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MODELING THE MACHINING PARAMETERS FOR ELECTRO CHEMICAL MACHINING OF ALUMINIUM COMPOSITES USING RSM

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ABSTRACT

Electro Chemical Machining (ECM) allowed success in the production of newer materials, especially for the aerospace and biomedical applications. Using ECM technology, complicated cuts can be made through difficult – to – machine hard materials. This paper highlights the development of mathematical models for correlating the interactive and higher order influences of various machining parameters on the dominant the machining criteria, i.e., the material removal rate and the surface roughness through response surface methodology (RSM), utilizing relevant experimental data as obtained through experimentation. Validity and correctiveness of the developed mathematical models have also been tested through Analysis of Variance (ANOVA). The present work also highlights the development of mathematical models for analyzing the effect of various process parameters such as, current, voltage, flow rate and gap width on the material removal rate and surface roughness.

Keywords: Electro Chemical Machining (ECM), Material Removal Rate (MRR), Surface Roughness (R_a), ANOVA, Response Surface Methodology (RSM).

1. INTRODUCTION

Non-conventional machining processes, e.g. ECM, Electro-Discharge Machining (EDM), Laser Beam Machining (LBM), and Ultrasonic Machining (USM) etc. have already been utilized for machining. EDM and LBM are thermal processes; therefore they cause the formation of heat-affected zones and micro-cracks on the workpiece. ECM machining techniques however do not produce thermal or mechanical stresses on the workpiece material and they have versatility that they can machine any kind of material. They have also additional advantage, such as they leave no heat-affected layer and produce no tool wear. The machining performance in ECM is governed by the anodic behavior of the workpiece material in a given electrolyte. Hence ECM on the other hand appears to be very promising technique since in many areas of application it offers several advantages that include higher machining rate, better precision and controlled material removal, and also wide range of materials that can be machined.

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In ECM, it is important to select machining parameters for achieving machining performance. Usually the desired machining parameters are determined based on experience or hand book values. However this does not ensure that the selected machining parameters result in optimal or near optimal machining performance for that Electro-Chemical Machine and environment. Detailed analysis of cutting involves certain costs, particularly in case of small series. In case of individual machining it is particularly necessary to shorten as much as possible the procedure of determination of the optimal cutting parameters, otherwise the cost analysis might exceed the economic efficiency which could be reached if working with optimum conditions.

H. Hocheng et al., [1] have proposed a method to predict the machine profile of the work. They have developed the machine profile as a function of time and the changing of gap opening. B. Bhattacharyya et al., [2] have investigated the influence of tool vibration on machine performance such as Metal Removal Rate and accuracy in Electro Chemical Micro-Machining (ECMM) of copper. Some authors have worked on Electro Chemical Discharge Machining (ECDM) [3 - 5]. They have concentrated on the improvement of machine performance. Jagannath Munda et al., [6] have investigated the ECMM through response surface methodology approach. They have taken MRR and radial over cut as objective measures and developed mathematical model. Both objectives were dealt separately and analyzed with reference to machining. SK Sorkhel [7] investigated into the influence of ECM process parameters on machining performance criteria through the development of mathematical models based on response surface methodology (RSM) utilizing the relevant experimental data as obtained through experimentation. S.J. Ebeid et al., [8] have developed mathematical models for correlating the inter relationships of various machining parameters such as voltage, feed rate, back pressure and vibration amplitude on over cut and conicity for achieving high controlled accuracy.

The present work is also highlights the development of mathematical models for correlating the inter relationships of various ECM machining parameters of Aluminium composite materials such as Current, Voltage, Flow rate and Gap width on material removal rate and surface roughness. The work has been established based on the response surface methodology. Mathematical models fitted to the experimental data will contribute towards the selection of the optimum process conditions.

2. EXPERIMENTAL PROCEDURE

The experimental set up is shown in Fg.1. The set up consists of three major sub systems:

1. Machining cell
2. Control Panel
3. Electrolyte Circulation

2.1. Machining Cell

The electro-mechanical assembly is a sturdy structure, associated with precision machined components, servo motorized vertical up/down movement of tool, an electrolyte dispensing arrangement. Illuminated machining chamber with see through window, job fixing vice, job table lifting mechanism and sturdy stand. All the exposed

Figure 1 *Experimental setup of ECM machine*

Components, parts have undergone proper material selection and coating/ plating for corrosion protection.

