Production of Aluminum 6063 Metal Matrix Composite with 12% Magnesium Oxide and 5% Graphite and its Machinability Studies using Micro Electrochemical Machining

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ABSTRACT

Hybrid Aluminum Metal Matrix Composites (AMMCs) are finding application in aerospace and automobile industries for its light weight. In this research hybrid AMMCs with 12% magnesium oxide (MgO) and 5% graphite (Gr) were fabricated and mechanical properties were studied. The compressive strength, bending stress frictional force, impact strength are found to be 292.94 N.mm^{-2}, 1.31 N.mm^{-2}, 11.3 N (maximum) J.m^{-2} = 0.4x10^5 respectively. Moreover the highest hardness values are obtained during Brinell and Rockwell testing's 127.23 BHN, 59 HRB respectively. Machinability studies using micro electrochemical machining (micro ECM) is performed on the hybrid AMMCs by varying the voltage, electrolyte concentration, duty cycle and electrolyte temperature. L$_9$ Orthogonal array (OA) is conducted and the experimental results are analyzed using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. Based on the TOPSIS analysis the optimal combination for the higher MRR and lesser OC is 9 V,25 gm.L^{-1},80 % duty cycle and 35ºC electrolyte temperature (A$_2$B$_2$C$_3$D$_1$). Analysis of Variance (ANOVA) shows that the duty cycle is the most significant factor followed by voltage and electrolyte temperature for higher material removal rate (MRR) and lower overcut (OC).

1. INTRODUCTION

The structural and non-structural applications use aluminum-based metal matrix composites (AMMCs) for its advantage namely higher specific strength and modulus [1]. Research on production of hybrid AMMCs is performed by many researchers, Reddy et al., [1] have developed and tested aluminium 6061-silicon carbide, boron carbide MMCs. The tensile, flexural, hardness and impact tests were performed and results shows that the hybrid composites had better properties than pure aluminum. Inegbenebor et al., [2] have used two-step mixing method of stir casting technique for production of aluminum (99.66 % C.P) and SiC (320 and 1200 grits). Reinforced aluminum silicon carbide showed an increase in Young's modulus (E) and marginal reduction of electrical conductivity. Arunachalam et al., [3] have used stir squeeze casting for production of MMCs and optimized the production process using Taguchi Grey method. Narayan et al., [4] have studied the tensile, impact and hardness of the hot forged aluminium metal matrix composites. The hardness and ultimate tensile strength of carbide reinforced AMMCs were found to be higher for water-cooled compared to furnace-cooled technique for direct sinter-forged cooling. Subbarao et al., [5] have studied mechanical properties like hardness, tensile strength, yield strength, % of elongation of AA6061 matrix with Boron carbide (B$_4$C) particles. The mechanical properties found to increase with increase in wt. % of the reinforcement up to 4% B$_4$C. Munisamy et al., [6] studied effect of zircon sand and boron carbide on the mechanical properties of Al6061. The mechanical testing of AMMCs

shows that the addition of zircon and B$_4$C improves the hardness, impact and flexural strength. The suitable application of AMMCs depends on the machining methods. The use of conventional machining methods for processing of AMMCs induce poor quality and residual stress on the products, on other way the use of non-conventional machining technique overcomes the difficulties of the former method [7]. Among the various existing methods, micro ECM is found suitable for machining AMMCs [8]. Recently researchers are working on machining of AMMCs using micro ECM. Maniraj et al., [9] have used micro ECM to machine AMMCs and reported that the heat electrode has significant effect on machining rate and accuracy. They have also optimized the micro ECM process parameters using TOPSIS method and percentage reinforcement of ground-granulated blast furnace slag has the significant effect on the machining speed and accuracy [10]. Prakash et al., [11] have analyzed the micro ECM performance using Teaching-Learning-Based Optimization (TLBO) algorithm and RSM method on AA7075 reinforced with nano silicon carbide particles and the results of these analysis are similar. Sathishkumar et al., [12] have fabricated the Al6061+ (6wt % SiC + 4wt % Gr) composites using stir casting process. The use of stir casting method improves the ductility and strength of this material when combined with SiC. Moreover they machined AMMCs using electrochemical machining parameters using L$_{27}$ OA experimental design and optimized the MRR and OC. Hynes et al., [13] critically reviewed the research work on ECM of AMMCs. They reported that, an increase of voltage, tool feed rate, electrolyte concentration, percentage reinforcement and

