Optimization and characterization of EDM of AA 6061/10%Al₂O₃ AMMC using Taguchi’s approach and utility concept

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ABSTRACT
In the present study a multi response optimization method using utility concept is proposed for electrical discharge machining (EDM) of AA 6061/10%Al₂O₃ AMMC. In the present study the required material is fabricated using stir casting process and characterization is done using SEM and EDX. The machining characteristics that are being investigated are material removal rate (MRR), tool wear rate (TWR), surface roughness (SR) and overcut (OC) along with surface topography of the drilled holes. Taguchi’s L27 orthogonal array design is used for experimentation. The investigation indicated that material removal rate, tool wear rate, overcut and surface roughness increases with increase in pulse-on time and peak current. But duty factor has less effect on these responses. Multi-response optimization with utility concept provides the collective optimization of both responses for improving the mean of the process.

1. Introduction
Metal matrix composites (MMCs) possess high specific strength and stiffness compared to common structural materials. The most popular type of MMC is aluminium metal matrix composite. Aluminium metal matrix composite consists of matrix phase and reinforcement phase. Matrix phase may be aluminium or aluminium alloy, and reinforcement phase may have graphite, boron carbide, aluminum oxide, silicon carbide, molybdenum, or tungsten in the form of fibers, particles, or whiskers. These composites are difficult to machine using conventional machining methods because of presence of hard reinforcement (SiC or Al₂O₃) in form of particles or fiber leads to excessive tool wear. To overcome such challenges, non conventional machining process such as EDM has gained supremacy in machining. Electric Discharge Drill Machine (EDDM) was used to generate micro holes in hard to machine and conductive materials. This process is used in space and aerospace, medical and automobile industries. In present research work a brass rod 2 mm diameter was used as a tool electrode. The best parameters such as pulse on-time, Pulse off-time and water pressure were studied
for best surface quality. This investigation presents the use of Taguchi approach for better SR in drilling of AA-7075. L27 Taguchi design method was selected for planning of experiments. The optimal levels and the significant drilling parameters on SR were obtained. The optimization results showed that the combination of minimum pulse on-time and maximum pulse off-time gives best SR (Sharma, Khanna, Preeti Garg, & Gupta, 2017). It was discussed about the use of Fly ash as a potential reinforcement for aluminum matrix composites (AMCs) to enhance selective properties and reduce the cost of fabrication. Their study focused on the preparation of cenosphere fly ash reinforced Al6061 alloys by compo casting method. X-ray diffraction analysis of the prepared AMCs exposes the presence of cenosphere particles without any formation of other intermetallic compounds (Debnath & Pandey, 2017). Razzaq, Abang, Majid, Ishak1, and Uday, (2017) discussed about the development of new methods for addition fine ceramic powders to Al aluminium alloy melts, which would lead to more uniform distribution and effective incorporation of the reinforcement particles into the aluminium matrix alloy (Razzaq et al., 2017). The use of multi response optimization technique based on Taguchi method coupled with grey relational analysis for electrical discharge machining operations on duplex (a–b) brass was discussed. Stir casting technique was used to fabricate the duplex brass plates. Experiments were conducted with three machining variables such as current, pulse-on time and spark voltage and planned as per Taguchi technique. Material removal rate (MRR), electrode wear rate (EWR), and surface roughness (SR) are chosen as output parameters for this study. Results showed that, peak current and spark voltage were the significant parameters to affect MRR, EWR, and SR as per grey relational grade (Marichamy, Saravanan, Ravichandran, & Veerappan, 2016)

The machinability of copper, graphite and brass electrodes while machining Inconel 718 super alloy was discussed. Taguchi's L27 orthogonal array has been employed to collect data for the study and analyze effect of machining parameters on performance measures. The important performance measures selected for this study are material removal rate, tool wear rate, surface roughness and radial overcut computational effort. The optimal parametric setting obtained through both the approaches is validated by conducting confirmation experiments (Mohanty, Mahapatra, & Singh, 2017). It was discussed about the wire electric discharge machining (WEDM) to machine of Hastelloy-C-276. While machining, time and surface quality still remains as major challenges. The input parameters are pulse on time ($T_{ON}$), pulse off time ($T_{OFF}$), wire feed rate and current and voltage were changed during the process. The optimization of analysis is performed by using Genetic Algorithm (GA) method L27 orthogonal array (Selvam & Kumar, 2017). It was discussed about the wire electrodischarge machining (WEDM) machining process of AISI D2 steel material. They found the effects of process variables like pulse on time, pulse off time, peak current, servo voltage, and wire feed on material removal rate (MRR), surface roughness (SR), gap voltage, gap current, and cutting rate in the WEDM machining process (Singh, Bhandari, & Yadav, 2016). It was found that precision and micro rotational parts are widely used in various industries, such as micro probes for medical instruments, contact pins for micro assembly applications, micro electrodes for micro Electrical discharge machining (μ-EDM) or micro Electro-chemical discharge machining (μ-ECDM). In their research, a uniform annular area layer by layer feeding strategy was proposed to fabricate high aspect ratio, small radii rotational components on a conventional Wire electrical discharge machining (WEDM) machine equipped with an auxiliary spindle (Zhu, Liang, Gu, & Zhao, 2017). It was discussed about the electrical discharge diamond peripheral surface grinding of Al/
SiCp/B4Cp hybrid metal matrix composite. Gap current, on-time, off-time, abrasive grit number, speed of wheel, and table speed were input process parameters considered. The influence of input process parameters were experimentally investigated on material removal rate and surface roughness using one parameter at a time approach (Yadav & Yadava, 2017). The multi response optimization method using utility concept was used for optimization for wire electrical discharge machining (WEDM) of Nimonic-80A alloy. They investigated the machining characteristics like material removal rate (MRR) and surface roughness (SR) along with surface topography of the machined surface (Goswami & Kumar, 2014).

