Performance Study of Electrochemical Micromachining of Al7075/Al2o3 Composite

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ABSTRACT-*Micromachining domain requires machining techniques that would fulfill the severe demands like machining quality, higher machining rate, dimensional accuracy, economy and so on. Among the many available non-conventional machining methods electrochemical machining is under continuous research to adopt it on commercial scale to fulfill the industry-specific applications. Al7075, a heat treatable alloy is widely employed for structural components in automotive and aero-space industries. Composites are made out of Al7075 alloy to enhance its properties by reinforcing with appropriate ceramic compounds. This study examines the applicability of electrochemical micromachining (EMM) to Al2O3 added Al7075 composite. The process input factors investigated are voltage, duty cycle and electrolyte concentration and the performance analyzed through responses such as machining rate (MR) and radial overcut (ROC). Taguchi's L9 design is used for experimental investigation to find the effect of process parameters and also carry out single-response as well as TOPSIS optimization. Electrolyte concentration was found to be the dominant parameter on the process. The TOPSIS method yielded the parametric combination of 12V, duty cycle of 70% and NaNO3 concentration of 40 g/lit to achieve higher MR and lower ROC.*

Keywords: Electrochemical micromachining; Al7075/ Al2O3 composite; machining rate; radial overcut; Taguchi; TOPSIS

1. INTRODUCTION

As an energy saving measure and to make the structures light-weight, structural components in many industries are now made with lighter materials like aluminium alloys instead of using heavier materials. Al7075 alloys particularly find application in automobile, aero and mobile industries to exploit their superior mechanical properties [1]. Still these light-weight materials like Al7075 are found deficient to certain extent like in hardness and tensile strength which can be enhanced by reinforcing hard ceramic particles into the such as Al2O3 and others into the matrix of the alloy in an uniform manner [2]. The capability of electrochemical micromachining process is tested through experimentation for different materials like pure metals, alloys and composites, different electrolytes and also applying various input conditions and approaches. Nimonic 75 alloy used in aero industry has been machined under EMM successfully using acidified electrolyte and un-acidified electrolyte (NaNO3+NaCl). The un-acidified electrolyte provided better performance and the parameters have been optimized using Topsis technique [3].Micro-circular impressions have been generated on stainless steel work-piece using EMM and it has reported that lesser pulse-on time, higher frequency level and usage of mixed electrolyte (sodium nitrate & sodium chloride) yielded good results [4]. The inner walls of cooling channel has also been machined for turbulation purpose through EMM by using electrically conducting gelatinous electrolyte at selected regions in the work-piece [5].Three different electrode materials, namely copper, bronze and tungsten-carbide have been used as tool electrodes to machine nickel-aluminium-bronze alloy to compare their performance. Copper removed maximum amount of material, tungsten-carbide provided good surface quality and less overcut while bronize exhibited moderate performance between these two materials [6]. In the process of EMM study, temperature effect on outcomes has also been studied by applying ultraviolet rays to the electrolyte solution to raise temperature to three different levels. The study has also employed three different optimization methods like GRA (Grey Relational Analysis), VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenjeto) and TOPSIS (The optimization techniques such as similarity to ideal solution) to compare the results [7]. Attempts have also been made to generate square holes through EMM process on SS-321 specimen using H2SO4 solution [8]. Even magnetic fields have also been used to localize the machining and avoid machining spreading to other adjacent areas [9]. Aluminium7075 composite reinforced with alumina and borosilicate glass powder has been machined under EMM to produce micro-holes on it using NaNO3 and NaCl electrolytes individually. Sodium chloride solution performed lesser due to its aggressive nature. The optimized input combination reported is 10 Volts of voltage , 1.2 Ampere of current and 12 micro-seconds pulse-on time [10]. To reduce the defects in the process of EMM, laser energy assisted hybrid machining has been applied and the process quality improved [11]. EMM process has also been applied using mask of non- conducting type on the surface not requiring machining and quality micro holes were obtained [12]. An aluminium composite containing Al6061+ GGBS (ground granulated blast furnace slag) has also been machined under EMM process using NaNO3 solution to investigate the effect of reinforcement percentage. It is reported that increase inall input parameters like machining voltage, duty-cycle, electrolyte-concentration and percentage of reinforcement increased both machining rate and the overcut of the machined micro-hole [13]. Blind holes have been machined on high proportion ceramic compounds added aluminium composite (Al+SiC) through electrochemical jet machining using sodium chloride solution. The process caused many micro-pits on the surface of the work material due to jet effect and the un-dissolving nature of SiC particles. The process has been recommended for aluminium composites containing large fraction of ceramic compounds [14]. Al7075 composite machined under EMM process using sodium nitrate solution heated through induction heating. The performance was revealed through machining speed, overcut of the hole and delamination formation and the process parameters were optimized using TOPSIS technique [15].