flow rate significantly influence the MRR. Jayaganthan et al., [14] studied the influence of micro ECM process parameters on magnesium based hybrid MMC through Taguchi approach. ANOVA results shows that the applied voltage is a major influencing parameter to affects the MRR and surface roughness of the developed MMC. Rajan et al., [15] have investigated the effect of ECM process on AMMCs reinforced with varying percentage of B_4C using the induction heated electrolyte. The use of induction heated electrolyte governs the machining rate and accuracy. Kalra et al., [16] have machined micro-hole on stir-cast hybrid aluminum/(alumina + silicon carbide + carbon particulates) metal matrix composite using micro ECM. The optimal process parameter combination for high machining rate with low taper OC, OC, and micro spark affected zone is 1.5A, 13V, 10μs pulse-on time, 10μs pulse-off time, 15g/L electrolyte concentration, and 0.2L/min electrolyte flow rate. Rajan et al. [17] have machined Al7075 using ECM and studied the effect of electrolyte temperature on depth of the micro-hole. The temperature of the electrolyte shows significant effect on the ECM. Shanian and Savadogo [18] have applied multiple-criteria decision analysis method namely TOPSIS for resolving the material selection problem of metallic bipolar plates for polymer electrolyte fuel cell. They reported that the TOPSIS is a potential method for solving the material selection problem.

It evident from the above literatures that production and mechanical properties of MMCs are studied by the researchers and machinability studies on hybrid AMMCs using micro ECM is sparse. Hence in this research the hybrid AMMCs is fabricated using aluminium 6063 reinforced with 12% magnesium oxide (MgO_2) and 5% graphite (Gr). The hybrid AMMCs developed is subjected to the various tests like impact, bending, hardness and wear and the results are obtained. Moreover to study the machinability of the hybrid AMMCs in micro ECM, the L_9 Orthogonal array(OA) design of experiments is used to drill blind micro-hole by varying the voltage, electrolyte concentration, duty cycle and electrolyte temperature. The aim of this work is to use the micro ECM setup for conducting the experiments. The setup consists of pulsed power supply, machining chamber, electrode and electrolyte supply system and electrolyte heating unit. Then, the TOPSIS and ANOVA methods are used to analyse the results of the experiments and determine similarities which may form data that exist on them. Based on the TOPSIS and ANOVA the electrical parameter shows the most significant contribution for higher MRR and lower OC.

2. EXPERIMENTAL SETUP

The hybrid AMMCs is developed using magnesium oxide and graphite as reinforcement on aluminium matrix. The ratio of these materials is aluminum 6063 with 83%, magnesium oxide with 12% & graphite with 5%. Argon gas plays a major role in casting process from beginning to end of this process. The hybrid AMMCs is made up of stir casting process and 600 gm of aluminum pure metal is heated upto 720ºC in resistance furnace. The reinforcement is preheated upto 300ºC for time duration to reduce the moisture. The stirring was maintained between 5 to 7 min at an impeller speed of 200 rpm. After melting, the molten metal is poured into the prepared die to make the required workpiece. Manganese, calcium silicate and aluminum are added into the furnace while heating to protect

AMMCs from cracking. The hybrid AMMCs is annealed to improve the strength of the composite material and finished by fettling process. The fabricated hybrid MMCs then cut to the ASTM standards for mechanical testing. ASTM E9-09 and ASTM E855 – 08 standard is followed for the compression test and bending test respectively. ASTM E23–18 is standard test methods for notched bar impact testing of specimen. A ball indenter of diameter 1.588 mm (1/16′) and load of 100 kgf are applied for 15s in the Rockwell hardness tester using the B-scale. Hardness readings were taken at different points on each specimen to obtain a representative average value. ASTM E18–20 standard test method is used for Rockwell hardness testing. A Brinell hardness with ball indenter of diameter 10mm and load of 500kgf is applied to known the Brinell hardness number. Wear tests were carried out in accordance with ASTM G99 on samples with a diameter of 10mm and height of 30mm. The load of 3 kg, speed of 500 rpm is applied for 300sec. Surface is prepared using fine sandpaper and alcohol washing. A pin-on-disc experiment is conducted in a DUCOM make.

