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Application of Taguchi Method, ANOVA Analysis, and TOPSIS Technique in Optimization of Process Parameters for Surface Roughness and Material Removal Rate in Electrochemical Machining of Al-SiC MMCs

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Abstract

Objectives: To evaluate the significance of advanced machining techniques, such as EDM, ECM, and USM, in increasing productivity and overcoming challenges associated with outdated Al-SiC MMC machining. To assess the surface roughness, tool wear, and machining cost implications of employing advanced machining methods for Al-SiC MMCs. **Methods** The parameters studied were voltage (V), feed rate (F), and electrolyte concentration (C) in electrochemical machining (ECM) of Al/15%SiC composites. To optimise process parameters, the Taguchi method for Design of Experiments (DOE) with an L27 orthogonal array was used. Signal responsiveness is optimised using the Taguchi approach. The Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) is used to find optimal machining settings. **Findings:** The outcome of this research is that the parameters affecting surface roughness and material removal rate are voltage, electrolyte concentration and feed rate. The minimum Surface Roughness achieved by selecting the best combination level is A2, B3, C3 (smaller is better) i.e., voltage 20 V, feed rate (f) 0.4 mm/min., electrolyte concentration (c) 30 g/lit. The maximum Material Removal Rate achieved by selecting the best combination level is A3, B3, C3 (larger-is-better) i.e., voltage 25V, feed rate (f) 0.4 mm/min., electrolyte concentration (c) 30 g/lit. **Novelty :** In this work, TOPSIS technique paired with Taguchi method is used which is rarely studied by other researchers. TOPSIS technique provides the best optimal solution as compared to other techniques.

Keywords: Al-SiC MMCs; ECM; MRR; Ra; Taguchi method; TOPSIS

1 Introduction

Electrochemical Machining (ECM) is a leading non-conventional machining process in industrial applications, particularly for shaping highly robust materials with complex geometries [1]. ECM enables the controlled anodic dissolution of work materials submerged in an electrolytic solution, allowing for the production of complex structures from tough substrates [2]. Despite their ubiquitous use, the complexities of ECM parameters such as voltage (V), feed rate (F), and electrolyte concentration (C) remain critical but poorly understood [3].

In the field of ECM, producing and machining Al/15% SiC composites is a considerable challenge. Traditional sand-casting procedures are used in composite production, followed by ECM processing to get the necessary forms and dimensions [4]. The optimisation of ECM parameters is critical in this setting, as their impact on surface roughness, material removal rate (MRR), and, ultimately, surface finish, cannot be emphasised [5].

Surface roughness, a measure of work piece quality, reflects the effectiveness of ECM operations. However, despite its importance, the relationship between input parameters and surface roughness has received insufficient attention, leaving a significant gap in understanding [6]. While surface roughness assessment techniques have advanced, their integration with ECM parameter optimisation is still in its early stages [7].

Furthermore, the quest of higher material removal rates (MRR) emphasises the importance of precise parameter selection and process optimisation. Current procedures for quantifying MRR frequently lack precision, prompting a reassessment of measurement techniques and their integration with ECM parameter optimisation schemes [8].

The weight loss measuring technique, which is often used to evaluate MRR, requires modification to assure accuracy and consistency. The lack of standardised techniques and reliance on traditional balance weight measuring devices reveal a key gap in quantifying MRR in ECM of Al/15%SiC composites [9].

In [10], discussed the production of Al / SiC composite and studied its suitability for application on the connecting rod. The results revealed that the composite rod is more efficient than conventional rods. In [11], studied the manufacturing and machining of aluminium metal matrix composites. The base metal was AA6603, and the reinforcing with TiC at concentrations ranging from 0 to 9 wt. percent. The material proposed finds use in aerospace sectors, and an electrochemical machining technique is used to achieve essential surface polish standards. In [12], investigated the Aluminium metal matrix reinforced with Boron Carbide (B4C) as a novel AMMC composite. This composite is commonly used in the automotive sector due of its outstanding wear resistance, high strength-to-weight ratio, enhanced thermal toughness, and high stiffness (brake pads and brake rotors). When compared to typical reinforcements such as Al_2O_3 and SiC, boron carbide exhibits unique properties such as neutron absorption. In [13], investigated the $NaNO_3$ and $NaClO_3$ electrolyte composition concentration, electrolyte pressure, applied voltage, and feed rate in electrochemical machining (ECM) of the innovative special purpose S-03 stainless steel material using an orthogonal array experiment. The machining efficiency, surface roughness of the work piece, and side gap between the cathode and anode work pieces were all studied. This study revealed that employing appropriate concentration electrolyte composition is a straightforward, low-cost, and practical way to improving the efficiency and surface quality of the new stainless steel S-03 processes. In [14], investigated the Ti_{60} is a high-temperature titanium alloy that is presently utilised in aviation engine components.

