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Analysis of Response Variables in ECM of Aluminium Metal Matrix Composite (Al, SiC) using DoE and GRA Method

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Abstract*: Al-SiC is one of the widely accepted MMC having specific properties like wear and impact resistance. This composite shows difficulty while machining with modern machining processes due to various reasons such as higher surface roughness, tool wear rate and machining cost. In recent years, the need for light weight MMCs products are becoming more valuable in aerospace, electronics, nuclear power plants and defence industries because of their specific properties. The machining of MMCs is a big concern and still an area of research. In this experimental work, ECM has been selected for machining of Al-SiC composite to get better product quality & satisfactory machining characteristics. The voltage, feed rate and electrolyte concentration were selected as process constraints to conduct experimental trials. The SR, radial over cut and MRR were considered as output responses. The experimental outcomes were optimized by multi-parametric optimization using DoE and Grey relational analysis method. The optimized parameters by multi-parametric optimization showed the considerable improvement in the process.

***Index Terms*: Electrochemical Machining, Al-SiC, SR, ROC, MRR, Grey Relational Analysis.**

I. INTRODUCTION

ECM (Electrochemical Machining) generally known as anodic cutting is the advanced and most useful non conventional machining. The ECM process uses a shaped tool or electrode which is linked to the cathode (-ve) terminal & work piece is connected to the anode (+ve) terminal. The spark gap of 0.05 to 0.03 mm is kept between the tool electrode and material which allows the passage of an electrolytic neutral salt solution (i.e. Sodium chloride, sodium nitrate and sodium chlorate) between the gap. D.C. of ranges from 1-20 V current is supplied to the tool and work piece. An electronic ion is pulled from the material surface when sufficient energy, i.e. 6eV is available. The -ve ions present in the electrolyte solution reacts with the +ve ions and form metallic hydroxide compounds. Therefore, the metal is anodically dissolved with the formation of sludge and MRR is generated by "Faraday's Law of electrolysis" as shown in figure 1. [1, 4]

Because of the ECM machining capability of machining metal alloys, fragile parts, complex shapes and insignificant tool wear; this process is mostly utilized to machine harder & tougher materials with stress free conditions. ECM process is the reverse process of Electroplating (i.e. If two electrode plates are placed in a bath containing conducting liquid and direct current is supplied across them, the metal depletes from the anode (+ve) plate to the cathode (-ve) plate) with certain modification. [2, 3]

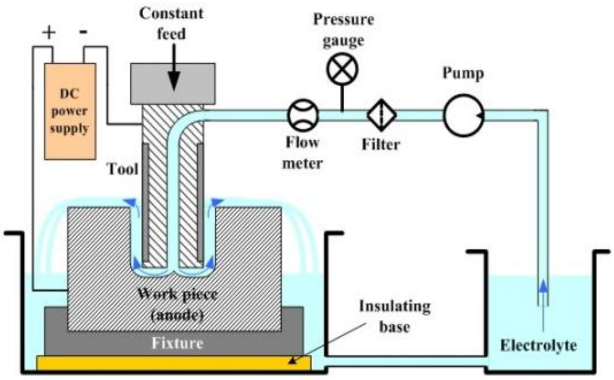

Fig.1. Schematic View of ECM

MMCs are the composites which are reinforced with fibers & ceramics and consist metal matrices, reinforced with fibers. It consists of the primary phase, i.e. metal matrix & secondary phase i.e. reinforcement. The primary phase consists of the bulk form of composite material; it holds the imbedded phase and conceals it. When an external force is employed primary phase distribute the force with secondary phase. The secondary phase increases the properties of the material, i.e. increase in strength, improvement in corrosion and shock resistance. In this experimental study, Al (matrix metal) is primary phase and SiC reinforced metal is the secondary phase. [1, 5]

Raj Kumar et al investigated the effect of D.C. voltage by using NaCl, NaNO3 aqueous solution at high speed. The authors concluded that 10-25 V voltage is suitable for ECM. [24] Neto et al investigated the effect of feed rate on valve steel and concluded that the value of SR decreases with the lower feed rate. [27] Ashokan et al investigated the ECM parameters using grey relational combined with an ANN method to analyze the effect of machining parameters such as current, voltage, flow rate and gap of hardened steel. [6] Rao et al concluded that the rate of MRR increase with feed rate, voltage and electrolytic concentration & decrease with %age of reinforcement.