The fabricated hybrid AMMC specimen is machined using micro ECM with various input parameters such as voltage, electrolyte concentration, duty cycle and temperature of the electrolyte on MRR and OC. L_9 OA experiments were conducted and process parameters and levels are presented in the Table 1 and results of the experiments are presented in the Table 2 [15]. The MRR is calculated by subtracting the weight of the material before and after machining with respect to time. The diameter OC is calculated by subtracting the micro-hole diameter from the diameter of the tool electrode of 500 μm. The thickness of the work piece is 1.5 mm. The sodium nitrate ($NaNO_3$) electrolyte is prepared by mixing the required amount of salt with one litre of distilled water. The electrolyte is heated using immersion water mini heater (250W) and temperature of the electrolyte is noted using the non-contact temperature detector. The TOPSIS and ANOVA methods are used to analysis the results of the experiments. The micro ECM setup is used for conducting the experiments. The setup consists of pulsed power supply, machining chamber, electrode and electrolyte supply system and electrolyte heating unit.

Table 1. Factors and levels

Factors	Notation	Level 1	Level 2	Level 3
Voltage (V)	A	7	9	11
Electrolyte concentration (gm.L^{-1})	B	15	25	35
Duty cycle (%)	C	50	65	80
Electrolyte temperature(ºC)	D	35	38	40

Table 2. L_9 OA and responses

Expt. No.	A	B	C	D	MRR gm.hr^{-1}	OC (μm)
1	7	15	50	35	4.76	314
2	7	25	65	38	4.86	216
3	7	35	80	40	5.20	131
4	9	15	65	40	5.22	162
5	9	25	80	35	5.45	100
6	9	35	50	38	5.98	143
7	11	15	80	38	6.66	122
8	11	25	50	40	6.72	132
9	11	35	65	35	6.90	202

3. RESULTS AND DISCUSSION

The ASTM standard specimen is imparted for the compressive load to determine the compressive strength of the specimen. The area of the specimen considered is 360 mm^2 and the failure load is 10750kgf. Hence the compressive strength is nothing but load by area, the calculated compressive strength of the specimen is 292.94 N.mm^{-2}.

The bending stress is nothing but 3PA/bd^2 where is the length of the specimen (155 mm),b is the breath of the specimen (27 mm), d is the thickness (10 mm) and P is the load at the failure(60 kgf). The estimated bending stress of the specimen is 1.31N.mm^{-2}. The specimen is also subjected to Rockwell (B scale) testing and based on the testing the Rockwell hardness numbers is found to be 50 HRB, 59 HRB, 54 HRB. The specimen had the highest hardness (59 HRB) due to the small size of its mixing ratio of Mg and Gr particles. The average grain size of the composite also contributed to its high hardness value since the grain boundaries acted as barriers for the propagation of dislocations. In Brinell hardness for impression diameters of 2.2mm, 2.3mm, 2.4mm the Brinell hardness number is found to be 127.23 BHN, 117.92 BHN, 109.89 BHN respectively as per the below mentioned Equation 1.

$$BHN = \frac{P}{\left(\frac{\pi D}{2\left(D - \sqrt{D^2 - d^2}\right)}\right)} \qquad (1)$$

The frictional force of 11.3 N (maximum) is obtained during wear test and impact strength of the specimen is calculated and it is found to be J.m^{-2} = 0.4x10^5. Area of cross section of specimen (A) = b x (d – d$_1$) mm^2.Impact strength (I) = K / A (J.mm^{-2}), Breath (b) =10 mm, Depth (d) =10 mm, Depth of notch (d$_1$) = 5 mm, Impact energy (K) = 2 J.