2. MATERIALS AND METHODS OF EXPERIMENTATION

The experimental setup used for the study is given in figure 1. The setup comprises all the essential sub-units required to carry out electrochemical micro-machining in a single axis of vertical tool movement along with a pulse generator to provide pulsed power. Compared to continuous power,the use of pulsed power provides pulse-off time during every pulse period during which the machining stops and the time is utilized to flush the debris from the machining site [16].

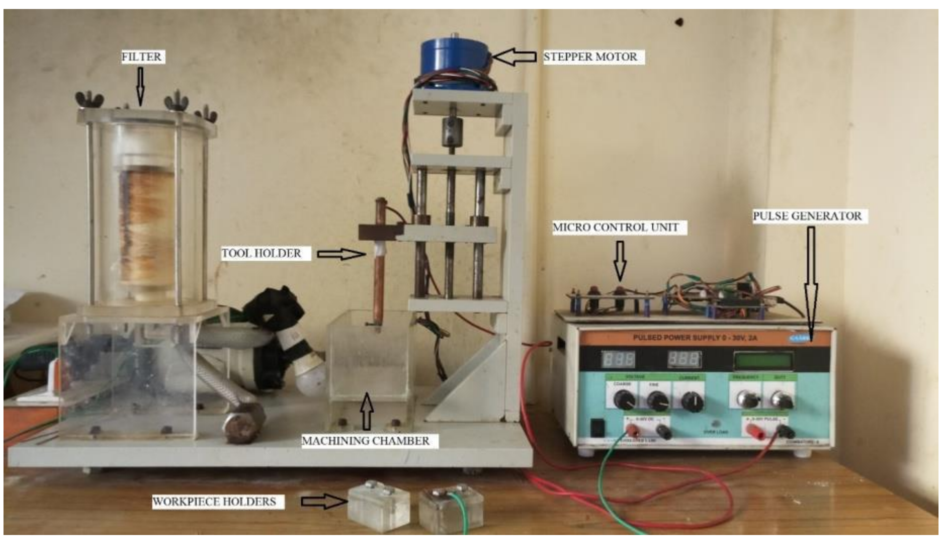

Fig. -1: EMM setup with assembly of all sub-units

The work material used as anode was Al7075 composite containing 2% of Al2O3 ceramic compound. The work material was cut to 100 mm X 50 mm X 0.6 mm from the cast composite. A stainless steel needle of 850 micrometer diameter with conical end (400 micrometer diameter) was employed in the cathode terminal as tool. To control stray machining and ensure localized removal, the tool surface was insulated laterally with polymer material. The electrolyte used for the experiments was NaNO3 solution, a passive electrolyte known to produce quality machining.

The input factors considered for this investigation were machining voltage, duty cycle (It is the percentage of pulse-on time in the total pulse period of one pulse-on time + pulse-off time). and electrolyte concentration (taken in gram per litre) that were found to be among the dominant process parameters as per literature study [17]. The electrode gap of 40 micrometer and the current frequency of 50 Hertz are kept constant for all the experiments. For a frequency of 50Hz, one pulse period is 1/50, which is equal to 20 milli-seconds. Here the duty cycle of 60% refers to 12:8 i.e 12 milliseconds of pulse-on time and 8 milliseconds of pulse-off time in the total of 20 milliseconds. The process parameters and their applied levels are given in table 1.

Table -1: Process parameters and levels

Symbol used	Process parameter	Level; 1	Level: 2	Level: 3
V	Machining Voltage (V)	10	11	12
DC	Duty cycle (%)	60	70	80
EC	Electrolyte Concentration (g/lit)	30	40	50

The objective of the investigation is to drill micro-holes on the aluminium composite specimens through EMM and study the performance. The output parameters considered for performance evaluation are Machining Rate and Radial Overcut. The machining rate is estimated through dividing the thickness of the work material by machining time. The radial overcut is obtained by dividing the difference between the diameter of the machined hole and the diameter of the tool by two.