It was found that the particle reinforced metal matrix composite have hard particles dispersed in matrix which make them difficult to machine with conventional machining methods. In experimental study of EDM of 10%Al2O3/Al metal matrix composites, it was found that the significant factors that affect material removal rate (MRR) and tool wear rate (TWR) have a direct relationship with current and an inverse relationship with pulse on-time (Sindhu, Batish, & Kumar, 2013). Electromagnetic stir casting technique was used to fabricate AA6082/SiC MMC. Silicon carbide (SiC) of 40 μm size was used as reinforcement and was varied by weight percentage as 0, 2.5, 5, 7.5 and 10% in alloy AA6082. It was found that significant machining parameters affecting the performance measures metal removal rate (MRR), surface roughness (SR) and tool wear rate were identified such as discharge current, and dielectric flushing pressure (Pali, Kumar, & Singh, 2016). Response surface methodology (RSM) and artificial neural network (ANN) approach was used for the process modelling and optimisation of wire electric discharge machining (WEDM) of SiCp/6061 Al metal matrix composite (MMC). The experiments were planned and carried out based on the design of experiments (DOE). Comparisons of ANN models and RSM models showed that ANN predictions were more accurate than RSM predictions (Shandilya, Jain, & Jain, 2016). Electrical discharge drilling (EDD was performed to make the hole in titanium alloy (Ti-6Al-4V) and also used altogether a new approach of hybrid of methodologies for modelling as well as optimisation of the hole made for MRR, average surface roughness ($R_a$) and average circularity ($C_a$). The used methodology comprises Taguchi methodology (TM) with response surface methodology (RSM) for modelling and RSM coupled with principal component analysis-based (PCA) grey relational analysis (GRA) for optimisation. The obtained results indicated that applied hybrid approaches in present study of EDD process were reasonable and substantiates with facts of improvement in MRR by 30.80%, $R_a$ by 24.81% and $C_a$ by 26.09% (Yadav & Yadava, 2015).

2. Methodology

Liquid state fabrication of Metal Matrix Composites – It involves incorporation of dispersed phase into a molten matrix metal, followed by its solidification. In order to provide high level of mechanical properties of the composite, good interfacial bonding (wetting) between the dispersed phase and the liquid matrix should be obtained. Wetting improvement may be achieved by coating the dispersed phase particles (fibers). Proper coating not only reduces interfacial energy, but also prevents chemical interaction between the dispersed phase and the matrix.

Stir Casting – It is a liquid state method of composite materials fabrication, in which a dispersed phase (ceramic particles, short fibres) is mixed with a molten matrix metal by
means of mechanical stirring. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional technologies.

### 2.1. Process parameters of EDM

- **Pulse Duration** \(T_{\text{ON}}\): It is the duration of time measured in micro seconds. During this time period the current is allowed to through the electrode towards the work material within a short gap known as spark gap. Pulse duration is also known as pulse on time and the sparks are produced at certain frequency. Material removal rate depends on longer or shorter pulse on time period. Longer pulse duration improves removal rate of debris from the machined area which also affects on the wear behavior of electrode.

- **Pulse Interval** \(T_{\text{OFF}}\): This parameter is to affect the speed and the stability of the cut. If the off-time is too short, it improves MRR but it will because more sparks to be unstable in the machining zone.

- **Duty cycle**: Duty cycle is a percentage of the on-time relative to the total cycle time. Generally, the higher duty cycles mean increased cutting efficiency. The duty cycle is calculated by dividing the on-time by the total cycle time \(\text{(on-time + off-time)}\). The result is multiplied by 100 for the percentage of efficiency or duty cycle.

- **Electrode gap (Spark gap)**: It is the distance between the electrode and the part during the process of EDM. An electro-mechanical and hydraulic systems are used to respond to average gap voltage. To obtain good performance and gap stability a suitable gap should be maintained. For the reaction speed, it must obtain a high speed so that it can respond to short circuits or even open gap circuits.

- **Polarity**: It may be positive or negative connected to tool electrode or work material. Polarity can affect processing speed, finish, wear and stability of the EDM operation. It has been proved that MRR is more when the tool electrodes are connected at positive polarity (+) than at negative terminal (−). This may be due to transfer of energy during the charging process is more in this condition of machining. The machining parameters at different levels were selected to investigate their effects on the machining of aluminum metal matrix composite.

### 2.2. Design of experiment based on Taguchi approach

In Taguchi experimental design orthogonal arrays are used to organize the parameters affecting the process and their levels. Instead of testing all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the data to determining the factors affecting the output most, with a minimum amount of experimentation, thus saving time and resources. Analysis of variance (ANOVA) analysis has been done to select new parameter values to optimize the performance characteristic.