4. MULTI-CRITERIA OPTIMIZATION

4.1 TOPSIS Method

TOPSIS is a competent multi criteria decision making tool for solving complex problems. So multi objective optimization like TOPSIS method is used to overcome or ensure the result which obtained from the other techniques.

In this research original TOPSIS method is used and which is effective in solving multi criteria decision making problems. In TOPSIS method a multi-criteria optimization problem is thus converted into a single objective optimization problem using a combined approach. The normalized matrix, weighted normalized decision matrix, separation of alternatives from ideal and non ideal solutions and preference values for TOPSIS obtained for each experimental run with the ranking order are presented. The closeness co-efficient to the ideal solution and its highest rank is considered as the best value and performance measure for the process. The step-by-step procedure for TOPSIS is as follows [15].

Create the decision matrix consisting of x alternatives and y criteria, by using the Equation 2.

$$\text{Decision Matrix} = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \dots & \lambda_{1y} \\ \lambda_{21} & \lambda_{22} & \dots & \lambda_{2y} \\ \dots & \dots & \dots & \dots \\ \lambda_{x1} & \lambda_{x2} & \dots & \lambda_{xy} \end{bmatrix} \qquad (2)$$

Estimate the normalized decision matrix, the normalized value δ_{ij} is calculated by the Equation 3.

$$\delta_{ij} = \frac{a_{ij}}{\sqrt{\sum_{j=1}^{m} a_{ij}^2}} \qquad (3)$$

j= 1,2,3,………,x , i=1,2,3,……..y.

Calculate the weighted normalized decision matrix by using Equation 4.

$$q_{ij} = \alpha_i\, \delta_{ij} \qquad (4)$$

j=1,2, 3,……,x , i=1,2,3,……..y.

Find positive-ideal and negative-ideal solutions from the following expressions 5 & 6

$$S^+ = \left(q_1^+, q_2^+, \dots q_y^+\right) \text{ for max values} \qquad (5)$$

$$S^- = \left(q_1^-, q_2^-, \dots, q_y^-\right) \text{ for min values} \qquad (6)$$

Obtain separation measures by using the following expressions 7 & 8.

$$d_j^+ = \sqrt{\sum_{i=1}^{n} \left(q_{ij} - q_i^+\right)^2} \qquad (7)$$

j=1, 2,……..x.

$$d_j^- = \sqrt{\sum_{i=1}^{n} \left(q_{ij} - q_i^-\right)^2} \qquad (8)$$

j=1, 2,……..x

Calculate the relative closeness coefficient by using the following Equation 9.

$$P_i = \frac{d_j^-}{d_j^+ + d_j^-} \qquad (9)$$

The normalization values, weighted normalization values, separation measures and closeness coefficient values are listed in Table 3. In this study, equal priority is given to all the three responses. Based on the TOPSIS analysis the optimal combination for the higher MRR and lesser OC is 9V, 25 gm.L^{-1}, 80% duty cycle and 35ºC electrolyte temperature (A$_2$B$_2$C$_3$D$_1$).

Table 3. Preference value of responses

δ_{ij}		q_{ij}		S⁺	S⁻	P_i	Rank
0.2734	0.5809	0.1367	0.2904	0.1979	0.0615	0.2369	9
0.2791	0.3996	0.1396	0.1998	0.1073	0.1079	0.5014	7
0.2987	0.2423	0.1493	0.1212	0.0313	0.1762	0.8490	2
0.2998	0.2997	0.1499	0.1498	0.0588	0.1486	0.7164	6
0.3130	0.1850	0.1565	0.0925	0.0198	0.2023	0.9108	1
0.3435	0.2645	0.1717	0.1323	0.0530	0.1604	0.7516	4
0.3825	0.2257	0.1913	0.1128	0.0582	0.1777	0.7532	3
0.3860	0.2442	0.1930	0.1221	0.0636	0.1684	0.7259	5
0.3963	0.3737	0.1981	0.1868	0.1126	0.1036	0.4792	8

The column headers for δ_{ij} and q_{ij} each span two data columns.