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[19] Senthil Kumar et al demonstrated a mathematical model by using RSM and NSGA for improvement of ECM parameters for Al-SiC composites. [20, 21]

The Aluminium metal matrix has several industrial applications and it deals with two types of reinforcements i.e. AL_2O_3 (aluminium oxide) and SiC (silicon carbide). It has advantages for various applications such as wear and impact resistance and neutron absorption; therefore, SiC is used in reinforcement phase. The interfacial reactions in Al composites depend mainly on fabrication method, chemical composition of the matrix and condition of fabrication. The properties of the interface changes by composition methods utilized. [7-13]

Based on the literatures, it is found that no plausible works are conducted on multi-parametric optimization using DoE and Grey relational method of machining Al_2SiC metal matrix composite in the ECM process [9, 10]. Taguchi method, MOORA, TOPSIS and GA (Genetic Algorithm) had been utilized to optimize the process parameters in ECM process. [16-20, 28, 30]. The design of experiments (DoE) and regression analysis was performed by the application of Taguchi's orthogonal array. In this work, MRR, Surface roughness and radial over cut has been considered. Even though, the goal of the ECM could be to acquire the supreme MRR after machining suitable parameters. The said problem has been described by multi-objective optimization by using DOE & Grey relational analysis.

II. EXPERIMENTAL PLAN

Design-of-experiments (DoE) needs cautious scheduling, practical layout of the trials, Taguchi has identical procedures for every DoE application steps and also DoE can dramatically decrease the amount of trials. Thus;

The four important machining parameters, i.e. Voltage (V), Feed rate (F) & electrolyte immersion had selected for the governing parameter, and each parametric quantity had four levels denoted by level 1, level 2, level 3 & level 4, as designated in the Table 1. These values were selected from previous literatures.

Table 1. Allocated Values of ECM Parameters and Their Levels

Parameter		Units	Level 1	Level 2	Level 3	Level 4
A	Voltage (V)	Volts	8	10	12	14
B	Feed rate (F)	mm/min.	0.1	0.2	0.3	0.4
C	Electrolytic concentration	g/lit.	10	15	20	25

A. Running Experiment

MCMAC Meta Tech Electrochemical machine was used for the experimentation as shown in figure 2. Al-SiC composite reinforced with 10-15 Wt% of SiC was used as a work material. As per DoE the experiments were conducted with a 20 V rated ECM machine and the work piece was used in the form of a cylindrical shape. The workpiece and the electrodes were linked up with +ve and -ve polarity in the D.C power source respectively. Circular cross sectional Copper tool with internal hole for the NaCl electrolyte flow was used for this experimental work. The values for surface roughness were measured with the help of the surface roughness tester. The mass of the workpiece before and after machining for every trial run was measured with digital weight-balance (up to 0.001 gram accuracy).

Fig.2. Meta Tech Electrochemical Machining Setup

The formula used to find the Workpiece Removal Rate (MRR) is given below:

$$WRR = \frac{\text{Weight/Volume of material removal}}{\text{Time}} \text{ (g / min)} \quad (1)$$

The formula used to find the Radial over-cut (ROC) is given below:

$$ROC = \frac{\text{DIA.of hole in material - DIA.of tool}}{2} \quad (2)$$

After machining of Al-SiC composite, radial over-cut of the material was evaluated with a digital vernier caliper. Each sample was evaluated by thrice and the mean values were considered.

III. MULTI-PARAMETRIC OPTIMIZATION USING GRA METHOD

To design the experiments, the first step is selection of appropriate Orthogonal Array, Assign each factor to columns, identify each trial circumstance, and decides the set up and repeating of trial circumstances. An OA Design matrix table is generated.[28, 30]

A. Experimentation

In the present experimentation work, L_{16} OA was chosen. L16 Orthogonal Array has 16 parametric combination therefore the total number of 16 experiments were conducted to measure the interactions between the various factors. The parameter combinations using the L_{16} or OA are shown in Table 2.

For accurate measurements minimum three values were taken for each specimen and the mean value was selected. The mean values of the SR, Radial over cut and MRR are shown in the table 3.