### 2.3. Utility concept

A product based on different quality characteristics is accessed by prospective buyer. The different characteristics are combined and evaluated by term composite index. Such a composite index represents the utility of the product. In this paper it is assumed that the overall
utility is the sum of utilities of individual quality characteristics. If $Z_i$ is the measure of effectiveness of an attribute $i$ and there are $n$ attributes evaluating the outcome space, then the utility function can be expressed as:

$$U(x_1, x_2, \ldots, x_n) = f[U_1(x_1), U_2(x_2), \ldots, U_n(x_n)]$$

In linear case, the function becomes:

$$U(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} W_i U(x_i)$$

### 2.4. Determination of utility value

A preference scale for each quality characteristic is constructed. To determine the utility value for a number of quality characteristics later these scales are weighted to obtain a composite number (overall utility). The weighting is done to satisfy the test of indifference on the various quality characteristics. The preference scale should be a logarithmic one (Gupta & Murthy, 1980). The minimum acceptable quality level for each quality characteristic is set out at 0 preference number and the best available quality is assigned a preference number of 9. If a log scale is chosen the preference number ($P_i$) is given by Equation (8.3) (Gupta & Murthy, 1980).

$$P = A \log \frac{x_i}{x_i^*},$$

where $x_i$ = any value of quality characteristic or attribute $i$ = minimum acceptable value of quality characteristic or attribute $i$ $A$ = a constant, At optimum value ($x_i^*$) of attribute $i$, $P_i = 9$.

So, $A = 9 / \log \frac{x_i}{x_i^*}$.

The next step is to assign weights or relative importance to the quality characteristics. This assignment is subjective and based on experience. Moreover, it depends on the end use of the product or it may depend on the customer’s requirements. The weightage should be assigned such that the following condition is satisfied:

$$\sum_{i=1}^{n} W_i = 1$$

The overall utility can be calculated as:

$$U_j = \sum_{i=1}^{n} W_i P_i$$

where $j$ = product index.

### 3. Experimentation

#### 3.1. Fabrication and characterization of composite and material selection

Phase: Aluminum 6061 alloy is selected. Aluminium alloy 6xxx series, especially 6061 is a general purpose alloy. It is used extensively in civil aviation and automobile sector. This is the least expensive and most versatile of the heat treatable aluminum alloys. It has very good corrosion resistance, finish-ability and excellent weld ability. The composition of Aluminium 6061 is shown in Table 1.
Reinforcement: Aluminium oxide (Al$_2$O$_3$) is also known as alumina. Grains of silicon carbide are bonded together by sintering to form very hard ceramics that are widely used in applications requiring high endurance, such as car brakes, car clutches and ceramic plates in bulletproof vests. Al$_2$O$_3$ particles are used as reinforcement in Aluminum metal matrix composite (Figure 1).

The composite is fabricated by stir casting process. The aluminium alloy was melted in a graphite crucible under controlled argon environment. A small amount of magnesium, less than .5% of total weight, was added to particles. A furnace temperature was maintained at 750 °C for 30 min till complete melting of aluminium alloy was achieved. Vortex was created by mechanical stirring at a speed of 600 rpm using graphite impeller. Specific amount of Al$_2$O$_3$ particles was preheated to 750 °C before pouring into molten metal crucible. Stirring was continued to facilitate uniform distribution of reinforcement particles into the molten metal. The composite melt was further stirred for 5 min and casted into permanent mould. The cast obtained by casting process is presented in Figure 2.

### 3.2. Characterization of fabricated material using SEM and EDX

The constitutional assessment of A6061/Al$_2$O$_3$ composite is made by SEM and EDX. Figure 3 shows SEM and EDX micrograph of 6061Al/10%Al$_2$O$_3$ composite respectively. White patches regions showing agglomeration of Al$_2$O$_3$. This agglomeration or clustering is distributed over the entire region resulting Al$_2$O$_3$ rich particle region. These agglomerations consist of larger particles surrounded by smaller particles as shown in SEM microscopic structure of aluminum phase solidification.

### 3.3. Experimental work on EDM

Experiments were performed on Ecoline 200 electrical discharge machine as shown in Figure 4 to study the material removal rate, tool wear rate, overcut and surface roughness at different setting of Peak current (I), Pulse-on time ($T_{ON}$), Duty factor (DF). At first pilot experiments should be performed to find the final process parameters ranges for final
experiments using L27 orthogonal array (three levels). The process parameters were tested for their effects on MRR, TWR, overcut and surface roughness. L27 orthogonal array (three levels) with three input variables was selected for experimentation. Tables shows the various process parameters with their values at three levels and L27 orthogonal array.

**Figure 2.** Casted samples of AA6061 with 10%Al₂O₃ AMMC.

**Figure 3.** SEM and EDX photographs of casted samples of AA6061/10%Al₂O₃ composite.

**Figure 4.** EDM set up for experiment.
For the present experimental work the three process parameters each at three levels have been decided. It is desirable to have three minimum levels of process parameters to reflect the true behavior of output parameters of study. The process parameters are renamed as factors and they are given in the adjacent column. The levels of the individual process parameters/factors are given in Table 2.

As per Taguchi experimental design philosophy a set of three levels assigned to each process parameter has two degrees of freedom (DOF). This gives a total of 12 DOF for six process parameters selected in this work. For three process parameters, pulse on time, pulse off time and spark gap set voltage, taking two parameters at a time we have three possible interactions (A × B, A × C and B × C) which have been included in the present study. As a two factor interaction consists of two process parameters and the degree of freedom of interaction will be equal to the product of DOF of the interacting factors. Thus each interaction e.g. A × B will have (3−1) × (3−1) = 4 DOF. This gives total DOF of 12 for three interactions A × B, A × C & B × C. Thus we have a total of 24 DOF for the factors as well as the interactions considered for the present experiments. The nearest three level orthogonal array available satisfying the criterion of selecting the OA is L27 having 26 DOF (Ross, 2005). For each trial in the L27 array, the levels of the process parameters are indicated in Table 3 and responses are tabulated in Table 4.