4.2 Mean Effect Plot

The mean effect plot shown in Figure 1 shows the voltage at level 2, electrolyte concentration at level 2, duty cycle at level 3 and electrolyte temperature at level 3. Based on mean effect Table 4 the optimal combination for the higher MRR and lesser OC is 9 V, 25 gm.L⁻¹, 80% and 40ºC.

Table 4. Mean effect table

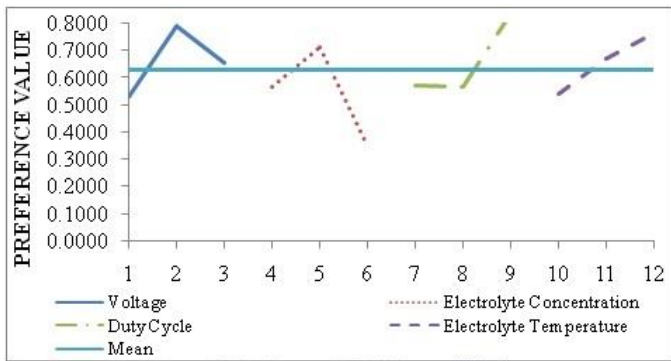| Factors	Level 1	Level 2	Level 3
A	0.5291	0.7929	0.6528
B	0.5688	0.7127	0.3466
C	0.5715	0.5656	0.8377
D	0.5423	0.6687	0.7638

Figure 1. Mean effect Plot

4.3 Characteristics of ANOVA

ANOVA is a set of statistical method used by Ronald Fisher, a statistician and evolutionary biologist, to calculate the differences among group means and their related procedures. ANOVA test are useful for comparing three or more groups/ variables for statistical significance. Formulae for ANOVA is as follows[19]:

$$\text{Total Sum of Squares (SS}_T) = \sum_{i,j=1}^{n}(x_{ij} - \ddot{x})^2 \qquad (10)$$

$$\text{Sum of squares within groups (SS}_G) = \sum_{i=1}^{n}(x_i - \ddot{x})^2 \quad (11)$$

$$\text{Error of sum of square (SS}_E) = \sum_{i=1}^{n}(x_{ij} - \bar{\bar{x}}_i)^2 \qquad (12)$$

$$\text{Therefore, SS}_T = \text{SS}_G + \text{SS}_E \qquad (13)$$

$$\text{Mean square of standard deviations (MS)} = \frac{SS_T}{DF} \qquad (14)$$

$$\text{Fisher Test value} = \frac{MS_G}{MS_E} \qquad (15)$$

$$\text{Percentage of Contribution} = \frac{SS_D}{SS_T} \qquad (16)$$

Where, $MS_G = \frac{SS_G}{DF_G}$, $MS_E = \frac{SS_E}{DF_E}$, DF = Degree of Freedom, MS_G = Mean Square Error, MS_E = Residual Error, SS_D = Sum of Square of deviations, n = No. of all individuals in experimental trials, i = No. of levels in experimental design, j = No. of tests in experimental design, $\ddot{x}$ = Grand mean of SNR or S/N ratio values x, x_{ij} = SNR value of iᵗʰ level, jᵗʰ test, x_i = SNR value of ith level, $\bar{\bar{x}}_i$ = Mean of SNR for iᵗʰ level

Moreover, the F-test named after fisher is also used to find out which factor have a major contribution on the performance characteristics [19]. Generally, the change of the process parameter has a notable effect on the performance measure when the F-value is large.

