MULTIPHYSICS SIMULATION OF ECM FOR THE MACHINING OF AL-SIC COMPOSITES

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ABSTRACT
Al-SiC composite is one of the widely used MMC in various application. It has some specific properties like high thermal conductivity and high strength to weight ratio which tends to use it in some high-end applications like microelectronics, aerospace and, automobile, etc. Inspite of its exceptional properties, Al-SiC is also one of the difficult composites to machine. So machining of Al-SiC composite with a conventional process would face challenges. Unconventional process like electrochemical machining process offers a better alternative in generating accurate complex geometries in difficult to machine material. By varying the parameters of ECM process the material removal of Al-SiC can be varied. Further, the material removal from ECM process is also influenced by the composition of Al-SiC. In this paper, multiphysics models have been developed in COMSOL to characterize the Electrochemical process to study the material removal of Al-SiC. The parametric study is also performed to study the influence of machining parameters on material removal. This work can provide details on the ECM process for the machining of Al-SiC.

KEYWORDS
Electrochemical machining, Validation, Metal matrix composites, Microbores, Material removal rate, COMSOL

1. INTRODUCTION

Aluminium reinforced SiC has excellent thermo-physical properties such as high thermal conductivity, low coefficient of thermal expansion and enhanced mechanical properties i.e. better wear resistance, high specific strength and improved specific modulus[1]. Because of these properties, Al-SiChas many potential applications like Packaging power devices[1], Aerospace industry[2], Automobile industry[3] and, Semiconductor equipment[4]. Although Al-SiC has many potential applications, the conventional machining of this composite has a lot of problems. For machining Al-SiC, high cutting speeds are employed which inturn causes tool wear[5]. To eliminate such problems unconventional machining process like Electrochemical machining is used. Nature of the ECM process is a non-contact type which eliminates the problem of tool wear. The electrochemical machining process is an unconventional machining process. Faraday in 1833 has invented the principles of this process. The first controlled ECM is patented by Gussef in the year 1929[6, 7]. The material removal in this process is by the mechanism of anodic dissolution with high current density[8]. The process is carried out by passing current through the electrolyte which is flowing through the inter-electrode gap. The process parameters are voltage (10-25 Volts), electrolyte flow velocity (10-60 m/s), inter-electrode gap (0.01-0.6 mm)[9]. The theoretical material removal rate is given by Faraday's law:

$$\frac{\Delta m}{\Delta t} = \frac{M.I}{z.F} \quad (1)$$

Where $\frac{\Delta m}{\Delta t}$ is the material removal rate, M is the atomic weight, I is the current, z is the valency of the dissolved metal and F is the Faraday constant. The electrolytes used are dilutes acids or aqan ueous solution of salts[10].Figure 1 shows the flow chart of ECM Process.

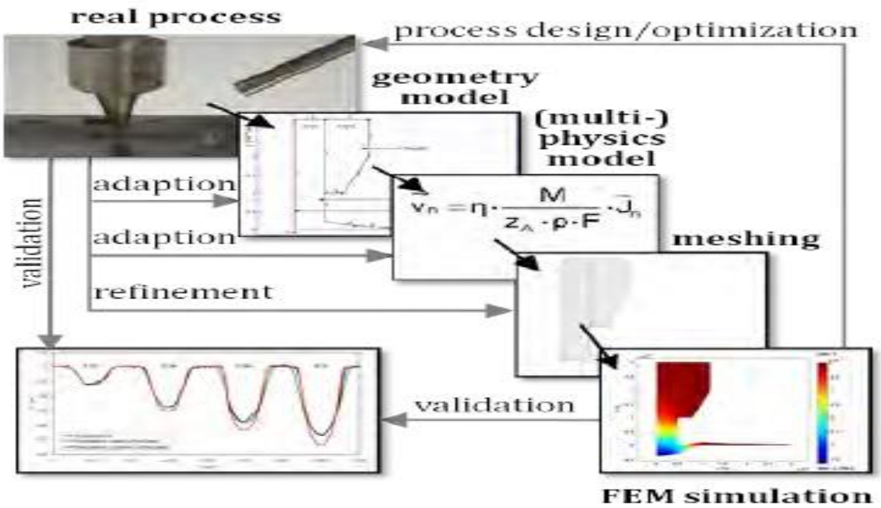


Figure 1. Flow chart for FEM simulation of ECM process[5]

The new research and development process in ECM has found out PECM (Pulse Electrochemical Machining) which uses pulse power instead of DC current. It is better in micromachining than ECM due to its improved electrolyte flow condition. In the past, it has been found that hollow cathode and pulse voltages help in effective control of heat generated and for effective design and better accuracy of tool design, a stable gap state, and smaller gap is required between the tool and work-piece[8].In this study, Al-SiC composite is used for ECM machining by varying different parameters to find there influence on MRR using COMSOL software for simulation.