- Tool area – 300 mm^2
- Cross head stroke -150 mm
- Job holder – 100 mm opening × 50 mm depth ×100 mm width
- Tool feed motor – DC Servo type

2.2. Control Panel

The power supply is a perfect integration of, high current electrical, power electronics and precision programmable micro controller based technologies. Since the machine operates at very low voltage, there are no chances of any electrical shocks during operation.

2.3. Electrolyte Circulation

The electrolyte is pumped from a tank, lined by corrosion resistant coating with the help of corrosion resistant pump and is fed to the job. Reservoir provides separate settling and siphoning compartments. All fittings are of corrosion resistant material.

2.4 Materials and process

The indigenous ECM experimental set has been used to analyze the influence of predominant machining parameters, i.e. current, machining voltage, electrolyte flow rate, and gap during ECM operation on the desired machining performance characteristic, i.e material removal rate and surface roughness. The experiment was conducted in “METATECH” Electro Chemical Machine having an operating current of range 0-300 amps, power supply of 415 V AC, 50 Hz and tool feed range of 0.2 - 2 mm/min.

The work material was Aluminum–Silicon carbide composites (LM25 Al/10%SiC) in the form of round bars with 30 mm diameter and 6mm thickness. The hardness of the work material was 55 HRB. Chemical composition of work material is given in Table 1. The tool material used was Copper and the electrolyte was fresh Sodium Chloride solution. Aluminum-Silicon carbide composite is used in aerospace industries.

2.4.1 Machining Processes

The job to be machined is fixed in the vice, in the machining chamber is corrosion resistant, and having window to see machining operation. Tool is brought near the job with the help of press buttons provided on the control panel and table lifting arrangement, maintaining particular gap. The tool progress is moved vertically by servo motor and is governed by micro controller based programmable drive. In ECM generally tool which is cathode, is made out of non reacting material such as copper. The process parameters are set like current, voltage, flow rate and gap. The process is started in the presence of an electrolyte flow that is circulated with the help of special pump filling the gap between anode (job) and cathode (tool). Electrolyte flow is adjusted by flow control valve. The machining is achieved by sinking of tool forming its replica. During the operation sophisticated control panel takes care of any damage to the machine by over load and short circuit protections. After desired time interval hooter gives an indication of completion of the time/ process. The small machining area with given power supply to be machined within 30 mins to one hour.

Table 1 *Chemical composition of LM25 Al/10%SiC*

Elements	% Composition
Mg	(0.2-0.45)
Si	(6.6-7.5)
Cu	0.2
Mn	0.1
Fe	0.2
Zn	0.1
Ti	0.2
SiC	10
Al	Remaining

3. DESIGN OF EXPERIMENTS

ECM removes material from a work piece by a chemical erosion process. Common methods of evaluating machining performance in the ECM operation are based on the following performance characteristics: MRR and Ra are correlated with machining parameters such as current, voltage, flow rate and gap setting. Proper selection of the machining parameters can result in higher material removal rate and surface finish. The second order Central Composite Rota table design [9] has been used in this work.

3.1 Response Surface Modeling

Response surface modeling is a procedure for determining the relationship between the machining parameters and responses and exploring these responses. A second order polynomial response surface model has been developed to correlate MRR and the machining parameters. Similarly the model has been developed to correlate surface roughness also. Based on the models developed, analysis has been carried out to investigate the interactions effects and the individual effects. Analysis of Variance (ANOVA) has been done to find out the significance of parameters on the responses.

3.2 Experimental plan

In this study, four operating factors were chosen as independent variables, namely, current (A), voltage (B), flow rate (C), gap setting (D), on the responses viz. Material removal rate and surface roughness. Different settings of current, voltage, flow rate and gap used in the experiments are summarized in Table 2. The experiments were performed according to the Central Composite Rotatable Design (CCRD) matrix given in Table 3. This design is composed of 2^4 factorial designs (runs 1 - 16; see Table 3), eight-star points (17–24) and 7 replicates runs (25 – 31).