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Table 2. DoE (Design of Experiment) Matrix of L_{16} Orthogonal array (OA)

Sl. No.	Voltage (A)	Feed Rate (B)	Electrolyte Concentration (C)
1.	8	0.1	10
2.	10	0.1	15
3.	12	0.1	20
4.	14	0.1	25
5.	8	0.2	15
6.	10	0.2	10
7.	12	0.2	25
8.	14	0.2	20
9.	8	0.3	20
10.	10	0.3	25
11.	12	0.3	10
12.	14	0.3	15
13.	8	0.4	25
14.	10	0.4	20
15.	12	0.4	10
16.	14	0.4	15

Table 3. Measured Values for Output Responses, as per DOE

Sl. No.	SR (µm)	ROC (mm)	MRR (g/min.)
1.	15.10	0.10	11.50
2.	10.14	0.15	2.54
3.	9.10	0.101	10.54
4.	4.99	0.21	14.70
5.	9.21	0.17	13.40
6.	8.21	0.02	21.80
7.	10.01	0.17	18.10
8.	11.90	0.20	10.01
9.	10.00	0.10	15.10
10.	15.90	0.075	17.50
11.	8.70	0.01	18.92
12.	5.40	0.30	16.80
13.	22.70	0.14	30.40
14.	10.80	0.03	9.40
15.	9.01	0.13	3.10
16.	7.60	0.25	20.20

B. Multi-parametric Optimization using the Grey Relational Method

The steps used for multi-parametric optimization using the Grey relational analysis are discussed below;

a) Normalization of the all experimental results: The normalized values for output responses were calculated by using the standard formula:

$$Normalized\ Results(X_{ij}) = \frac{(y_{ij}) - (\min_j y_{ij})}{(\max_j y_{ij}) - (\min_{ij} y_{ij})} \quad (3)$$

Where,

y_{ij} = i^{th} experiment results in j^{th} experiment.

(b) Calculation for the Grey relational coefficients:
The standard formula used for the computation of Grey relational coefficients is given below:

$$\delta_{ij} = \frac{\min_i \min_j |x_i^0 - x_{ij}| + \xi \max_i \max_j |x_i^0 - x_{ij}|}{|x_i^0 - x_{ij}| + \xi \max_i \max_j |x_i^0 - x_{ij}|}, 0 < \xi < 1 \quad (4)$$

Where,

x^o_i = ideal normalized result

(c) Calculation for the Grey relational grade:
The grades are evaluated by the average of Grey relational coefficient using the formula given below:

$$\alpha_j = \frac{1}{m}\sum_{i=1}^{m} \delta_{ij} \quad (5)$$

Where,

α_j = Grey relational grade
m = No. of execution grade characteristics

Table 4. Calculated values for Grey Relational Grade

Sl. No.	Voltage (A)	Feed Rate (B)	Electrolyte Concentration (C)	Grey relational Grade
1	8	0.1	10	0.502747016
2	10	0.1	15	0.491459817
3	12	0.1	20	0.569883866
4	14	0.1	25	0.630140493
5	8	0.2	15	0.534342766
6	10	0.2	10	**0.762367978**
7	12	0.2	25	0.548226442
8	14	0.2	20	0.466802961
9	8	0.3	20	0.577414981
10	10	0.3	25	0.552561763
11	12	0.3	10	**0.750981581**
12	14	0.3	15	0.598358077
13	8	0.4	25	0.62020202
14	10	0.4	20	0.627134697
15	12	0.4	10	0.524265861
16	14	0.4	15	0.57542123

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(d) Calculation of the optimum levels: optimum levels are calculated to find the significant parameter.

(e) Selection of the optimal levels of parameters by taking the highest values of levels for each parameter from the optimum level table.

The highest value of process parameters for each parameter showed the best optimized value.

(f) Confirmation of experiment and verification of the optimized process parameters.

Table 5. Grey Relational Grade Response Table

Process Parameters	Level 1	Level 2	Level 3	Level 4
A	0.559	**0.608**	0.598	0.568
B	0.549	**0.619**	0.578	0.587
C	**0.635**	0.549	0.560	0.588
Average Grey relational grade= 0.5832694				

C. Confirmation of Experiment

After obtaining the optimized values of process parameters the last step is to confirm the experimentation.