Electrochemical machining (ECM) is a promising method with a number of advantages, including a high machining rate and the ability to treat a wide range of difficult-to-process materials. In this article, orthogonal tests are carried out to explore the ECM of Ti_{60} in order to determine the effects of various electrochemical process factors on surface roughness. Furthermore, blisk blades have been treated satisfactorily with these improved settings.

Considering the above literature study, an attempt has been made to bridge the gap by utilising the Taguchi method for Design of Experiments (DOE) and incorporating the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to determine ideal ECM settings. This study intends to improve understanding of ECM parameter optimisation while also providing practical insights for the machining of Al/15%SiC composites.

2 Methodology

Aluminium 2124 alloy is characterized by high corrosion resistance and a high-strength alloy generally used in the aerospace industry for making structural components. The SiC is considered as high wear-resistant ceramic particles that are added in alloy to enhance the mechanical properties. The Al-SiC is manufactured using sand casting conventional technique with 15% SiC in Aluminium by weight.

2.1 ECM Working

ECM process is based on Faraday's Laws of Electrolysis, the tool acts as a cathode, and the work piece acts as an anode. The work piece and tool are kept close to each other with a small gap (up to 0.5 mm) between them. A DC voltage of about 3-30 V is applied in the tool and work piece, and the electrolyte is pumped into the gap. Due to applied voltage-current starts flowing via electrolyte with positively charged ions being attracted towards the tool and negatively charged ions being attracted towards the work piece. Due to this, an electrochemical reaction is carried out, and hence there is the removal of metal from the work piece in the form of sludge.

This sludge is taken away from the gap by the electrolyte which is flowing continuously. The area where the work piece and tool are closer experiences low resistance, hence there is a flow of higher current. Hence, MRR in this area is higher due to which tool shape is reproduced on the work piece. In the process, the tool is fed at constant speed by using a servomotor and the work piece is held stationary.

2.2 Materials and equipment

The details of work piece materials and different types of equipment used in this experimental investigation are summarized in Table 1.

Table 1. Equipment and materials

Workpiece material	Al-SiC
Dimensions of workpiece	(Ø 25mm, L=10mm)
Number of samples	27
Electrolyte	Sodium chloride
Machine	ECM
Tool	Copper Electrode
Surface analyser	Surface roughness tester

2.3 Selection of input parameters

Table 2 illustrates, the 3 varying working parameters (Voltage, Feed rate, Electrolyte concentration) of the ECM machining process with 3 different levels for Voltage (15, 20, 25), Feed rate (0.2, 0.3, 0.4), and Electrolyte concentration (10, 20, 30), respectively.

Table 2. Process input parameter With Their Levels

Parameters	Unit	Level I	Level II	Level III
A. Voltage (V)	V	15	20	25
B. Feed rate (F)	mm/min	0.2	0.3	0.4
C. Electrolyte concentration (C)	g/lit	10	20	30

2.4 Experimental Procedure

This research considered 3 varying parameters with 3 different levels. Taguchi L27 orthogonal array was used for this work. From this method obtained 27 tests. The process parameters are summarized in Table 2 and DOE for experimentation is shown in Table 3. Machining of Al-SiC workpiece of size Ø 25mm, L=10mm is carried out on an ECM machine. The experimental setup for ECM is shown in Figure 1. As per DOE, all the experiments were conducted. The surface roughness tester/analyser is used to measure the surface roughness of machined work pieces and MRR is measured using MRR is calculated using the volume loss from the work piece material as gram per second (g/s) are summarized in Table 3. The photographic view of the work piece before and after machining is shown in Figures 2 and 3 respectively.

Fig 1. The experimental setup of ECM

Fig 2. Work piece before machining

Fig 3. Work piece after machining

3 Results and Discussion

3.1 Effects of input parameters on output parameters

The surface roughness of the work piece is generally connected with the surface quality of machined products. In this study, the surface roughness of the machined work piece was measured using a surface roughness tester but the surface roughness is directly proportional to MRR, i.e., the surface roughness increases with increasing MMR and vice-versa. After experimental work following results are obtained, which are shown in Table 3.