The initial input parameters were set by running preliminary trial runs. The experimental input values have been designed as per Taguchi's L9 Orthogonal Array. The effects and contributions of each factor on the process have been studied and the input parameters have been optimized using TOPSIS technique to get a single set of optimal values to achieve both maximum machining rate and minimum radial overcut.

3. RESULTS AND DISCUSSION

The results obtained from the experimentation and the optimization process is discussed in the following sections.

3.1 Optimization Process

The experiments have been carried out as per L9 Orthogonal Array and the results calculated from the obtained readings of machining time and the micro-hole diameter are given below in table 2.

Table -2: Experimental Results

Ex. No.	Voltage (V)	Duty cycle (%)	NaNO3	Concentration (g/lit)	Machining Time (Sec)	
					Machining Rate (μm/s)	Radial Overcut (μm)
1	10	60	30	1038	0.578	284
2	10	70	40	810	0.741	157
3	10	80	50	738	0.813	134
4	11	60	40	789	0.760	103
5	11	70	50	813	0.738	189
6	11	80	30	729	0.823	317
7	12	60	50	675	0.889	84
8	12	70	30	801	0.749	158
9	12	80	40	573	1.047	149

32 Single –Response Optimization: Taguchi Process

In the Taguchi process, finding the Signal to Noise ratio is the crucial step in the process of optimizing the input parameters. The steps are discussed below.

SN ratio:

One of the objective of this investigation is improving the MR and reducing the overcut while processing the Al composite under EMM. The expressions used for the calculation of S/N Ratio varies depending on whether the said performance parameter is required to be improved, reduced or nominal. In this research increase in MR and decrease in overcut are required. Hence, higher the better for MR and smaller the better for overcut are used and the corresponding S/N ratio equations given in equations (1) and (2). Higher the Better:

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{y^2}\right) \frac{S}{N} = -10\ \boldsymbol{\log}\ \log\left(\sum \quad \left(\frac{1}{Y^2}\right)/n\right) \qquad (1)$$

Smaller the Better:

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right) \qquad (2)$$

Here, "n" is a total number of observations and "y" is the observed reading.

The S/N ratio responses and their mean effects plots are obtained by employing Minitab19 software. The Mean effects plots for MR and ROC are presented in figures 2 and 3 respectively.

3.3 Analysis of Machining Rate

From the analysis of the Main effects plot of MR (Fig. 2), the combination of voltage 12V, Duty cycle 80% and NaNO3 Concentration 40 g/lit are identified as optimal parameters for attaining maximum MR among the parameter levels applied.

The combination involves the high level input of voltage and duty cycle and the low level value of electrolyte concentration. When the voltage is high, the electron movements would be forceful and hence more number of ions are removed from the anode work material leading to increased machining rate. For increase in duty ratio, the pulse-on time increases which means more time is available for machining and naturally the machining rate tend to increase. In the case of increased electrolyte concentration, more ions will be available in the solution which may lead to clogging of inter electrode gap (machining area) or passivation mechanism. It is because of this reason that medium level of electrolyte concentration leads to maximum MR. Past research works have shown similar results in EMM study [18].

3.4 Analysis of Contribution of Input Parameters for MR

The contribution of different parameters applied in the process can be found out through analysis of variance and its outcomes are presented in table 4.

ANOVA for MR was done and the results are plotted in table 4. The ANOVA of MR, exhibits that voltage provides the most significant contribution of 40.51%. And duty cycle's contribution is 35.46% which also a significant factor.

Table -3: Response Table for SN Ratios of MR

Level	Voltage (V)	Duty cycle (%)	NaNO3 Concentration (g/lit)
1	-3.054	-2.722	-2.988
2	-2.238	-2.584	-1.529
3	-1.044	-1.030	-1.820
Delta	2.010	1.692	1.458
Rank	1	2	3