Table 6. Confirmation of Experiment

Predicted Value		Experimentation
Level	$A_3B_3C_1$	$A_2B_2C_1$
SR (µm)	8.70	8.21
ROC	0.01	0.02
MRR (g/min.)	18.92	21.80
Grade	0.750981581	0.762367978
Improvement in Grey relational grade: 0.011386		

The estimated Grey relational grade can be calculated from the following given relation:

$$\hat{\alpha} = \alpha_m + \sum_{i=1}^{q} (\overline{\alpha}_i - \alpha_m) \qquad (6)$$

Where,

α_m = Total mean of the Grey relational grade

q = No. of process parameters.

IV. TAGUCHI ANALYSIS

DOE is the first step of experimental work and a statistical technique introduced by R.A. Fisher (1920). In DOE the change in corresponding output variables is measured by changing the values of Input variables and used to find the most efficient and effective conclusions by designing, planning and organizing.

To design the experiments, the first step is selection of appropriate Orthogonal Array, Assign each factor to columns, identify each trial circumstance, and decides the order and repetitions of trial circumstances. Taguchi analysis is used for the selection of best-optimized parameter value for the individual process parameter and to measure the influence of each parameter at different levels.

A. Influence of Input Parameters on Surface Roughness

The main effect plot for means (for surface roughness) generated by Minitab 16 Software is shown in the Figure 3. This graph indicates the effect of individual input parameters on the surface roughness. In this analysis "Smaller is better" S/N ratio was used. This graph shows the best optimized values for surface roughness.

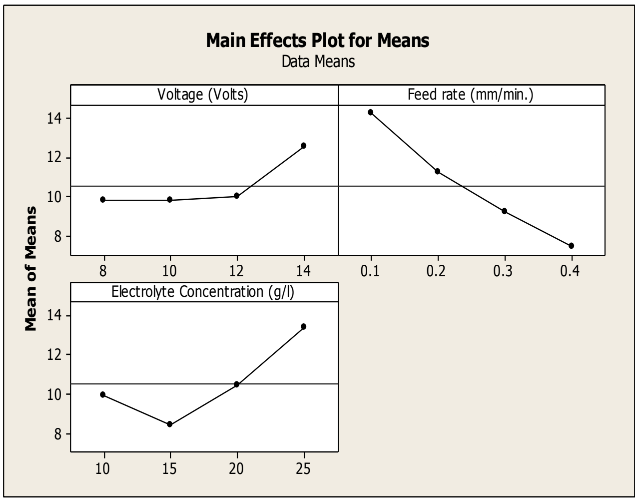

Fig.3. Main Effect Plot for Means (Surface Roughness)

The best optimized level values for surface roughness are:

Optimized Parameters	Voltage (A)	Feed Rate (B)	Electrolyte Concentration (C)
Levels	2	4	2

The surface roughness response table for means is shown in the table 7. This table represents the most significant parameter and least significant parameter for surface roughness (SR). The table clearly indicates that the feed rate and electrolyte concentration are the most significant parameters for surface roughness whereas the voltage has the least significance.

Table 7. Surface Roughness Response table for means (Smaller is better)

Level	Voltage (A)	Feed Rate (B)	Electrolyte Concentration (C)
1	9.833	14.253	9.903
2	9.832	11.262	8.440
3	10.000	9.205	10.450
4	12.528	7.473	13.400
Delta	2.695	6.780	4.960
Rank	3	1	2

The influence on surface roughness in relation to change of ECM process parameters is illustrated in Figure 4.