Table 3. Experimental outcomes for 27 runs

Sr. No.	Voltage (V)	Feed Rate (mm/min)	Electrolyte concentration (g/lit)	Surface Roughness(Ra) (μm)	Material Removal Rate(MRR) g/sec
1	15	0.2	10	2.04	0.169
2	15	0.2	20	2.09	0.237
3	15	0.2	30	1.69	0.127
4	15	0.3	10	2.01	0.253
5	15	0.3	20	1.59	0.348
6	15	0.3	30	1.82	0.32
7	15	0.4	10	1.69	0.589
8	15	0.4	20	1.45	0.454
9	15	0.4	30	1.32	0.603
10	20	0.2	10	1.99	0.221
11	20	0.2	20	1.89	0.229
12	20	0.2	30	1.39	0.388
13	20	0.3	10	1.64	0.279
14	20	0.3	20	1.49	0.202
15	20	0.3	30	1.09	0.483
16	20	0.4	10	1.39	0.515
17	20	0.4	20	1.44	0.519
18	20	0.4	30	0.69	0.712
19	25	0.2	10	2.59	0.182
20	25	0.2	20	1.89	0.499
21	25	0.2	30	1.69	0.5
22	25	0.3	10	2.3	0.426
23	25	0.3	20	1.99	0.588
24	25	0.3	30	1.59	0.63
25	25	0.4	10	2.09	0.58
26	25	0.4	20	1.49	0.787
27	25	0.4	30	1.09	0.844

3.2 Taguchi Analysis

Main effects plot for means:

The main effect plot indicates how each factor influences the output/response parameter (S/N ratio, Means, Slops, Standard deviations, etc.). Figures 4 and 5 show the main effects plot for means and Tables 4 and 5 shows response table for S/N ratio.

A. Taguchi Analysis: Surface Roughness versus Voltage (V), Feed Rate (mm/min), Electrolyte concentration (g/lit)-

Table 4 indicates the most significant factor which affects surface roughness is feed rate and followed by voltage and electrolyte concentration. Also, the data illustrates the surface roughness of work piece decreases with increase in voltage, feed rate and electrolyte concentration.

B. Taguchi Analysis: Material removal rate versus Voltage (V), Feed Rate (mm/min), Electrolyte concentration (g/lit)-

Table 4. Response for Signal to Noise Ratios (Smaller is better) for Surface Roughness

Level	Voltage	Feed	Electrolyte concentration
1	-0.6455	-0.7842	-1.5177
2	-2.8712	-1.9052	-2.9463
3	-4.2408	-5.0681	-3.2934
Delta	3.5953	4.2839	1.7757
Rank	2	1	3

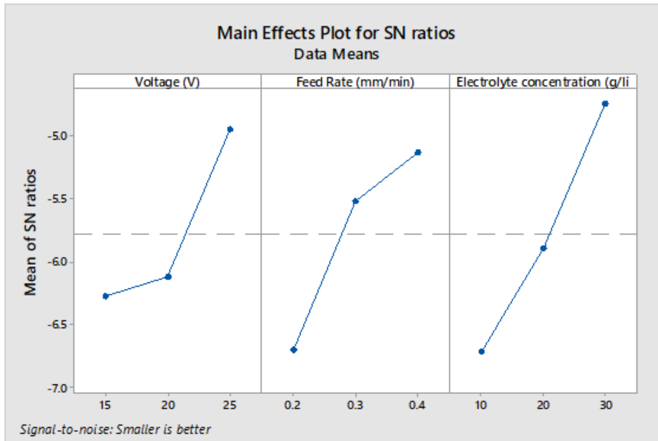

Fig 4. Main effect plots for SN ratios of surface roughness

Table 5 indicates the most significant factor which effects on material removal rate is feed rate and followed by voltage and electrolyte concentration. Also, the data illustrates the material removal rate of work piece increases with increase in voltage, feed rate and electrolyte concentration.

Table 5. Response for Signal to Noise Ratios (Larger is better) for material removal rate

Level	Voltage	Feed	Electrolyte concentration
1	-0.6455	-0.7842	-1.5177
2	-2.8712	-1.9052	-2.9463
3	-4.2408	-5.0681	-3.2934
Delta	3.5953	4.2839	1.7757
Rank	2	1	3

3.3 Analysis of variance

General Linear Model: Surface Roughness versus Voltage (V), Feed Rate (mm/min), Electrolyte concentration (g/lit)-

Table 6 shows the input parameter are significant or not which can be decided using the P values consist less than 0.05. For surface roughness of machined work piece using ECM, all the input parameter (voltage, feed, electrolyte concentration) are significant.