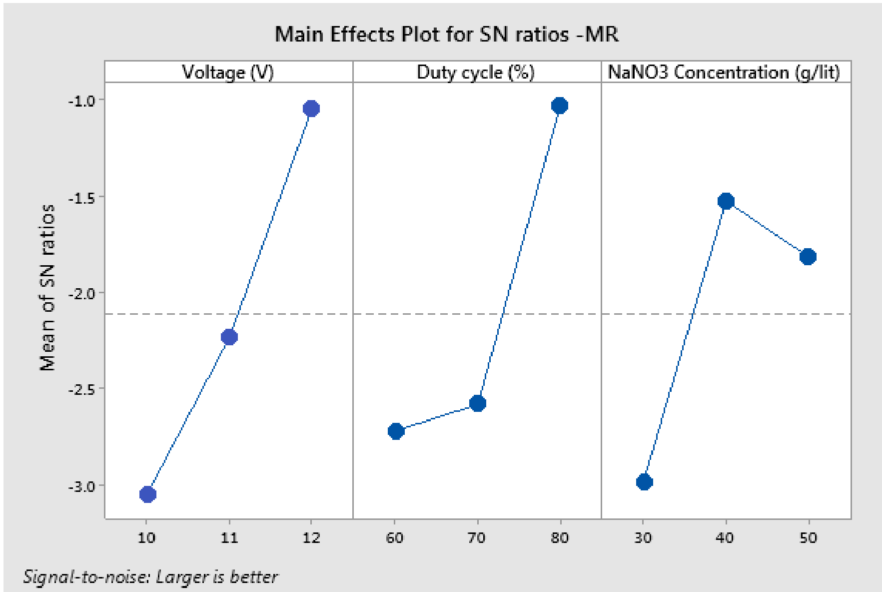

Chart -1: SN ratio Plot of MR

Table -4: Analysis of Variance of MR

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% contribution
Voltage (V)	2	0.052670	0.026335	17.59	0.054	40.51
Duty cycle (%)	2	0.046107	0.023053	15.40	0.061	35.46
NaNO3 Concentration (g/lit)	2	0.028241	0.014120	9.43	0.096	21.72
Error	2	0.002994	0.001497			2.30
Total	8	0.130011				100.00

3.5 Analysis of Radial Overcut

The main effects plot of ROC (Fig. 3) reveals that the optimal combination for attaining lower overcut is given by level 3 of voltage (high) and level 1 of duty cycle (low) and level 3 NaNO3 Concentration (high) which respectively are voltage 12V, Duty cycle 60% and NaNO3 Concentration 50 g/lit.

The optimized results clearly reveal that the voltage of 12V provides optimum force to the ions leading to increased machining speed and also restricting the tendency to stray cut. The duty cycle of level 1 gives the lowest possible pulse-on time and the maximum pulse-off time. When the pulse-off time is more, extended time will be available for flushing the debris from the machining area which lowers the tendency for stray machining. If the sledge deposited at the inter electrode gap are more it may cause short circuit resulting in sparks and cut the adjacent areas. The high level of electrolyte concentration produces required number of ions in the charge carrying solution to cause reactions in the machining area.

From the ANOVA values of ROC table 6, it can be noticed that, NaNO3 Concentration is the most dominant factor for ROC in the EMM process of Al composite compared to voltage and duty cycle which play less significant roles. It is clear from this revelation that electrolyte concentration level is significant for EMM as it is basically an ionic dissolution process that cause material removal from the anode material.

Table -5: Response Table for S/N Ratios of ROC

Level	Voltage (V)	Duty cycle (%)	NaNO3 Concentration (g/lit)
1	-45.18	-42.60	-47.69
2	-45.27	-44.47	-42.55
3	-41.97	-45.34	-42.19
Delta	3.29	2.74	5.50
Rank	2	3	1