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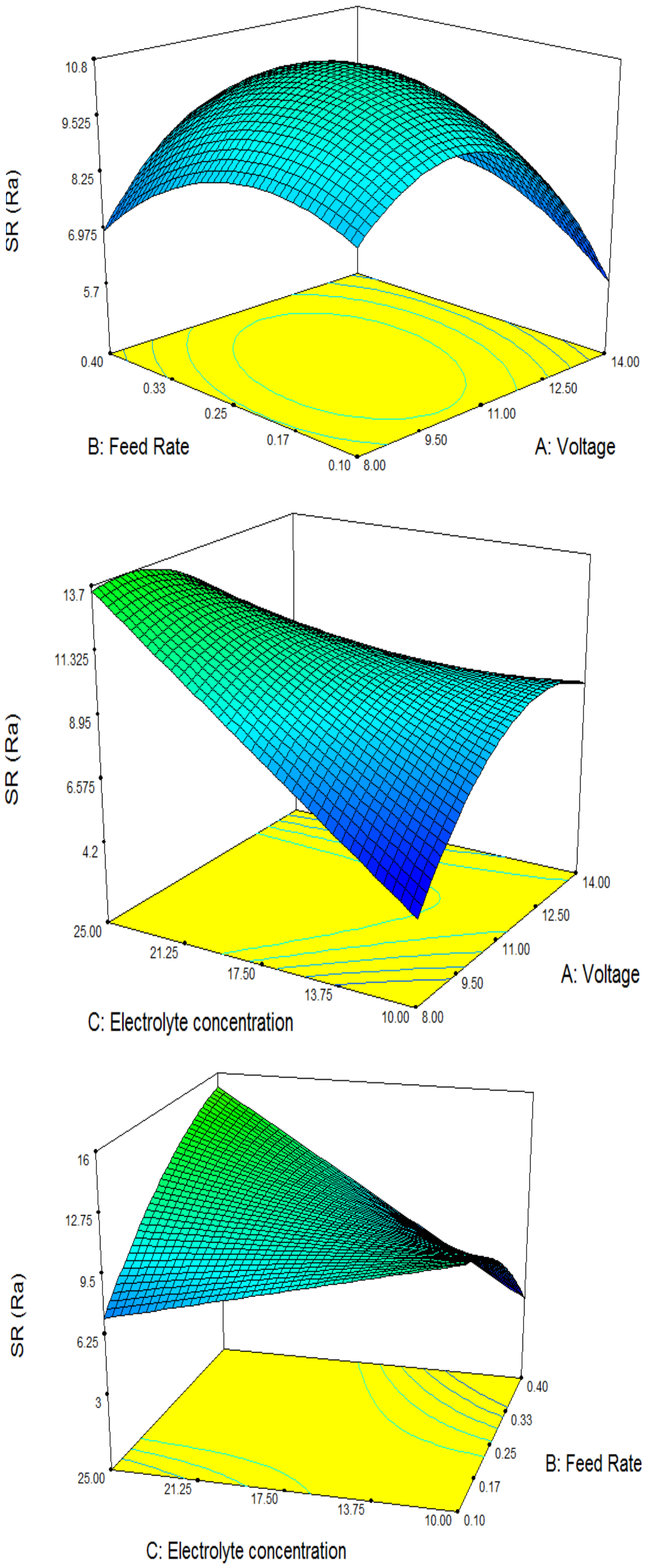

Fig.4. Influence on Surface Roughness in Relation to Change of (i) Voltage and Feed Rate, (ii) Voltage and Electrolyte Concentration and (iii) Feed rate and Electrolyte Concentration

B. Influence of Input Parameters on ROC

The main effect plot for means (for ROC) generated by Minitab 16 Software is shown in the Figure 5. This graph indicates the effect of individual input parameters on the ROC (Radial over Cut). In this analysis "Smaller is better" S/N ratio was used. This graph shows the best optimized values for ROC.

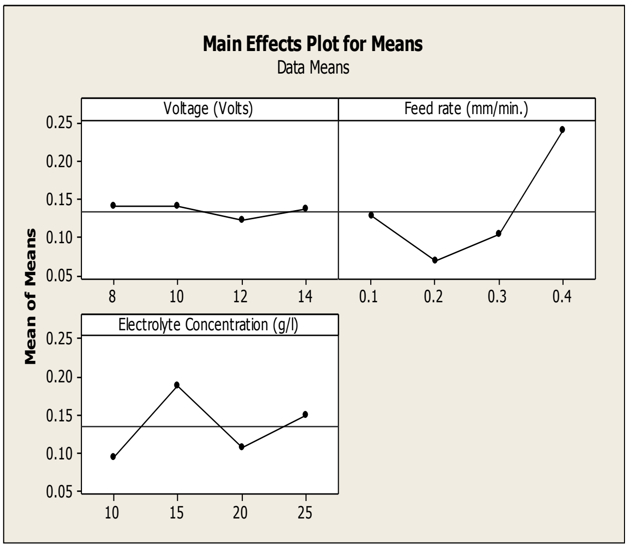

Fig. 5. Main Effect Plot for Means (ROC)

The best optimized level values for ROC are:

Optimized Parameters	Voltage (A)	Feed Rate (B)	Electrolyte Concentration (C)
Levels	3	2	1

The ROC response table for means is shown in the table 8. This table represents the most significant parameter and least significant parameter for ROC. The table clearly indicates that the feed rate and electrolyte concentration has the most significance on ROC whereas the voltage has least significance.