5. EFFECT OF PROCESS PARAMETERS

5.1 Effect of voltage

It is evident from the table 2 that higher voltage shows better MRR and OC. During higher voltage the current required for machining is more; moreover the electrolyte temperature improves the machining efficiency contributes for higher MRR. During the increase in electrolyte temperature the micro stirring effect dispels the debris from the machining zone resulting in lesser OC. Figure 2 shows the blind micro hole machined at 11 V, 15 gm.L⁻¹, 80 %, 38 ºC. It is clear from the SEM micrograph that profile of the blind micro hole is found to be circular.
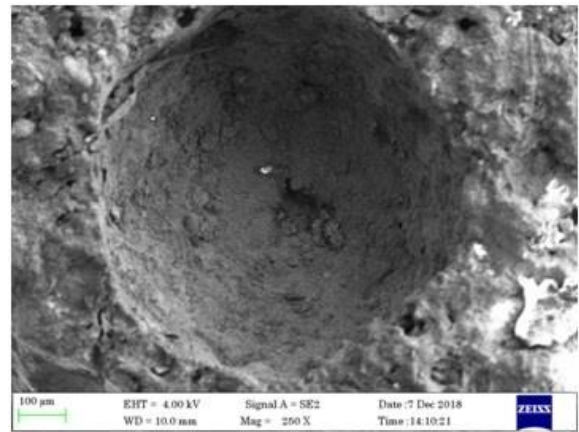

Figure 2. Circular micro-hole machined at 11V, 15 gm.L⁻¹, 80 % and 38 ºC

5.2 Effect of electrolyte concentration

The electrolyte concentration has significant effect on MRR and OC. The medium level of electrolyte concentration found to be suitable for higher MRR and lesser OC. Based on the mean effect plot the electrolyte concentration of 25 gm.L⁻¹ is found to be suitable for better output performance. The lesser electrolyte concentration will have insufficient amount of ions required for machining, moreover higher electrolyte concentration supply more ions hence the amount of sludge formation reduces the machining efficiency. Figure 3 shows the over etched blind micro-hole machined at 7V, 35 gm.L⁻¹,

80% and 40ºC. The sludge formation in between the inter electrode gap obstructs the current density required for machining and resulting in unstable machining. The distribution of current density causes the stray current effect on the workpiece. This stray current effect results in over etched surface on the workpiece. Moreover, the increase in temperature of the electrolyte improves the movement of ions in the electrolyte, contributing for higher MRR. The faster machining reaction due higher concentration and heating of electrolyte removes the wanted material from the workpiece resulting in over etched blind holes.

Figure 3. Over etched blind micro-hole machined at 7 V, 35 gm.L⁻¹, 80 % and 40ºC

5.3   Effect of duty cycle

The ratio of pulse on time to total time is called duty cycle and the machining is performed at 50 Hz and 1 A constant frequency and current respectively. Higher duty cycle shows higher MRR and lesser OC. At higher duty cycle the pulse time required for the machining is more which removes more materials for longer duration. Hence during higher pulse on time the more MRR takes and additionally the higher electrolyte temperature increase the concentration of the electrolyte. These increases in concentration make more ions available in the machining zone leading to higher machining efficiency. Figure 4 shows the blind micro-hole machined at 9V, 25 gm.L⁻¹, 80% and 35ºC.