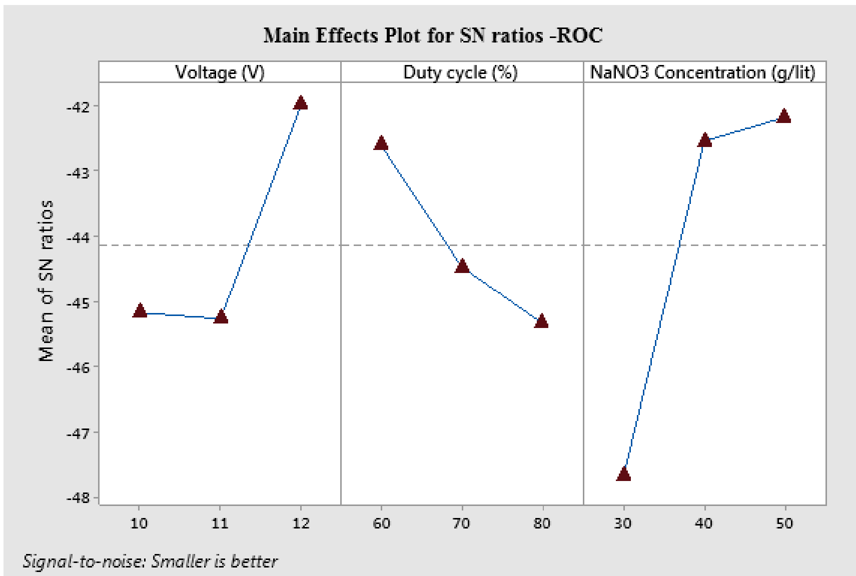

Chart -2: S/N ratio Plot of ROC

Table -6: Analysis of Variance of ROC

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% contribution
Voltage (V)	2	9171	4585	1.00	0.499	18.84
Duty cycle (%)	2	2994	1497	0.33	0.753	6.15
NaNO3 Concentration (g/lit)	2	27379	13689	3.00	0.250	56.25
Error	2	9133	4566			18.76
Total	8	48676				100.00

3.6 Multi-Response Optimization – Topsis

To achieve required magnitude of different performance parameters of a process from a single set of optimum input factors, multi-objective optimization is carried out. TOPSIS is one such optimization technique that provides effective results [19]. TOPSIS technique is followed for multi-objective parametric optimization in this work. The process is detailed below.

The first step in TOPSIS method is the process of identifying decision matrix which is generally represented by (rij) and given in equation 3. Next to this, weight for each response is to be allocated. The decision matrix and the preferred weights are used to define the Normalized value and related expression is given in equation (4). (Note: *aij* is ith value of experimental order 'j')

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}} \tag{3}$$

$$V_{ij} = W_i \times r_{ij} \tag{4}$$

Here w_i= weight of j_i

Next in the process, Positive and negative ideal solution (S+ and S-) are calculated using equations 5 and 6.

$$S_i^+ = \sqrt{\sum_{j=1}^{M} (v_{ij} - v_j^+)^2} \tag{5}$$

$$S_i^- = \sqrt{\sum_{j=1}^{M} (v_{ij} - v_j^-)^2} \tag{6}$$

In final step, CC (closeness coefficient) is determined through equation 7. Once CC is evaluated, Rank is given to experiments, considering the order from the higher values of CC.

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{7}$$

The normalization values of Separation measures and the Closeness Coefficient values of MR and ROC obtained from TOPSIS analysis are presented in table 7. All the process parameters involved are given equal weight in this study. The table 7 reveals that the highest CC value is obtained for experiment number 7 with the value of 0.8673. The least value for CC is found for experiment number one. Based on CC values the preferred run order is like this: 7>9>4>3>8>2>5>6>1. The response table (Table 9) obtained from the analysed reveals that NaNO3 Concentration as the most dominant factor (58.46%) followed by voltage (25.63%) and duty cycle showing insignificant impact on the process.

The ions present in the electrolyte solution show great impact on the process because electrochemical process works on the principle of electrolysis and the machining mainly due to ionization process. The influence of voltage is to provide forcible movements to the ions which if not at higher level may not have a significant impact on the process. If duty cycle is within the limit of providing enough time for machining and flushing, its impact would not be realised.

The main effects plot for CC* of TOPSIS study is given in figure 4 for the input parameters. The plot shows that V3D2C2 is the optimal condition for obtaining maximum MR and minimum ROC. The optimum combination is 12V (level 3 of voltage), 70% duty cycle (level 2) and 40 g/lit (level 2 of electrolyte concentration).

It can be observed from the results that 12V gives enough force to relieve from the anode satisfying both the requirements of maximum machining rate and minimum overcut. Medium level duty cycle of 70% provides sufficient pulse-off time to achieve the objectives. Also the medium level of NaNO3 concentration in the solution generates adequate ions to support machining speed and maintain localized machining. The EMM process is influenced by many other factors apart from the ones we select for study. Also the interactions between different process parameters are a complicated issue which requires continuous research [20].