Table 8. ROC Response Table for Means (Smaller is Better)

Level	**Voltage (A)**	**Feed Rate (B)**	**Electrolyte Concentration (C)**
1	0.1403	0.128	0.095
2	0.140	0.069	0.186
3	0.121	0.103	0.108
4	0.138	0.240	0.149
Delta	0.019	0.171	0.0925
Rank	3	1	2

The influence on ROC in relation change of voltage, feed rate and electrolyte concentration levels is illustrated in Figure 6.

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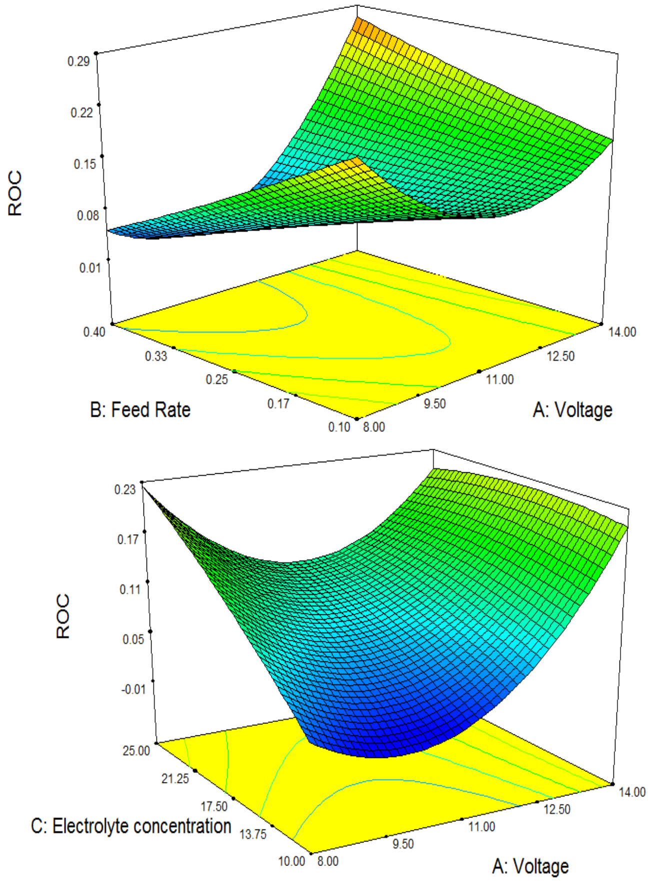

Fig.6. Influence on ROC in Relation to Change of (i) Voltage and Feed Rate and (ii) Voltage and Electrolyte Concentration

C. Influence of Input Parameters on MRR

The main effect plot for means (for MRR) generated by Minitab 16 Software is shown in the Figure 7. This graph indicates the effect of individual input parameters on the MRR (Material removal rate). In this analysis "Larger is better" S/N ratio was used. This graph shows the best optimized values for MRR.

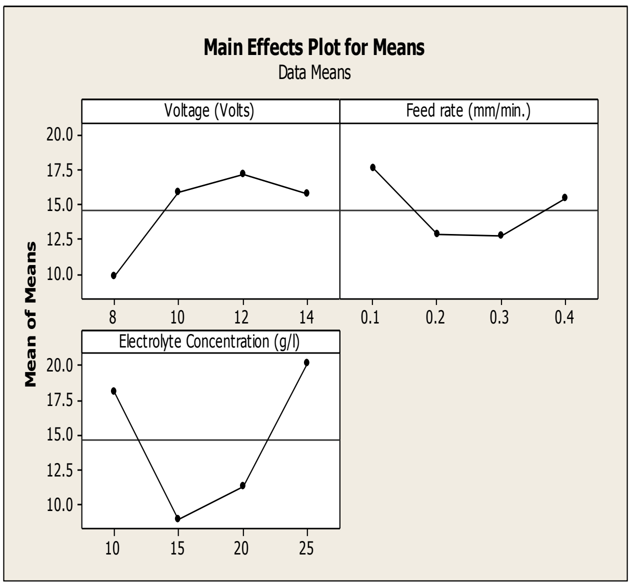

Fig.7. Main Effect Plot for Means (MRR)