4. Single response optimization using Taguchi concept

The EDM experiments were conducted by using the parametric approach of the Taguchi’s method. The effects of individual EDM process parameters, on the selected quality characteristics – cutting rate, surface roughness, gap current and dimensional deviation, have been discussed in this section. The average value and S/N ratio of the response characteristics for each variable at different levels were calculated from experimental data.

4.1. Analysis of variance

In this study, ANOVA was performed to investigate the statistical significance of the process parameters affecting the MRR, SR, TWR and OC. The objective was to analyze the influence of peak current, pulse on time and duty factor on the total variance of the results. This analysis was undertaken for a level of significance of .5%, i.e. for a level of confidence of 99.5%. The ANOVA table also consists of the $F$-values and the percentage contributions. By comparing the $F$-values with the tabulated ones, the significance of the factors can be understood. If the obtained $F$ value of a parameter is greater than the tabulated one, then that particular parameter has a significant influence over the response variable.

The main effects of process variables both for raw data and S/N data were plotted. The response curves (main effects) are used for examining the parametric effects on the response characteristics in the present study.

Table 2. Process parameters and their levels.

| Factors | Parameters     | Levels |
|---------|----------------|--------|
| A       | Peak current   | L1     | L2     | L3     |
|         | 6              | 10     | 14     |
| B       | Pulse on time  | 75     | 100    | 200    |
| C       | Duty factor    | .5     | .6     | .7     |
characteristics. The ANOVA of raw data and S/N data is carried out to identify the significant variables and to quantify their effects on the response characteristics. The most favorable values (optimal settings) of process variables in terms of mean response characteristics are established by analyzing the response curves in Figure 5 and the ANOVA Tables 5–8.

4.2. Estimation of optimum response characteristics

In this section, the optimal values of the response characteristics (material removal rate, tool wear rate, surface roughness and overcut) along with their respective confidence intervals have been predicted. These relations are used to find out the optimum response characteristics. The results of confirmation experiments are also presented to validate the optimal results.

The 95% confidence intervals of confirmation experiments (CI_{CE}) and of population (CI_{POP}) were calculated by using the Equations as mentioned below.

\[
CI_{CE} = \sqrt{F_{\alpha, (f_e) V_e}} \left[ \frac{1}{\eta_{eff}} + \frac{1}{R} \right]
\]

\[
CI_{POP} = \frac{F_{\alpha, (f_e) V_e}}{\eta_{eff}}
\]
where $F_{α}(1, f_e) = \text{The } F \text{ ratio at the confidence level of } (1 - α) \text{ against DOF } 1 \text{ and error degree of freedom } f_e$. 

Table 4. Design layout with actual parameters and experimental results for MRR.

| Run | A | B | C | Avg. MRR | Avg. TWR | Avg. SR | Avg. overcut |
|-----|---|---|---|---------|---------|--------|-------------|
| 1   | 6 | 75 | .5 | 19.008  | .225    | 6.44   | .204        |
| 2   | 6 | 75 | .6 | 18.025  | .106    | 7.88   | .234        |
| 3   | 6 | 75 | .7 | 18.367  | .041    | 7.45   | .243        |
| 4   | 6 | 100| .5 | 13.931  | .212    | 7.65   | .249        |
| 5   | 6 | 100| .6 | 14.569  | .11     | 7.5    | .257        |
| 6   | 6 | 100| .7 | 14.781  | .025    | 7.45   | .262        |
| 7   | 6 | 200| .5 | 15.507  | .187    | 7.56   | .277        |
| 8   | 6 | 200| .6 | 13.673  | .063    | 7.45   | .283        |
| 9   | 6 | 200| .7 | 15.593  | .401    | 6.44   | .323        |
| 10  | 10| 75 | .5 | 28.888  | .425    | 6.7    | .326        |
| 11  | 10| 75 | .6 | 25.333  | .302    | 6.85   | .327        |
| 12  | 10| 75 | .7 | 23.72   | .098    | 6.72   | .329        |
| 13  | 10| 100| .5 | 29.575  | .361    | 6.7    | .33         |
| 14  | 10| 100| .6 | 25.978  | .245    | 7.83   | .336        |
| 15  | 10| 100| .7 | 23.2    | .118    | 7.76   | .339        |
| 16  | 10| 200| .5 | 18.492  | .242    | 8.9    | .341        |
| 17  | 10| 200| .6 | 17.631  | .2      | 7.83   | .344        |
| 18  | 10| 200| .7 | 17.5    | .092    | 10.39  | .336        |
| 19  | 14| 75 | .5 | 33.629  | .387    | 8.8    | .341        |
| 20  | 14| 75 | .6 | 32.471  | .322    | 10.55  | .348        |
| 21  | 14| 75 | .7 | 33.357  | .144    | 10.58  | .352        |
| 22  | 14| 100| .5 | 30.138  | .308    | 12.83  | .357        |
| 23  | 14| 100| .6 | 28.75   | .265    | 9.77   | .362        |
| 24  | 14| 100| .7 | 27.163  | .162    | 9.77   | .365        |
| 25  | 14| 200| .5 | 24.25   | .344    | 12.83  | .37         |
| 26  | 14| 200| .6 | 22.78   | .212    | 13.12  | .373        |
| 27  | 14| 200| .7 | 21.49   | .167    | 13.19  | .377        |