Table -7: S/N ratio, Normalization, CC calculations of TOPSIS

SN Ratio		Normalization		Weighted Normalization		Separation measures		CC*	Rank
MR	ROC	MR	ROC	MR	ROC	S+	S-		
-4.761	-49.066	0.2402	0.4987	0.1201	0.2494	0.20083	0.02897	0.1261	9
-2.604	-43.918	0.3079	0.2757	0.1540	0.1378	0.09028	0.14451	0.6155	6
-1.798	-42.542	0.3378	0.2353	0.1689	0.1177	0.06551	0.16793	0.7194	4
-2.384	-40.257	0.3158	0.1809	0.1579	0.0904	0.06192	0.19166	0.7558	3
-2.639	-45.529	0.3067	0.3319	0.1533	0.1659	0.11234	0.11720	0.5106	7
-1.692	-50.021	0.3420	0.5567	0.1710	0.2783	0.20980	0.05090	0.1953	8
-1.022	-38.486	0.3694	0.1475	0.1847	0.0738	0.03283	0.21454	0.8673	1
-2.510	-43.973	0.3112	0.2774	0.1556	0.1387	0.08975	0.14405	0.6161	5
0.399	-43.464	0.4351	0.2616	0.2175	0.1308	0.05707	0.17679	0.7560	2

Table -8: Response Table for Signal to Noise Ratios –CC*

Level	Voltage (V)	Duty cycle (%)	NaNO3 Concentration (g/lit)
1	-8.354	-7.218	-12.127
2	-7.486	-4.754	-3.026
3	-2.624	-6.493	-3.312
Delta	5.730	2.465	9.101
Rank	2	3	1

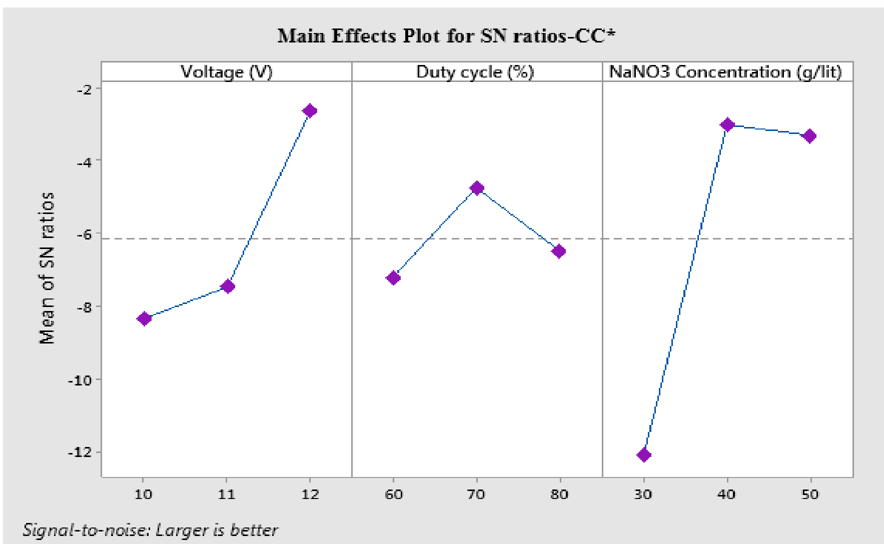

Chart -3: SN ratio Plot of CC*

Table -9: Analysis of Variance-CC*

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% contribution
Voltage (V)	2	0.134536	0.067268	1.64	0.379	25.63
Duty cycle (%)	2	0.001261	0.000631	0.02	0.985	0.24
NaNO3 Concentration (g/lit)	2	0.306844	0.153422	3.73	0.211	58.46
Error	2	0.082275	0.041138			15.67
Total	8	0.524916				100.00

3.7 Confirmation Experiment

The optimized combination may not be available in the experimental set. Hence confirmation experiment should be conducted to verify the result of the optimal set. The details of the confirmation experiment are shown in table 10. The experimental result of the optimized set (voltage 12V, Duty cycle 70% and NaNO3 Concentration 40 g/lit) is compared with the parameter set of first experiment to evaluate the improvement. The optimal set gave a machining rate of 0.978 µm/s (against 0.578 µm/s of initial set) and a radial overcut of 98 µm (against 284 µm of initial set). Optimal parameters were found to produce considerable improvement in the CC value.

Table 10. Confirmation test details

	Initial Parameters	**Optimal Parameters**	
		Prediction	**Experiment**
Setting level	**V1D1C1**	**V3D2C2**	**V3D2C2**
MR **(µm/s)**	0.578	--	0.976
ROC (µm)	284	--	98
CC*	**0.1261**	**0.8915**	**0.9180**
Improvement in CC **= 0.7919**			

3.8 SEM images of micro-holes

The micro-holes generated on the Al7075 Al2O3 composite specimens at 12V, 60% duty cycle and 50 g/lit electrolyte concentration is shown in figure 5. The hole generated at 11V, 60% duty cycle and 40 g/lit electrolyte concentration is shown in figure 6.