Table 2 Original values of machining parameters

Parameters	**Symbols**	**Levels**				
		-2	**-1**	**0**	**1**	**2**
Current (A)	A	200	220	240	260	280
Voltage (V)	B	20	24	28	32	36
Flow rate (lit/min)	C	5	6	7	8	9
Gap (mm)	D	0.1	0.2	0.3	0.4	0.5

Table 3 Experimental design and the results of MRR and Surface roughness

S.No.	Current (A)	Voltage (V)	Flow rate (lpm)	Gap (mm)	MRR (gm/min)	Ra (µm)
1	220	24	6	0.2	0.335	7.89
2	260	24	6	0.2	0.343	6.82
3	220	32	6	0.2	0.361	6.78
4	260	32	6	0.2	0.368	5.98
5	220	24	8	0.2	0.382	6.89
6	260	24	8	0.2	0.388	6.75
7	220	32	8	0.2	0.385	6.82
8	260	32	8	0.2	0.413	6.89
9	220	24	6	0.4	0.312	6.68
10	260	24	6	0.4	0.322	6.39
11	220	32	6	0.4	0.338	6.36
12	260	32	6	0.4	0.345	6.21
13	220	24	8	0.4	0.358	6.23
14	260	24	8	0.4	0.363	6.35
15	220	32	8	0.4	0.382	6.49
16	260	32	8	0.4	0.391	6.34
17	200	28	7	0.3	0.311	7.98
18	280	28	7	0.3	0.344	6.06
19	240	20	7	0.3	0.363	7.42
20	240	36	7	0.3	0.382	6.24
21	240	28	5	0.3	0.312	6.98
22	240	28	9	0.3	0.421	7.98
23	240	28	7	0.1	0.352	7.15
24	240	28	7	0.5	0.361	5.21
25	240	28	7	0.3	0.395	6.02
26	240	28	7	0.3	0.392	6.12
27	240	28	7	0.3	0.398	6.03
28	240	28	7	0.3	0.395	6.48
29	240	28	7	0.3	0.389	6.14
30	240	28	7	0.3	0.388	6.11
31	240	28	7	0.3	0.388	6.10

4. RESULTS & DISCUSSION

Response surface methodology approach is the procedure for determining the relationship between various process parameters with the various machining criteria and exploring the effect of these process parameters on the coupled responses. In order to study the effect of ECM process parameters of Aluminium composite material on the volumetric metal removal rate and surface roughness, a second-order polynomial response can be fitted into the following equation of

$$\mathbf{Y_u} = \mathbf{b_0} + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_i X_i^{2} + \sum_{j=1}^{k} b_i X_i \mathbf{X_j}$$

where Y_u is the response, e.g. MRR and Ra of the ECM process in the present research. Using the results presented in Table 3, the form of the derived model as follows;

Table 4 *ANOVA Table for MRR*

Source Value	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-Prob>1**	**Observation**
Model	**0.022**	**14**	**1.59E-03**	**30.85**	**< 0.0001**	**significant**
A-current	*7.48E-04*	*1*	*7.48E-04*	*14.54*	*0.0017*	
B-Gap Voltage	*1.12E-03*	*1*	*1.12E-03*	*21.79*	*0.0003*	
C-Flow rate	*9.13E-03*	*1*	*9.13E-03*	*177.41*	*< 0.0001*	
D-Gap setting	*1.29E-03*	*1*	*1.29E-03*	*25.09*	*0.0002*	
AB	*1.56E-04*	*1*	*1.56E-04*	*3.04*	*0.1018*	
AC	*2.50E-07*	*1*	*2.50E-07*	*4.86E-03*	*0.9453*	
AD	*2.25E-06*	*1*	*2.25E-06*	*0.044*	*0.8371*	
BC	*4.00E-06*	*1*	*4.00E-06*	*0.078*	*0.7842*	
BD	*3.61E-04*	*1*	*3.61E-04*	*7.02*	*0.0182*	
CD	*4.90E-05*	*1*	*4.90E-05*	*0.95*	*0.3445*	
A^2	*6.88E-03*	*1*	*6.88E-03*	*133.68*	*< 0.0001*	
B^2	*5.76E-04*	*1*	*5.76E-04*	*11.2*	*0.0044*	
C^2	*4.88E-05*	*1*	*4.88E-05*	*0.95*	*0.3457*	
D^2	*3.52E-03*	*1*	*3.52E-03*	*68.49*	*< 0.0001*	
Residual	7.72E-04	15	5.14E-05			
Lack of Fit	***6.97E-04***	***10***	***6.97E-05***	***4.66***	***0.0517***	***not significant***
Pure Error	*7.48E-05*	*5*	*1.50E-05*			
Corrected Sum of Squares Total	0.023	29				