Figure 5. Main effect plot for MRR, TWR, SR and OC.
4.3. Material removal rate

The optimum value of MRR is predicted at the selected levels of significant variables as stated above viz. peak current ($A_3$), pulse on time ($B_1$) and duty factor ($C_1$). The estimated mean of the response characteristic MRR can be as

\[
\eta_{\text{eff}} = \frac{N}{1 + \text{DOF associated in estimate of mean response}}
\]

Table 5. Analysis of variance for means for MRR.

| Source                  | DF | Seq SS   | Adj SS   | Adj MS   | F      | P     |
|-------------------------|----|----------|----------|----------|--------|-------|
| Current                 | 2  | 689.16   | 689.16   | 344.582  | 273.38 | .000  |
| Pulse on time           | 2  | 246.15   | 246.15   | 123.075  | 97.65  | .000  |
| Duty factor             | 2  | 20.41    | 20.409   | 10.204   | 8.10   | .012  |
| Current × pulse on time | 4  | 79.38    | 79.377   | 19.844   | 15.74  | .001  |
| Current × duty factor   | 4  | 13.91    | 13.910   | 3.478    | 2.76   | .104  |
| Pulse on time × duty factor | 4  | 2.81     | 2.810    | .703     | .56    | .700  |
| Residual error          | 8  | 10.08    | 10.083   | 1.260    |        |       |
| Total                   | 26 | 1061.90  |          | 101.90   |        |       |

Table 6. Analysis of variance for means for TWR.

| Source                  | DF | Seq SS   | Adj SS   | Adj MS   | F      | P     |
|-------------------------|----|----------|----------|----------|--------|-------|
| Current                 | 2  | .053521  | .053521  | .026760  | 5.49   | .032  |
| Pulse on time           | 2  | .003325  | .003325  | .001663  | .34    | .721  |
| Duty factor             | 2  | .117540  | .117540  | .058770  | 12.07  | .004  |
| Current × pulse on time | 4  | .033591  | .033591  | .008398  | 1.72   | .237  |
| Current × duty factor   | 4  | .044385  | .044385  | .011096  | 2.28   | .149  |
| Pulse on time × duty factor | 4  | .049188  | .049188  | .012297  | 2.52   | .123  |
| Residual error          | 8  | .038964  | .038964  | .004870  |        |       |
| Total                   | 26 | .340513  |          | .130513  |        |       |

Table 7. Analysis of variance for means for SR.

| Source                  | DF | Seq SS   | Adj SS   | Adj MS   | F      | P     |
|-------------------------|----|----------|----------|----------|--------|-------|
| Current                 | 2  | 84.903   | 84.903   | 42.4515  | 38.12  | .000  |
| Pulse on time           | 2  | 14.257   | 14.2568  | 7.1284   | 6.40   | .022  |
| Duty factor             | 2  | .106     | .1064    | .0532    | .05    | .954  |
| Current × pulse on time | 4  | 9.416    | 9.416    | 2.3540   | 2.11   | .171  |
| Current × duty factor   | 4  | 1.874    | 1.8740   | .4685    | .42    | .790  |
| Pulse on time × duty factor | 4  | 3.501    | 3.5006   | .8751    | .79    | .565  |
| Residual error          | 8  | 8.910    | 8.9095   | 1.1137   |        |       |
| Total                   | 26 | 122.966  |          | 4.666    |        |       |

Table 8. Analysis of variance for means for OC.

| Source                  | DF | Seq SS   | Adj SS   | Adj MS   | F      | P     |
|-------------------------|----|----------|----------|----------|--------|-------|
| Current                 | 2  | .049878  | .049878  | .024939  | 384.28 | .000  |
| Pulse on time           | 2  | .005693  | .005693  | .002846  | 43.86  | .000  |
| Duty factor             | 2  | .000954  | .000954  | .000477  | 7.35   | .015  |
| Current × pulse on time | 4  | .002451  | .002451  | .000613  | 9.44   | .004  |
| Current × duty factor   | 4  | .000783  | .000783  | .000196  | 3.02   | .086  |
| Pulse on time × duty factor | 4  | .000113  | .000113  | .000028  | .43    | .781  |
| Residual error          | 8  | .000519  | .000519  | .000065  |        |       |
| Total                   | 26 | .060391  |          | .023984  |        |       |
\[ \mu_{\text{MRR}} = A_3 + B_1 + C_1 - 2T_{\text{MRR}} \]

where, \( T \) = overall mean of MRR = \( (\Sigma R_1 + \Sigma R_2 + \Sigma R_3)/81 \) = 22.511.

\[ \mu_{\text{MRR}} = 28.23 + 25.87 + 23.71 - 2(22.511) = 32.788 \]

So, \( \text{CI}_{\text{CE}} \) = ±.6786 and \( \text{CI}_{\text{POP}} \) = ±.7612.