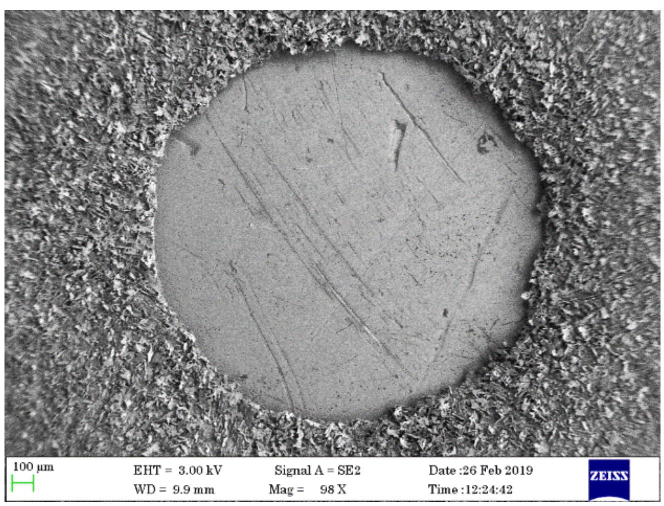

Fig.- 2: SEM micrograph of micro-hole produced at 12V, 60% duty cycle and 50 g/lit

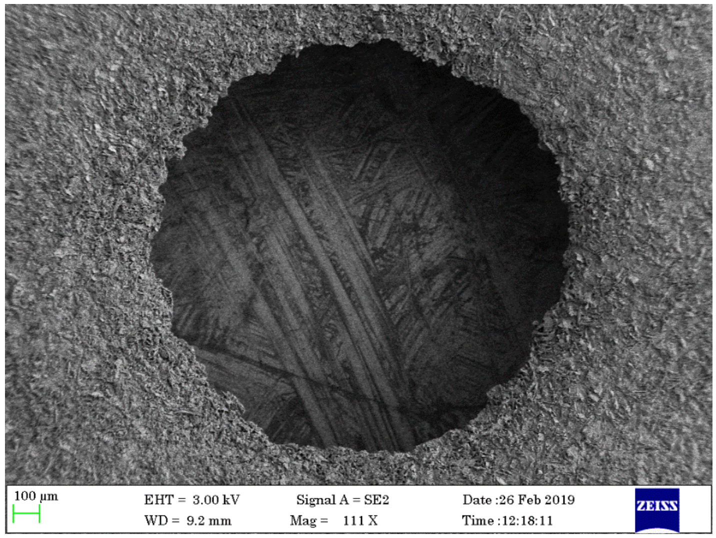

Fig. -3: SEM micrograph of micro-hole produced at 11V, 60% duty cycle and 40 g/lit

The edge of the circumference of the micro hole at some places look rough and irregular with protruding particles. The composite specimen contains aluminium (major part), alloying metals and a little amount of alumina (ceramic material). The electrical conductivity of these metals differ from one another and the electrolyte solution could not dissolve the ceramic material. This inhomogeneous composition of the anode material results in the uneven dissolution at the circumference.

4. CONCLUSIONS

The main objective of this work is to study the performance of electrochemical micromachining process to generate micro holes on Al7075/ Al2O3 composite specimens and optimize the process parameters to achieve maximum machining rate and minimum radial overcut. The important results of the experimental work are given below.

- The EMM process can be successfully used to generate quality micro holes on Al7075/ Al2O3 composite specimens with optimized parameters.
- Single-objective optimization by Taguchi yielded the combination of 12V, Duty cycle 80% and NaNO3 Concentration 40 g/lit for attaining maximum machining rate and the combination of 12V, duty cycle 60% and NaNO3 concentration 50 g/lit for obtaining minimum radial overcut.
- The TOPSIS multi-response optimization process revealed the parametric combination of 12V, duty cycle 70% and NaNO3 concentration 40 g/lit for achieving both maximum machining rate and minimum overcut simultaneously.
- The optimal set of parameters obtained through TOPSIS was validated through confirmation experiment which yielded considerable improvement in the increase of machining rate (69.2%) and in the reduction of radial overcut (65.5%) compared to initial set of parameters.
- The influence of electrolyte concentration on EMM process was found to be significant in achieving dimensional accuracy of the hole.
- It was also observed that machining voltage influences mainly the rate of machining whereas the impact of duty cycle and electrolyte concentration is more pronounced on radial overcut.

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