2. FINITE ELEMENTAL MODELLING

2.1.Geometry

The geometry of the model consists of the workpiece(anode), insulation and tool(cathode) as shown in Figure 2.Because of high metal conductivities and small potential gradients of the electrodes the electrode domains are not included in the model. As the insulating layer is electrochemically inert, and hence it is not included either. The electrolyte is the only modelled geometry in the simulation. The symmetrical geometry consists of four domains and those are an electrolyte, workpiece, cathode, and insulation. The geometrical dimensions for modelling in COMSOL are shown in Figure 2.

2.2.Al-SiC

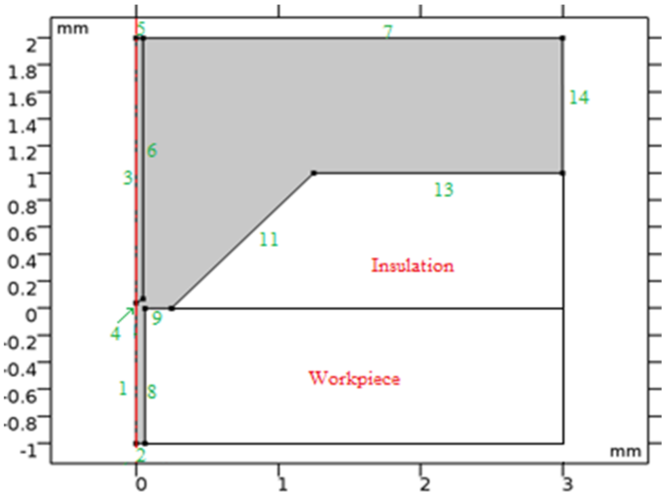
Four Multiphysics models were developed for four different studies as shown in Table 1. The material properties used are given in Table2. In the first study, three different compositions of Al-SiC were taken and the properties were found out using the rule of mixture given in Table 3. In other studies, the middle composition was taken. Using the rule of mixture the physical properties of the materials have been found[11].

Applying Rule of mixture for the first composite {Al(95%)+SiC(5%)}:

- Molar mass(M)=0.95×26.98+0.05×40.11=27.638g/mol (2)
- Molar density(ρ)=0.95×2.7+0.05×3.21=2.73g/cm^3 (3)

- No of participating electrons=0.95×3+0.05×6.5=3.175 (4)

The same procedure is followed to find the physical properties of other composites. The physical properties of the three different compositions considered in the studies are mentioned in Table 3.



Insulation radius	0.25mm
Insulation thickness	1mm
Cathode radius	50μm
Cathode tip length	40μm
Borehole radius	64μm

Figure 2.ECM geometry 2D axial-symmetric

Table 1: Different parametric studies performed

	Input Parameters		**Output parameters**		
	Variable	**Constant**	**MR at each second**		
Study 1	Composition	Voltage, Electrolyte conductivity, Interelectrode gap	MR_1	MR_2	MR_3
Study 2	Voltage	Composition, Electrolyte conductivity, Interelectrode gap	MR_1	MR_2	MR_3
Study 3	Interelectrode gap	Composition, Electrolyte conductivity, Voltage	MR_1	MR_2	MR_3
Study 4	Electrolyte conductivity	Voltage, Composition, Interelectrode gap	MR_1	MR_2	MR_3

Table 2: Material properties

Properties	**Al**	**SiC**
Molar mass(g/mol)	26.982	40.110
Molar density(g/cm^3)	2.70	3.21
No of participating electrons	3	6.5

Table 3: Physical properties of the composition

Composition(%)		**Molar mass(g/mol)**	**Molar density(g/cm^3)**	**No of participating electrons**
Al	**SiC**			
95	5	27.638	2.730	3.175
90	10	28.294	2.751	3.350
85	15	28.951	2.777	3.525

2.3.Physics

The simulation of material removal was done in COMSOL Multiphysics by coupling the primary current distribution and deformed geometry. A time-dependent analysis was taken into account for the material removal. The electrolyte conductivity(sigma σ) and molar mass(M), molar density(ρ), no of participating electrons(z) of the workpiece were given in the parameter section by assigning corresponding variables. These variables were called wherever they were required during the simulation. The boundary conditions considered for the simulation of the model shown in Figure 2has been tabulated in table 4.