Figure 4. Blind micro-hole machined at 9 V, 25 gm.L⁻¹, 80 % and 35 ºC

6. ANALYSIS OF MACHINED SURFACE

The fabricated work piece material is analyzed using energy dispersive X-ray spectroscopy (EDAX). The EDAX test is conducted on the blind hole and on the circumference of the blind micro-hole. Based on the Figure 5(a&b), it is clear that there is equal distribution of reinforcement particles within the composites are observed. The EDAX confirms the presence oxides like silicon dioxide, aluminium oxide, calcium oxide and magnesium oxide. During micro ECM process the generation of oxides attribute for cluster of pits in the machining zone which is clearly noticed in the Figure 3. From the Figure 6 (a&b), it is observed that other elements such as Mn, Fe, Ni and Cu are present in the matrix material.
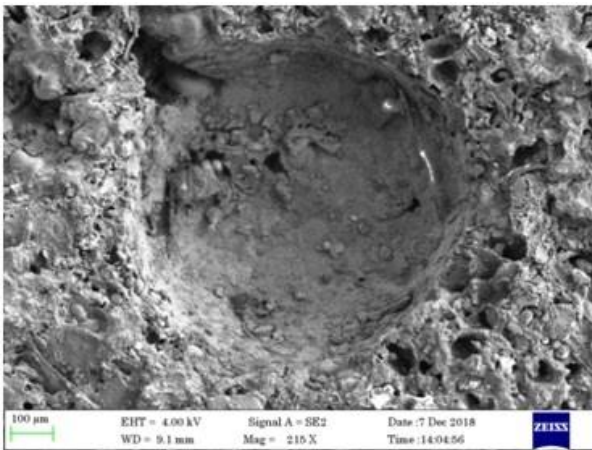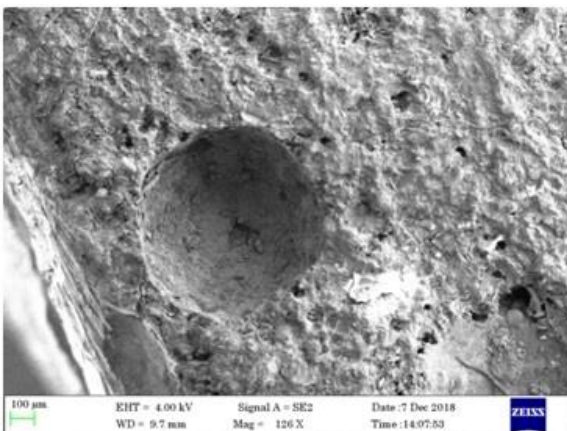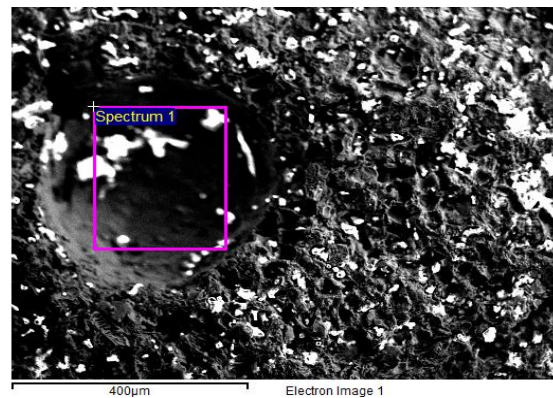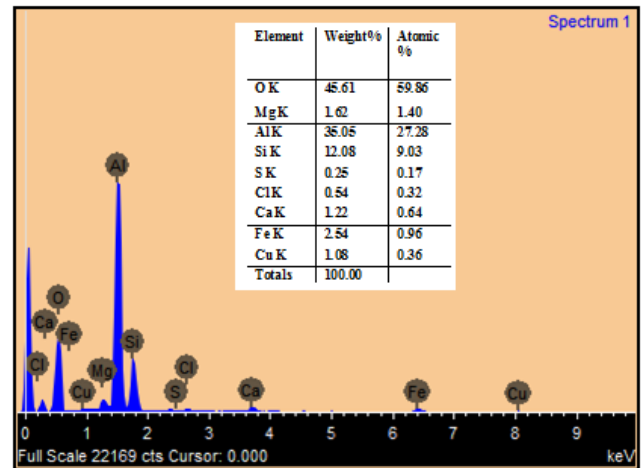

Figure 5(a). EDAX analysis on the micro-hole

Element	Weight%	Atomic %
O K	45.61	59.86
Mg K	1.62	1.40
Al K	35.05	27.28
Si K	12.08	9.03
S K	0.25	0.17
Cl K	0.54	0.32
Ca K	1.22	0.64
Fe K	2.54	0.96
Cu K	1.08	0.36
Totals	100.00	