The Model F-value of 30.85 implies the model is significant.There is only a 0.01% chance that a "Model F-Value" this large could occur d model terms are not significant. The "Predicted R-Squared" of 0.8207 is in reasonable agreement with the "Adjusted R-Squared" of 0.9351.

4.1. Final Equation in Terms of Coded Factors

MRR = +0.39 +5.583E-003 *A +6.833E-003 * B +0.020 * C -7.333E-003 * D+3.125E-003 * A * B +1.250E-004 * A * C -3.750E-004 * A * D +5.000E-004 * B * C +4.750E – 03 * B * D +1.750E-003 * C * D -0.016 * A^2 -4.583E-003 * B^2 -1.333E-003 * C^2 -0.011* D^2

Table 5. *ANOVA Table for Surface Roughness (Ra)*

Source Value	Sum of Squares	df	Mean Square	F Value	p-Prob>1	Observation
Model	**8.32**	**16**	**0.52**	**8.26**	**0.0002**	**Significant**
A-current	*0.83*	*1*	*0.83*	*13.17*	*0.0031*	
B-Gap Voltage	*0.15*	*1*	*0.15*	*2.32*	*0.1519*	
C-Flow rate	*0.5*	*1*	*0.5*	*7.95*	*0.0145*	
D-Gap setting	*2.44*	*1*	*2.44*	*38.85*	*< 0.0001*	
AB	*8.10E-03*	*1*	*8.10E-03*	*0.13*	*0.7255*	
AC	*0.3*	*1*	*0.3*	*4.81*	*0.0471*	
AD	*0.14*	*1*	*0.14*	*2.18*	*0.164*	
BC	*0.48*	*1*	*0.48*	*7.57*	*0.0165*	
BD	*0.17*	*1*	*0.17*	*2.67*	*0.1262*	
CD	*9.00E-04*	*1*	*9.00E-04*	*0.014*	*0.9066*	
A^2	*0.24*	*1*	*0.24*	*3.83*	*0.0721*	
B^2	*0.17*	*1*	*0.17*	*2.7*	*0.1241*	
C^2	*2.83*	*1*	*2.83*	*44.98*	*< 0.0001*	
D^2	*3.86E-04*	*1*	*3.86E-04*	*6.13E-03*	*0.9388*	
A^2B	*8.33E-06*	*1*	*8.33E-06*	*1.32E-04*	*0.991*	
A^2C	*0.39*	*1*	*0.39*	*6.24*	*0.0267*	
Residual	0.82	13	0.063			
Lack of Fit	***0.68***	***8***	***0.084***	***2.96***	***0.1239***	***not significant***

The Model F-value of 8.26 implies the model is significant. There is onlya 0.02% chance that a "Model F-Value" this large could occur due to noise. Values of "Probabiity > F-Test Value" less than 0.0500 indicate model terms are significant.

In this case A, C, D, AC, BC, C^2, A^2C are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The "Predicted R-Squared" of 0.3700 is not as close to the "Adjusted R-Squared" of 0.8003 as one might normally expect.

4.2 Final Equation in Terms of Coded Factors

$$Ra = +6.15-0.19 * A -0.13 * B +0.25 * C -0.32 * D +0.023* A * B +0.14* A * C + 0.093 * A * D +0.17* B * C + 0.10* B * D -7.500E-003 * C * D+0.094 * A^2 +0.079*B^2+0.32*C^2-3.750E-003*D^2 +1.250E-003 * A^2 * B-0.27 * A^2 * C$$

It should be noted from the final equations that there are some coefficients omitted. These coefficients are non-significant according to the *t*-test that determined the significant and non-significant parameters. Also, the final models tested by variance analysis (*F*-test) indicated that the adequacy of models was established. The computed values of the response parameters from the above regressions were plotted to study the influence of the process parameters on the output variables MRR and Ra as follows.