Table 4: Boundary conditions arrested in the model

Boundary	Definition
1	Axisymmetry
2	$\vec{n}.\vec{j} = 0$
3	Axisymmetry
4	Continuity
5	$U_0 = 0$ V
6	Continuity
7	$\vec{n}.\vec{j} = 0$
8,9	$U_0 = 20$ V
11-14	$\vec{n}.\vec{j} = 0$

From Faradays law, the relation between the volume of material removed and charge Q is given by[12]

$$V = \eta.\frac{M}{\rho.z.F}.Q \quad (5)$$

Where η is the current efficiency, M is the molar mass, ρ is the mass denisity, z is the no of participating electrons and, F is the Faradays constant. The material removal also depends on velocity vector in the normal direction $\overrightarrow{v_n}$ and the current density vector in the normal direction $\overrightarrow{J_n}$. The relation is given by[13]

$$\overrightarrow{v_n} = \frac{M}{\rho.z.F}.\overrightarrow{J_n}.\eta(J) \quad (6)$$

By implementing a condition for material removal

$$\eta(J) = \begin{cases} 1 \text{ for J} > Jmin \\ 0 \text{ for J} \leq \text{Jmin} \end{cases} \quad (7)$$

From literature, J_{min} is considered to be 10(A/cm^2) for optimum machining[14].

2.4.Meshing

Meshing is usually critical in the finite elements especially when diffusion at edges is involved is shown in Figure 3. For lower computation times and accurate results, the effect of mesh refinements on electrode edges has been taken into account. The meshing is done using triangular element type, a total number of elements is 5393. The above-mentioned element type supports re-meshing criteria.

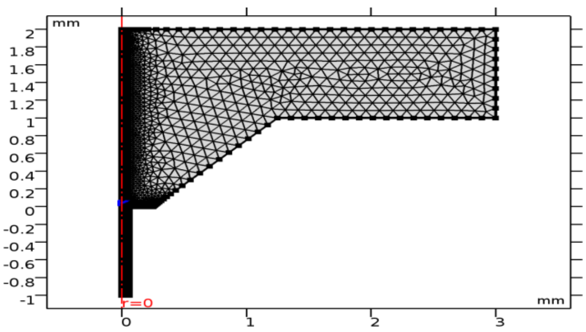


Figure 3. Mesh for simulation

3. RESULTS AND DISCUSSION

The four different studies have been performed using COMSOL simulation for 3seconds with a step size of 1second to find material removal.

3.1.Study 1: Effect of Composition

In this study, three different compositions of Al-SiC have been varied by maintaining constant Voltage, Electrolyte conductivity and, Interelectrode gap to get material removal at each second of the simulation as shown in Table 5. The electrolyte used in this study is $NaNO_3$.

Table 5: Input parameters used in the study1

Composition(%)		Voltage(V)	Electrolyte conductivity (S/m)	Interelectrode gap(mm)
Al	SiC			
95	5	14	7	0.04
90	10	14	7	0.04
85	15	14	7	0.04

For the input parameters shown in Table 5, the material removal values at each second for three compositions were found and a plot between MR and Time for each composite is shown in Figure 5a. It is observed that the MR is varying linearly in every composite and further the MR decreases with an increase in the composition of SiC.

3.2.Study 2: Effect of Voltage

In this study, three different voltages have been varied by maintaining constant composition, electrolyte conductivity and the interelectrode gap to get material removal at each second of the simulation as shown in Table 6. The electrolyte used in this study is $NaNO_3$.

Table 6: Input parameters used in the study2

Composition(%)		Voltage(V)	Electrolyte conductivity (S/m)	Interelectrode gap(mm)
Al	SiC			
90	10	12	7	0.04
90	10	14	7	0.04
90	10	16	7	0.04

For the input parameters shown in Table 6, the material removal values at each second for three different voltages were found and a plot between MR and Time for each voltage is shown in Figure 5b. It is observed that the MR is varying linearly for every voltage and MR increases with increase in the voltage.

3.3.Study 3: Effect of Interelectrode gap

In this study, three different Interelectrode gaps have been varied by maintaining constant composition, electrolyte conductivity and, the voltage to get material removal at each second of the simulation as shown in Table 7. The electrolyte used in this study is $NaNO_3$.

Table 7: Input parameters used in the study3

Composition(%)		Voltage(V)	Electrolyte conductivity (S/m)	Interelectrode gap(mm)
Al	SiC			
90	10	14	7	0.06
90	10	14	7	0.04
90	10	14	7	0.02

For the input parameters shown in Table 7, the material removal values at each second for three interelectrode gaps were found and a plot between MR and Time for each interelectrode gap has been drawn as shown in Figure 5c. It is observed that the MR is varying linearly in each plot and MR decreases with increase in the interelectrode gap.

3.4.Study 4: Effect of Electrolyte

In this study, three different electrolytes with their corresponding electrolyte conductivities have been varied by maintaining constant composition, Interelectrode gap and, Voltage to get material removal at 3 seconds of the simulation as shown in Table 8.