Figure 5 (b). Results of EDAX analysis

Figure 6(a). EDAX analysis on the outer region of the micro-hole

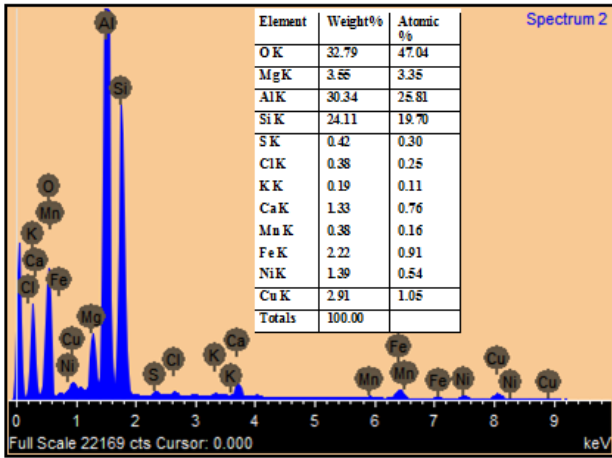| Element	Weight%	Atomic %
O K	32.79	47.04
Mg K	3.55	3.35
Al K	30.34	25.81
Si K	24.11	19.70
S K	0.42	0.30
Cl K	0.38	0.25
K K	0.19	0.11
Ca K	1.33	0.76
Mn K	0.38	0.16
Fe K	2.22	0.91
Ni K	1.39	0.54
Cu K	2.91	1.05
Totals	100.00	

Figure 6(b). EDAX analysis results on the outer region of micro-hole

7. ANALYSIS OF VARIANCE (ANOVA)

The effect of individual factors on MRR and OC is analyzed using ANOVA. The machining parameters and its degrees of freedom are presented in the table 5. Each factor has three levels and the degrees of freedom are number of levels -1 and hence each factor has 2 degrees of freedom. The sum of the squares (SS) and mean sum of the squares (MS) are calculated and presented in the table. Higher the F values shows significant contribution and hence duty cycle shows 0.2533 which is of 40.24% compared to other parameters. Next contributing factors are voltage followed by electrolyte temperature. Electrolyte temperature shows 20.57% significant contribution among all factors.

Table 5. Parameters of the Analysis of Variance

Symbol	DF	SS	MS	F	% Contribution
A	2	0.1045	0.0523	0.1828	29.0345
B	2	0.0366	0.0183	0.0639	10.1528
C	2	0.1449	0.0724	0.2533	40.2413
D	2	0.0741	0.0370	0.1295	20.5714
E	1	0.2860	0.2860		0.0000
	9	0.6460	0.0718		100

8. CONCLUSIONS

1. Hybrid aluminium MMCs with 12 % magnesium oxide (MgO) and 5 % graphite (Gr) were fabricated and mechanical properties were studied. The compressive strength, bending stress frictional force, impact strength were found to be 292.94 N.mm^{-2}, 1.31 N.mm^{-2}, 11.3 N (maximum) J.m^{-2} = 0.4x10^5 respectively.
2. The highest hardness value is obtained during Brinell and Rockwell testing 127.23 BHN, 59 HRB respectively.
3. Machinability testing using micro electrochemical machining (micro ECM) is performed on the hybrid AMMCs by varying the voltage, electrolyte concentration, duty cycle and electrolyte temperature.
4. L$_9$ OA is conducted and the experimental results are analyzed using the TOPSIS method. Based on the TOPSIS analysis the optimal combination for the higher MRR and lesser OC is 9V, 25 gm.L^{-1}, 80% duty cycle and 35 ºC electrolyte temperature (A2B2C3D1).
5. ANOVA shows that the duty cycle is the most significant factor followed by voltage and electrolyte temperature for higher material removal rate (MRR) and lower over cut (OC).
6. The experimental results obtained from TOPSIS and ANOVA shows that the electrical parameters such as higher level of duty cycle and medium level of voltage shows a significant contribution on the MRR and OC. Moreover electrolyte temperature shows 20.57% significant contribution among all factors.
7. Based on mean effect table the optimal combination for the higher MRR and lesser OC is 9 V, 25 gm.L^{-1}, 80 % and 40 ºC.
8. The EDAX confirms the presence and significant distribution of major alloying elements like silicon, aluminium, calcium and magnesium. Moreover the oxides are formed after the micro-ECM process.

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