4.2. Effect of various parameters on the Material Removal Rate

The effect of various parameters in the MRR is shown in 3D surface graphs and 2D plots. The following Figure 2 (a) (b) shows the effect of current and voltage on MRR.

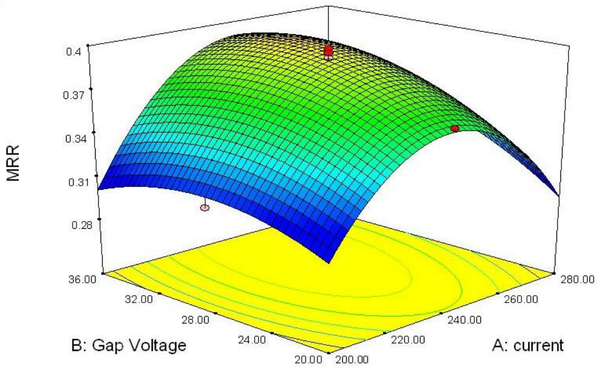

Figure 2(a)

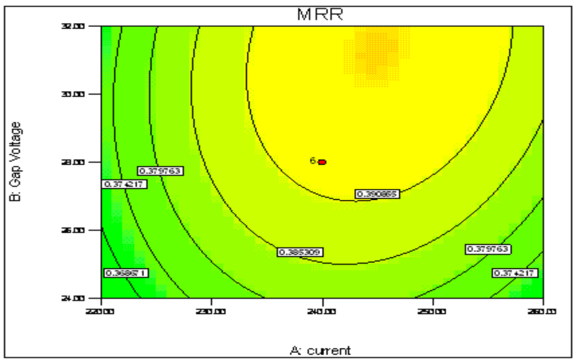

Figure2 (b)

Figure 2 (a),(b) *Effect of Current and Voltage on Material Removal Rate (MRR)*

The material removal rate increases nonlinearly with increase in the applied voltage for constant electrolytic concentrations. This is because of the increase in the voltage it causes greater electrolyzing current to be available in the machining gap (Ref. Fig 2) as well as causing a greater stray current intensity.

Figure 3 (a), (b) indicates that increase in the electrolyte flow rate also causes an increase in the material removal rate. The MRR continue to increase with increased electrolyte concentration because increase in electrolyte flow rate and it causes an increasing amount of negative electrolytic ions to produce electrochemical reactions with the metallic ions. Moreover, the increased flow rates lead to faster removal of the reactions products from the surface of the workpiece.

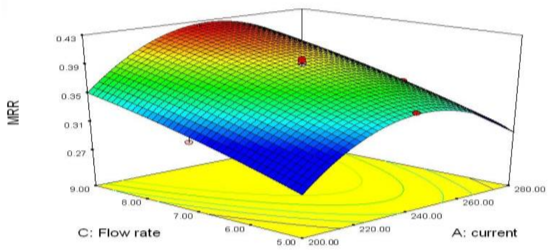

Figure3(a)

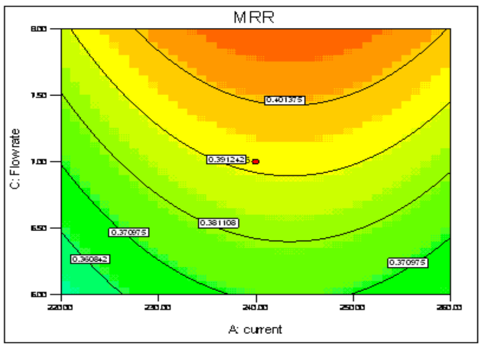

Figure 3(b)

Figure 3(a),(b) *Effect of Current and Flow Rate on Material Removal Rate (MRR)*

As increased inter electrode gap width Ref. Fig. 4(a), (b) for a preset voltage and electrolyte concentrations have a nonlinear effect on the MRR for varying electrolyte flow rates. However, increased gap width under such operating conditions weakens the stray current at flow path of electrolyte.