Therefore, the predicted confidence interval for confirmation experiments is:

\[ \text{Mean } \mu_{\text{MRR}} - \text{CI}_{\text{CE}} < \mu_{\text{MRR}} < \text{Mean } \mu_{\text{MRR}} + \text{CI}_{\text{CE}} \]

\[ 32.788 - 1.679 < 32.788 < 32.788 + 1.679 \]

\[ 31.109 < 32.788 < 34.469 \]

The 95% confirmation interval of the predicted mean is:

\[ \text{Mean } \mu_{\text{MRR}} - \text{CI}_{\text{POP}} < \mu_{\text{MRR}} < \text{Mean } \mu_{\text{MRR}} + \text{CI}_{\text{POP}} \]

\[ 32.027 < 32.788 < 33.549 \]

The optimal values of process variables at their selected levels are as follows:

Third level of peak current \( (A_3) \): 14 A
First level of pulse on time \( (B_1) \): 75 μs
First level of duty factor \( (C_1) \): .5

4.4. Tool wear rate

The optimum value of TWR is predicted at the selected levels of significant variables as stated above viz. peak current \( (A_3) \), pulse on time \( (B_1) \) and duty factor \( (C_1) \). The estimated mean of the response characteristic TWR can be determined as

\[ \mu_{\text{TWR}} = A_1 + B_1 + C_1 - 2T_{\text{TWR}}(7.25) \]

where, \( T \) = overall mean of TWR = \( (\Sigma R_1 + \Sigma R_2 + \Sigma R_3)/81 \) = .2135.

\[ \mu_{\text{TWR}} = .1522 + .2278 + .2990 - 2(.2135) = .252 \]

The 95% confidence intervals of confirmation experiments \( (\text{CI}_{\text{CE}}) \) and of population \( (\text{CI}_{\text{POP}}) \) were calculated by equations.

So, \( \text{CI}_{\text{CE}} \) = ±.1039.

And \( \text{CI}_{\text{POP}} \) = ±.04715.

Therefore, the predicted confidence interval for confirmation experiments is:

\[ \text{Mean } \mu_{\text{TWR}} - \text{CI}_{\text{CE}} < \mu_{\text{TWR}} < \text{Mean } \mu_{\text{TWR}} + \text{CI}_{\text{CE}} \]

\[ .1481 < .252 < .3559 \]

The 95% confirmation interval of the predicted mean is:

\[ \text{Mean } \mu_{\text{TWR}} - \text{CI}_{\text{POP}} < \mu_{\text{TWR}} < \text{Mean } \mu_{\text{TWR}} + \text{CI}_{\text{POP}} \]

\[ .2040 < .252 < .2992 \]
The optimal values of process variables at their selected levels are as follows:

| Process Variable                | Level |
|---------------------------------|-------|
| Third level of peak current     | 6 A   |
| First level of pulse on time    | 75 μs |
| First level of duty factor      | .5    |

### 4.5. Surface roughness

The optimum value of SR is predicted at the selected levels of significant variables as stated above viz. peak current \(A_1\), pulse on time \(B_1\) and duty factor \(C_1\). The estimated mean of the response characteristic SR can be determined as

\[
\mu_{SR} = A_1 + B_1 + C_1 - 2T_{SR} (7.25)
\]

where, \(T = \text{overall mean of MRR} = (\sum R_1 + \sum R_2 + \sum R_3)/81 = 8.775\).

\[
\mu_{SR} = 7.313 + 7.997 + 8.712 - 2(8.775) = 6.472
\]

The 95% confidence intervals of confirmation experiments \((CIE_C)\) and of population \((CIP_P)\) were calculated by using the equations.

So, \(CIE_C = \pm 1.5769\) and \(CIP_P = \pm .7156\).

Therefore, the predicted confidence interval for confirmation experiments is:

\[
\text{Mean } \mu_{SR} - CIE_C < \mu_{SR} < \text{Mean } \mu_{SR} + CIE_C
\]

4.8951 < 6.472 < 8.0489

The 95% confirmation interval of the predicted mean is:

\[
\text{Mean } \mu_{SR} - CIP_P < \mu_{SR} < \text{Mean } \mu_{SR} + CIP_P
\]

5.7564 < 6.472 < 7.1876

The optimal values of process variables at their selected levels are as follows:

| Process Variant                | Level |
|--------------------------------|-------|
| Third level of peak current    | 6 A   |
| First level of pulse on time   | 75 μs |
| First level of duty factor     | .5    |

### 4.6. Overcut

The optimum value of OC is predicted at the selected levels of significant variables as stated above viz. peak current \(A_1\), pulse on time \(B_1\) and duty factor \(C_1\). The estimated mean of the response characteristic OC can be determined as

\[
\mu_{OC} = A_1 + B_1 + C_1 - 2T_{OC}
\]

where, \(T = \text{overall mean of MRR} = (\sum R_1 + \sum R_2 + \sum R_3)/81 = .3180\).

\[
\mu_{MRR} = .2591 + .3004 + .3106 - 2(.3180) = .2341
\]

The 95% confidence intervals of confirmation experiments \((CIE_C)\) and of population \((CIP_P)\) were calculated by using the equations.

\(CIE_C = \pm .01205\) and \(CIP_P = \pm .005467\).
Therefore, the predicted confidence interval for confirmation experiments is:

\[
\text{Mean } \mu_{OC} - CI_{CE} < \mu_{OC} < \text{Mean } \mu_{OC} + CI_{CE}
\]

\[.22205 < .2341 < .24615\]

The 95% confirmation interval of the predicted mean is:

\[
\text{Mean } \mu_{OC} - CI_{POP} < \mu_{OC} < \text{Mean } \mu_{OC} + CI_{POP}
\]

\[.2286 < .2341 < .2396\]

The optimal values of process variables at their selected levels are as follows:

| Process Variable          | Level | Value   |
|---------------------------|-------|---------|
| Third level of peak current | A₁    | 6 A     |
| First level of pulse on time | B₁    | 75 μs   |
| First level of duty factor    | C₁    | 0.5     |

5. Confirmation experiment

In order to validate the results obtained, three confirmation experiments were conducted for each of the response characteristics (MRR, TWR, SR and OC) at optimal levels of the process variables. The results are given in Table 9.