Regression Equation:

Ra = 1.6826 + 0.0619 v_15 - 0.2370 v_20 + 0.1752 v_25 + 0.2352 f_0.2 + 0.0419 f_0.3- 0.2770 f_0.4 + 0.2885 c_10 + 0.0196 c_20 - 0.3081 c_30

Table 7General Linear Model: MRR versus Voltage (V), Feed Rate (mm/min), Electrolyte concentration (g/lit)-

Table 7 shows the input parameter are significant or not which can be decided using the P values consist less than 0.05. For material removal rate of machined work piece using ECM, all the input parameter (voltage, feed, electrolyte concentration) are significant.

Regression Equation:

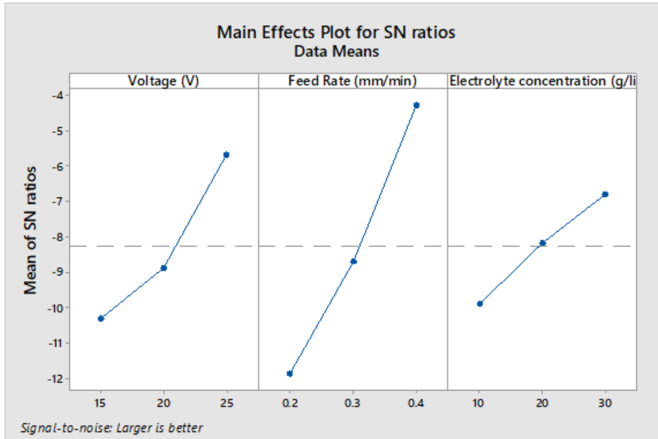

Fig 5. Main effect plots for SN ratios of material removal rate

Table 6. General Linear Model: Surface Roughness versus Voltage (V), Feed Rate (mm/min), Electrolyte concentration (g/lit)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significance
V	2	0.8163	0.40816	12.88	0	significant
f	2	1.2043	0.60216	18.99	0	significant
c	2	1.6073	0.80363	25.35	0	significant
Error	20	0.634	0.0317			
Total	26	4.2619				
Model Summary						
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**			
0.17805	85.12%	80.66%	72.89%			

Table 7. General Linear Model: MRR versus Voltage (V), Feed Rate (mm/min), Electrolyte concentration (g/lit)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significance
V	2	0.2283	0.11413	15.98	0	Significant
f	2	0.5394	0.26972	37.76	0	Significant
c	2	0.108	0.05399	7.56	0.004	Significant
Error	20	0.1429	0.00714			
Total	28	1.0185				
Model Summary						
S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**			
0.08452	85.97%	81.77%	74.44%			

MRR = 0.4327 - 0.0883 v_15 - 0.0385 v_20 + 0.1268 v_25 - 0.1492 f_0.2 - 0.0406 f_0.3+ 0.1898 f_0.4 - 0.0756 c_10 - 0.0035 c_20 + 0.0791 c_30

3.4 Optimization Technique

Technique for order preference by similarity to ideal solution (TOPSIS) is a simple and effective Multi-Criteria Decision Making (MCDM) tool used in many applications like process parameter selection in manufacturing etc. To solve multi-objective problems, TOPSIS is one of the multi-criteria decision-making methods (MCDM) which is used. The following steps have been applied in this approach.

1] Making a matrix

In this experimental work, there are 3 response variables and 27 ways. Hence, the matrix is [27,3].

2] Calculate normalized matrix

The calculation of normalized matrix is done in this step.

$$\bar{X}ij = \frac{X_{ij}}{\sqrt{\sum_{i-1}^{n} Xij^2}} \quad (1)$$

3] Calculation of weighted normalized matrix (Vij)

The weightage for each response is given in this step. For this experimental work, the weightage of both the response parameters are 0.5 because they have equally important.

$$V_{ij} = \bar{X}_{ij} \times W_j \quad (2)$$

4] Calculation of ideal positive (Vj+) and ideal negative (Vj -) solution

In this step, an ideal positive and ideal negative solution is calculated for both the response parameters.