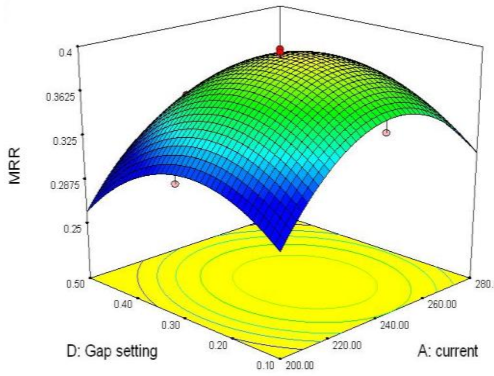

Figure 4(a)

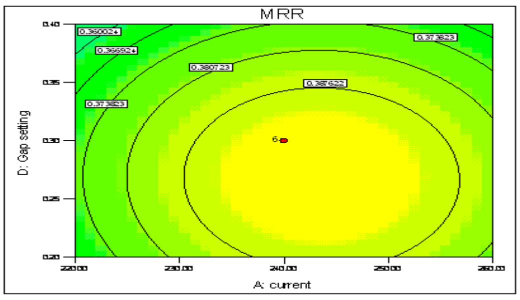

Figure 4(b)

Figure 4 (a),(b) *Effect of Current and Gap setting on Material Removal Rate (MRR)*

4.3. Effect of Various Parameters on the Surface Roughness

The effect of various parameters in the SR is shown in 3D surface graphs and 2D plots. The following figure5 (a), (b) shows the effect of current and voltage on SR.

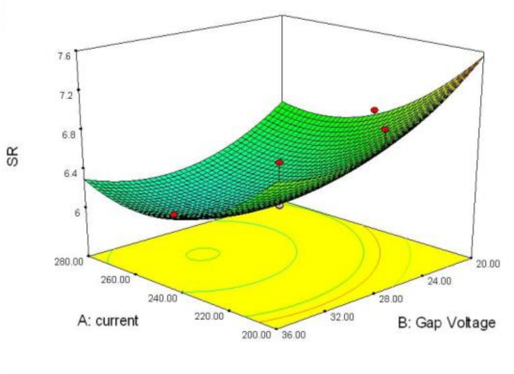

Figure5 (a)

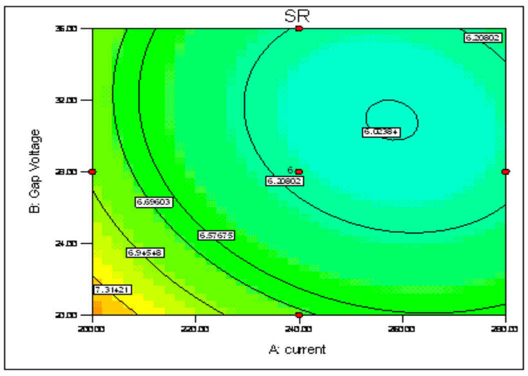

Figure5 (b)

Figure 5 (a),(b) *Effects of Gap Voltage and Current on Surface Roughness (Ra)*

Figure 5(a), (b) shows the 3D surface graph and 2D plots for the surface roughness at a current of 240 A and Voltage of 28 V. It is observed that the value of surface roughness (Ra) is high. Surface roughness (Ra) decreases with voltage increases. The gap voltage is the most significant factor influencing on surface roughness. Fig.6 (a), (b) at low flow rate the process of material Removal Rate (MRR) is instable. The results in an increase in the gap width between tool and workpiece it affects the surface roughness .The preset value of flow rate and gap setting the gap voltage increases the surface roughness also increases. Flow rate is the most influencing parameter on surface roughness.

Fig.7 (a), (b) If the machining gap width is not maintained at specified minimum value; the shape of the tool will not be accurately duplicated in the work piece. In this case, the roughness can be affected. The gap setting value increases at the preset value of voltage and flow rate the surface roughness also increases.