5.1. Multi response optimization using utility concept

Material removal rate, surface roughness, and overcut, tool wear rate.

The optimal settings of process parameters and the optimal values of cutting rate, surface roughness, gap current and dimensional deviation (when they are optimized individually) have already been established (Figure 6).

(i) Preference scale construction

Material removal rate (MRR)
\[P_{MRR} = 19.033 \log \left( \frac{x}{11.037} \right)\]

Surface roughness (SR)
\[P_{SR} = -28.9835 \log \left( \frac{x}{13.23} \right)\]

Overcut (OC)
\[P_{OC} = -43.2504 \log \left( \frac{x}{.378} \right)\]

Table 9. Predicted optimal values, confidence intervals and results of confirmation experiments.

| Performance Measures/responses | Optimal set of parameters | Predicted optimal value | Predicted confidence intervals at 95% confidence level | Actual value (average of three confirmation experiments) |
|--------------------------------|---------------------------|-------------------------|-------------------------------------------------------|-----------------------------------------------------|
| Material removal rate | A₁B₁C₁ | 32.788 | CI_{POP}: 32.027 < \mu_{MRR} < 33.549  | 34.650 |
| Tool wear rate | A₁B₁C₁ | 0.2520 | CI_{POP}: 0.2040 < \mu_{TWR} < 0.2992 | 0.285 |
| Surface roughness | A₁B₁C₁ | 6.472 μm | CI_{POP}: 5.7564 < \mu_{SR} < 7.1876 | 7.452 μm |
| Overcut | A₁B₁C₁ | 0.234 mm | CI_{POP}: 0.2286 < \mu_{OC} < 0.2396 | 0.254 mm |
Tool wear rate (TWR)

\[ P_{TWR} = -37.1821 \log \left( \frac{x}{.5727} \right) \]

(ii) Weightage of quality characteristic

It has been assumed that both the quality characteristics CR and SR are equally important and hence equal weightage has been assigned. Further the quality characteristics IG and DD, have been assigned to be equally important and assigned equal weight. However, there is no constraint on the weightage and it can be any value between 0 and 1 subjected to the condition specified in Utility theory. The weighted assign to the characteristics are:

\[ W_{MRR} = \text{weightage for MRR} = .3 \]
\[ W_{SR} = \text{weightage for SR} = .3 \]
\[ W_{OC} = \text{weightage for OC} = .3 \]
\[ W_{TWR} = \text{weightage for TWR} = .1 \]

(iii) Utility value calculation

The utility value of each machined part has been calculated using the following relation:

\[ U(n, R) = P_{MRR}(n, R) \times W_{MRR} + P_{SR}(n, R) \times W_{SR} + P_{OC}(n, R) \times W_{OC} + P_{TWR}(n, R) \times W_{TWR}, \]

where, \( n = \) trial number, \( n = 1, 2, \ldots, 27 \) \( R = \) repetition, \( R = 1, 2, 3 \)

The utility values thus calculated are given in Table 10.

The optimal settings of process parameters for optimization of cutting rate, surface roughness, gap current and dimensional deviation for EDM process ascertained from main effects plots are given below in Table 11.

5.2. SEM analysis of machined samples

Due to generation of high temperature during discharge, the material is melted and vaporized within the plasma channel formed between two electrodes. This molten material is partly flushed by dielectric fluid and rest is cooled rapidly and resolidified on surface called resolidified layer or recast layer.

Figures 7–9 shows the micrographs of machined holes under parameter combinations (a) Discharge current – 6 A, pulse on time – 100 and duty factor – .6, (b) Discharge current – 10 A, pulse on time – 100 and duty factor – .6, (c) Discharge current – 14 A, pulse on

![Main Effects Plot for SN ratios](image)

**Figure 6.** Effects of process parameters on utility function \( U_{MRR, SR, OC, TWR} \) for raw data and S/N data.
The Figure 9 clearly shows the effect of discharge current at constant pulse on time of 100 μs and constant duty factor of .6. It shows that the recast layer, which is formed on the wall of machined holes, increases as discharge current increases. Also the shape of hole is of better finish at lower discharge current as compared to high discharge current. Since duty factor does not have a strong effect on machining characteristics. It is found that craters are produced at the recast layer when there is increase in discharge current which is supported by previous researches.

Figures 10–12 shows the effect of pulse on time on recast layer of machined holes under parameter combinations (a) Discharge current – 6 A, pulse on time – 75 and duty factor – .5, (b) Discharge current – 6 A, pulse on time – 100 and duty factor – .5, (c) Discharge current – 6 A, pulse on time – 200 and duty factor – .5. The figure clearly shows the effect of discharge current at constant discharge current of 6 A and constant duty factor of .5. It

Table 10. Utility data based on quality characteristics. (a) Material removal rate (b) surface roughness (c) overcut (d) tool wear rate.