The best optimized level values for MRR are:

Optimized Parameters	Voltage (A)	Feed Rate (B)	Electrolyte Concentration (C)
Levels	3	1	4

The MRR (Material removal rate) table for means is shown in the table 9. This table represents the most significant parameter and least significant parameter for MRR. The table clearly indicates that the electrolyte concentration and voltage has the most significance on MRR whereas the feed rate has the least significance.

Table 9. MRR Response Table for Means (Larger is Better)

Level	Voltage (A)	Feed Rate (B)	Electrolyte Concentration (C)
1	9.820	17.600	18.105
2	15.828	12.810	8.960
3	17.080	12.665	11.262
4	15.775	15.428	20.175
Delta	7.260	4.935	11.215
Rank	2	3	1

The influence on MRR in relation change of ECM process parameters is illustrated in Figure 8.

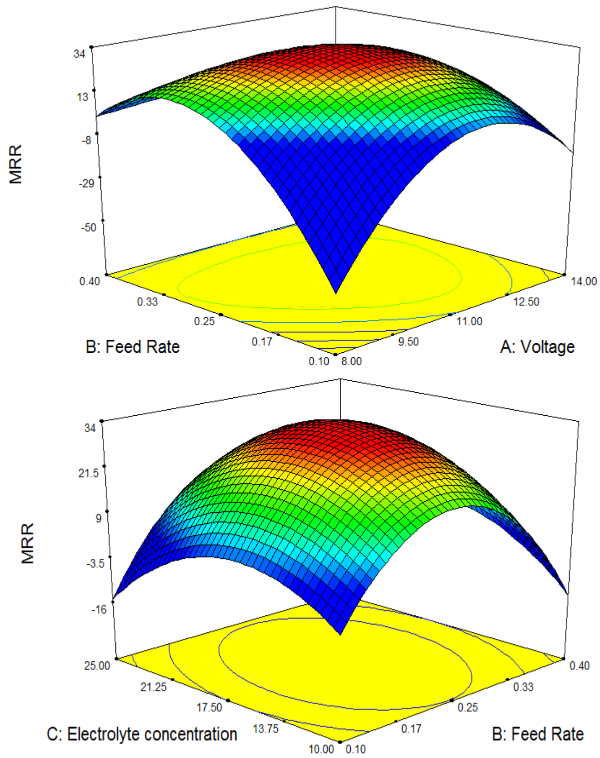

Fig.8. Influence on MRR in relation to change of (i) voltage and feed rate and (ii) Feed rate and electrolyte concentration

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V. RESULTS AND CONCLUSION

1) The ECM process parameters for AMMCs namely Al-SiC had optimized by using DoE and grey relational analysis. The optimal solution had calculated for Surface Roughness (SR), radial over-cut and MRR.
2) An attempt had also been made to attain Max. and Min. MRR, radial over cut & SR evaluation of process parameters respectively. The optimized outcomes had also been examined through a real experiment and established to be satisfactory.
3) The optimized parameters for the response of SR, MRR, and radial over cut in ECM process are: 10 Volts of applied voltage (V), 0.2 mm/min. Feed rate (F) &10 g/l electrolytic concentration.
4) The Grey relational technique simplifies the optimization method by convert of the multi response variables to a single response grade by normalizing. Thus, the experimental results showed the considerable advancement in the process.
5) For MRR, the electrolyte concentration and voltage has the most significance, whereas the feed rate has the least significance.
6) For ROC and SR (Ra value), the feed rate and electrolyte concentration have the most significance, whereas the voltage has least significance.
7) The optimized values through this experimentation will facilitate ECM industries to enhance and improve productivity and quality while machining Al-SiC composite.

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