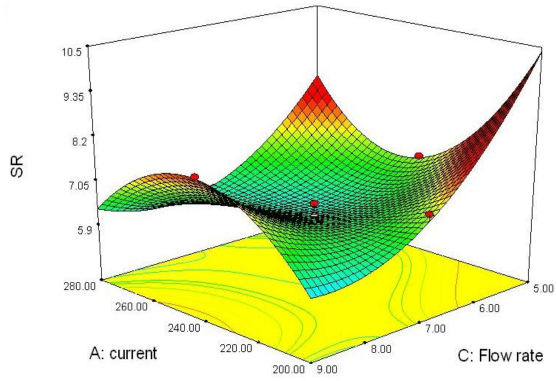

Fig. 6 (a)

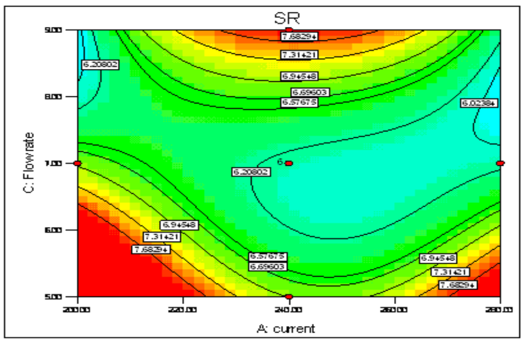

Figure6 (b)

Figure 6 (a),(b) *Effects of Flow Rate and Current on Surface Roughness (Ra)*

5. CONCLUSION

The mathematical models have been developed on the basis of RSM, utilizing the data from experiments of the ECM of Aluminium composites. Investigations were carried out for analysis of the control conditions need. The Material Removal Rate (MRR) generally increases with the increase of current and voltage ed for the control of the MRR and the Ra value

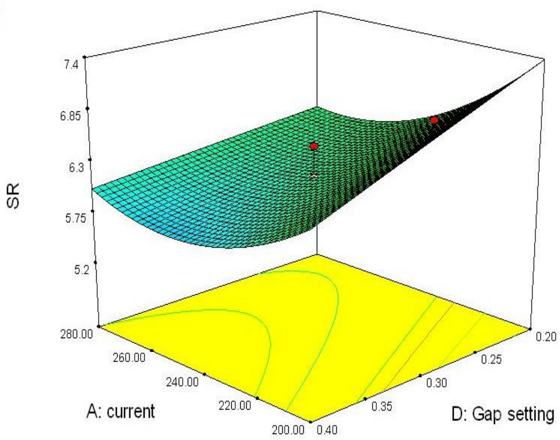

Fig.7 (a)

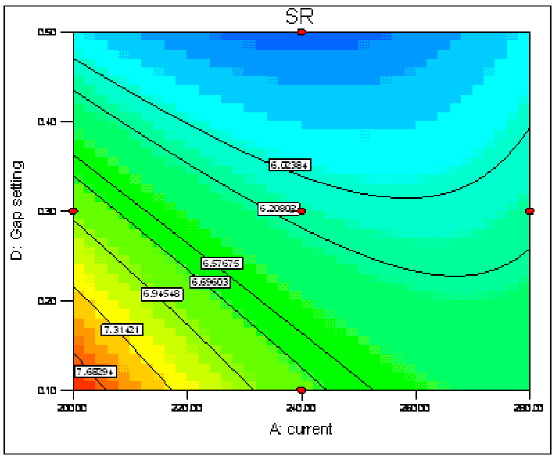

Fig. 7(b)

Figure 7 (a),(b) *Effects of Gap Setting and Current on Surface Roughness (Ra)*

The surface roughness (Ra) increases with the increase of current and decreases with the flow rate. The best surface finish that has been reached 6.24 μm. The ECM process has proved its adequacy to machine aluminium composite material under acceptable Material Removal Rate which reached 0.39 gm/min.

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NOMENCLATURE

A – Current in Amperes
B – Voltage in Volts
C – Flow Rate in Litre/Minutes
D – Gap Setting in millimeter
Y_U – Response for Material Removal Rate and Surface Roughness
bo, bi – Regression Co-efficients
x_{iu} – The Code Values of i^{th} Machining Parameters for u^{th} Experiments
n – Number of Machining Parameters
Hz – Frequency in Hertz
μ_m – Micron Meter
R_a - Surface Roughness

ACRONYMS

ECM - Electro Chemical Machining
MRR - Material Removal Rate
SR - Surface Roughness
ECMM - Electro Chemical Micro-Machining
ECDM - Electro Chemical Discharge Machining
USM - Ultrasonic Machining
EDM - Electro-Discharge Machining
LBM - Laser Beam Machining
RSM - Response Surface Methodology
ANOVA - Analysis of Variance
CCRD - Central Composite Rotatable Design