Table 8: Input parameters used in the study4

Composition(%)		Voltage(V)	Electrolyte		Interelectrode gap(mm)
Al	SiC		Chemical name	conductivity (S/m)	
90	10	14	Sea Water	5	0.04
90	10	14	HCl	1.1	0.04
90	10	14	$NaNO_3$	7	0.04

Here in this analysis, the simulation time is increased to 3 seconds as there is no appreciable amount of material removal at 1 second.

For the input parameters shown in Table 8, the material removal values at 3 seconds for three electrolytes were found and a plot between MR and Time for each electrolyte has been drawn as shown in Figure 5d. It is observed that the MR is varying linearly in each plot and MR decreases with decrease in electrolytic conductivity.

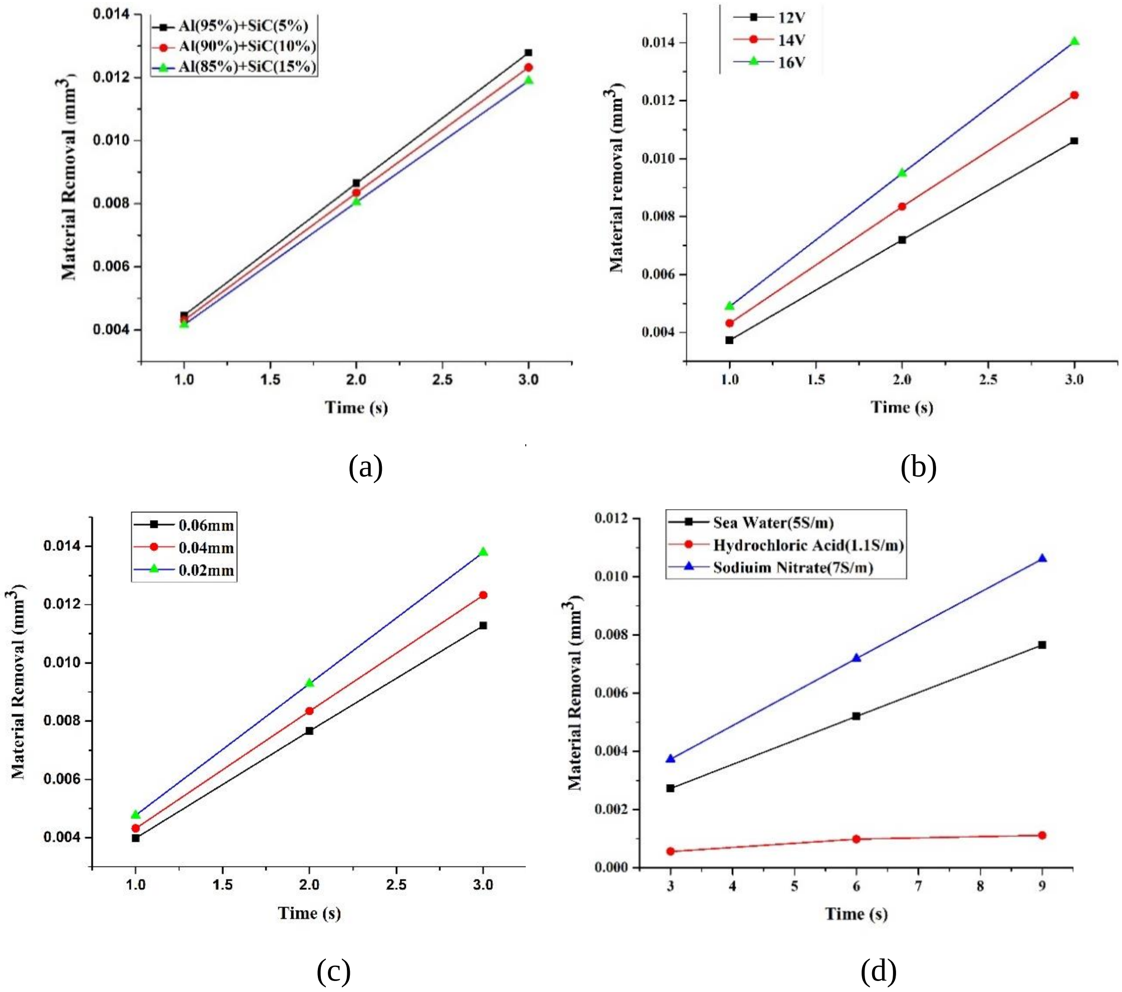


Figure 5.Showing the variation of Material removal for different (a) compositions, (b) voltages, (c) interelectrode gap and (d) electrolytes.

4. CONCLUSION

These studies give detailed information about how the material removal varies with different input parameters and time. First three studies have shown that the material removal in each second of the machining has almost the same value. The fourth study shows completely different values in comparison with the other three. This variation is because of the variable parameter "electrolyte conductivity" used different electrolytes for the simulation. Hence it can be concluded that electrolyte conductivity has more impact on material removal. This work can be further extended to optimize the process parameters for multi responses.

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