5] Calculate the Euclidean distance from the ideal best and ideal worst distance between alternative i and ideal negative solution

$$S_i^+ = \left[\sum_{j-1}^{m} (V_{ij} - V_j)^2\right]^{0.5} \quad (3)$$

$$S_i^- = \left[\sum_{j-1}^{m} (V_{ij} - V_j)^2\right]^{0.5} \quad (4)$$

6] calculate performance score and rank

In this last step, the performance score is calculated. The rank is inversely proportional to the performance score.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (5)$$

The TOPSIS optimization table for ECM process is mentioned in Table 8.

Results of previous studies has been compared with this research results. The study shows that there is very less work has been carried out on ECM machining of Al/Si-C composite material using Taguchi and TOPSIS technique[10] [15]. There is improvement in results due to proper use of Optimization Technique.

4 Conclusion

This study throws light on the key elements that influence surface roughness and material removal rate in Electrochemical Machining (ECM) of Metal Matrix Composites (MMCs). The important discoveries from extensive experimentation and analysis are as follows:

1. Feed rate is the most important parameter influencing both surface roughness and material removal rate, followed by voltage and electrolyte concentrations. This emphasises the importance of feed rate in optimising ECM procedures for MMC machining.
2. The optimal surface roughness (Ra) is produced by combining a voltage of 20 V, a feed rate of 0.4 mm/min, and an electrolyte concentration of 30 g/lit. This represents the possibilities for improving surface quality by carefully selecting ECM parameters.
3. The maximum material removal rate (MRR) is achieved by combining voltage at 25 V, feed rate at 0.4 mm/min, and electrolyte concentration at 30 g/lit (A3, B3, C3). This emphasises the necessity of parameter optimisation in increasing material removal efficiency.

The novelty of this research lies in its focused exploration of MMC machining within ECM, aiming to enhance both surface roughness and material removal rate simultaneously. By identifying optimal parameter combinations and their implications on machining performance, this work provides new insights into ECM's potential for MMC processing. Looking ahead, further research could focus on enhanced optimisation approaches and the integration of innovative materials and ECM methodologies. Furthermore, the creation of predictive models based on experimental data could simplify parameter selection and improve ECM process efficiency. Overall, this research provides the framework for future advances in ECM-based machining of MMCs, paving the door for higher productivity and surface quality in industrial settings.

Table 8. TOPSIS optimization table for ECM process

Voltage (v)	Feed Rate (mm/min)	Electrolyte concentration (g/lit)	Ra	MRR	Si+	Si-	Pi	Rank
15	0.2	10	2.04	0.169	0.1562	0.0566	0.2661	25
15	0.2	20	2.09	0.237	0.1457	0.0518	0.2622	26
15	0.2	30	1.69	0.127	0.1557	0.0777	0.333	20
15	0.3	10	2.01	0.253	0.1406	0.0563	0.2857	23
15	0.3	20	1.59	0.348	0.1124	0.0824	0.4229	16
15	0.3	30	1.82	0.32	0.1235	0.0686	0.3569	19
15	0.4	10	1.69	0.589	0.076	0.1019	0.5728	8
15	0.4	20	1.45	0.454	0.0897	0.0972	0.5201	10
15	0.4	30	1.32	0.603	0.0602	0.1194	0.665	4
20	0.2	10	1.99	0.221	0.1456	0.0575	0.2832	24
20	0.2	20	1.89	0.229	0.1415	0.063	0.308	21
20	0.2	30	1.39	0.388	0.1004	0.0953	0.4871	13
20	0.3	10	1.64	0.279	0.1262	0.0771	0.3793	18
20	0.3	20	1.49	0.202	0.1376	0.0856	0.3834	17
20	0.3	30	1.09	0.483	0.0765	0.1179	0.6063	6
20	0.4	10	1.39	0.515	0.0773	0.1061	0.5786	7
20	0.4	20	1.44	0.519	0.078	0.1042	0.5717	9
20	0.4	30	0.69	0.712	0.0268	0.1607	0.8572	2
25	0.2	10	2.59	0.182	0.1709	0.027	0.1366	27
25	0.2	20	1.89	0.499	0.0967	0.0815	0.4571	15
25	0.2	30	1.69	0.5	0.0893	0.0904	0.5033	12
25	0.3	10	2.3	0.426	0.1234	0.0545	0.3064	22
25	0.3	20	1.99	0.588	0.0891	0.0903	0.5035	11
25	0.3	30	1.59	0.63	0.0663	0.1117	0.6275	5
25	0.4	10	2.09	0.58	0.0946	0.0856	0.4752	14
25	0.4	20	1.49	0.787	0.046	0.1393	0.7517	3
25	0.4	30	1.09	0.844	0.0223	0.1624	0.8794	1

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