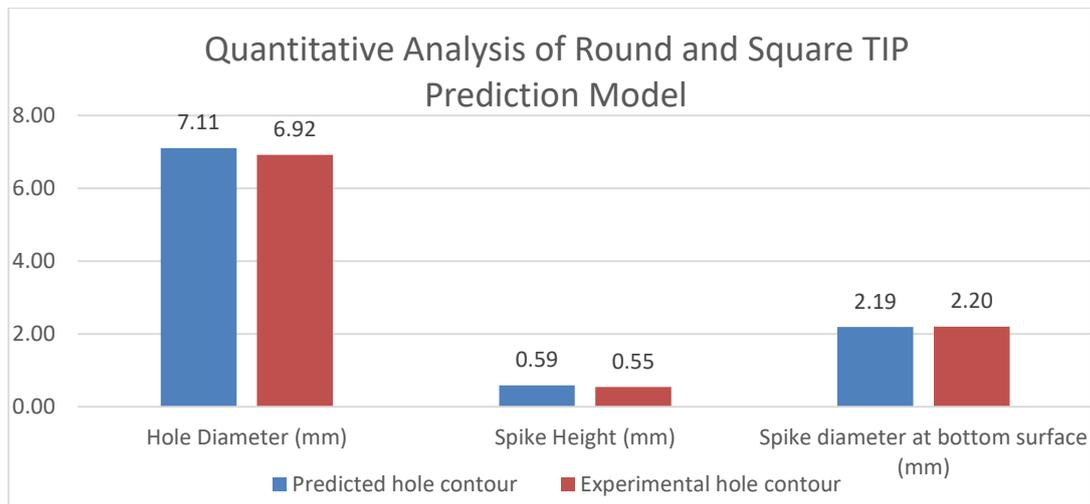| Round and Square Tip			
Parameters	Predicted hole Contour	Experimental hole contour	Percentage error with respect to experiment
Hole Diameter (mm)	7.108	6.917	-2.76
Spike Height (mm)	0.588	0.550	-6.80
Spike diameter at bottom surface (mm)	2.194	2.2	0.27

Figure 15. Quantitative analysis of Prediction Model

It is observed from the comparison Table 4 and comparison chart Figure 15 that the diameter of the predicted hole contour is almost same with the experimental result. The predicted value of spike height is also almost same with the experimental value. The variation in Spike diameter at bottom surface is very small. The reason for this variation may be the change in the electrolyte concentration and the gas generation which were not considered in the ECM simulation model.

The results show a good agreement between the simulation results and the experimental results.

CONCLUSIONS

❖ In this work a Multiphysics anode shape prediction simulation model is developed. The designed work piece profile and the profile of the work piece developed during experimentation agreed well.

❖ In the developed model electrodynamics and mesh displacement are used. It is observed that due to fresh electrolyte supply and the localization of the current density within it, ECM can be simulated and can be used to predict the profile generation and visualization of the process.

II. ACKNOWLEDGMENT

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