| Trial no. | Raw data (utility values) | S/N ratios (dB) |
|-----------|---------------------------|-----------------|
|           | R1 | R2 | R3 | R1 | R2 | R3 |
| 1         | 8.955369 | 9.127859 | 9.068791 | 19.13361727 |
| 2         | 8.648092 | 8.978858 | 8.149135 | 18.68191433 |
| 3         | 10.1478 | 10.16771 | 10.22659 | 20.15555061 |
| 4         | 6.721724 | 6.916329 | 6.125297 | 16.37478601 |
| 5         | 7.712216 | 7.576039 | 7.677331 | 17.67927692 |
| 6         | 9.746327 | 9.700188 | 10.64452 | 20.02631723 |
| 7         | 6.711215 | 6.687438 | 6.114476 | 16.26411305 |
| 8         | 8.073029 | 8.070697 | 7.470067 | 17.92088963 |
| 9         | 5.010932 | 4.711052 | 5.372749 | 14.03408371 |
| 10        | 6.155427 | 6.013279 | 6.624193 | 15.93745074 |
| 11        | 6.138062 | 6.408635 | 6.683396 | 16.13720233 |
| 12        | 8.256515 | 8.471457 | 7.551229 | 18.16226289 |
| 13        | 6.432908 | 6.43598 | 6.697606 | 16.28783564 |
| 14        | 6.020723 | 6.258249 | 6.131643 | 15.75894111 |
| 15        | 7.220734 | 7.24245 | 6.558123 | 16.91076951 |
| 16        | 5.017825 | 4.678511 | 4.530934 | 13.5200059 |
| 17        | 4.992574 | 5.316582 | 5.842679 | 14.62201216 |
| 18        | 5.62539 | 5.949842 | 4.561647 | 15.08537596 |
| 19        | 5.391664 | 5.505858 | 5.648851 | 14.83163151 |
| 20        | 4.936194 | 4.845572 | 4.995866 | 13.84967171 |
| 21        | 6.29039 | 6.024381 | 6.342515 | 15.87454437 |
| 22        | 4.147423 | 3.852306 | 3.782127 | 11.8818492 |
| 23        | 5.30836 | 4.957453 | 4.755242 | 13.99158393 |
| 24        | 5.721309 | 5.885119 | 5.197727 | 14.96590858 |
| 25        | 2.929736 | 3.221602 | 2.877736 | 9.57043923 |
| 26        | 3.366409 | 3.548554 | 3.605099 | 10.8979406 |
| 27        | 3.770515 | 3.912643 | 3.264947 | 11.24435422 |

Note: R1, R2, R3 – Repetitions of experiments against each of the trial conditions.

Table 11. Predicted optimal values, confidence intervals and results of confirmation experiments for utility functions.

| Performance measures in terms of utility function | Optimal set of parameters | Predicted optimal value | Predicted confidence intervals at 95% confidence level | Actual value (average of three confirmation experiments) |
|--------------------------------------------------|---------------------------|------------------------|-------------------------------------------------------|-------------------------------------------------------|
| $U_{MMR,SRLC,TWR}$                              | $A_1B_1C_3$               | 9.501                  | $C_{1:} 8.209 < \mu_{MMR,SRLC,TWR} < 10.793$          | 9.083                                                 |
|                                                  |                           |                        | $C_{1:s} 8.915 < \mu_{MMR,SRLC,TWR} < 10.087$        |                                                       |

time – 100 and duty factor – .6. The Figure 9 clearly shows the effect of discharge current at constant pulse on time of 100 μs and constant duty factor of .6. It shows that the recast layer, which is formed on the wall of machined holes, increases as discharge current increases. Also the shape of hole is of better finish at lower discharge current as compared to high discharge current. Since duty factor does not have a strong effect on machining characteristics. It is found that craters are produced at the recast layer when there is increase in discharge current which is supported by previous researches.

Figures 10–12 shows the effect of pulse on time on recast layer of machined holes under parameter combinations (a) Discharge current – 6 A, pulse on time – 75 and duty factor – .5, (b) Discharge current – 6 A, pulse on time – 100 and duty factor – .5, (c) Discharge current – 6 A, pulse on time – 200 and duty factor – .5. The figure clearly shows the effect of discharge current at constant discharge current of 6 A and constant duty factor of .5. It
shows that the recast layer, which is formed on the wall of machined holes, increases as the pulse on time increases. As $T_{\text{ON}}$ increases, the period of active machining time increases per cycle and molten material gets solidified because of less time for flushing. So it is found that as there is increase in discharge current and pulse on time, craters are produced at the recast layer.

Figure 7. SEM micrographs at discharge current – 6 A, pulse on time – 100 and duty factor – .6.

Figure 8. SEM micrographs at discharge current – 10 A, pulse on time – 100 and duty factor – .6.

Figure 9. SEM micrographs at discharge current – 14 A, pulse on time – 100 and duty factor – .6.
6. Conclusion

In this research, the experiments have been planned and conducted in order to investigate the effects of cutting parameters on material removal rate, tool wear rate, overcut and surface roughness in the EDM process. The composite material was fabricated using developed stir casting set up and characterisation was done using SEM/EDX. After fabrication of work piece, the machining was done using EDM process. Optimized process conditions have been obtained for four responses-MRR, TWR, overcut and surface roughness using both Single
response optimization with Taguchi approach and Multi response optimization technique with Utility function. Following conclusions could be drawn from this investigation:

- All the selected process parameters play significant role for MRR in Spark EDM., Higher MRR can be achieved at higher setting of current, pulse on time as observed in single response optimisation.
- TWR increases significantly with increase in current where as higher pulse on time yields a moderate reduction in tool wear rate. Duty factor is not a significant parameter for TWR, keeping other parameters constant, optimum combination of electrical parameters namely peak current, pulse on time and duty factor gives lowest tool wear.
- Current and pulse on time are most significant factors affecting surface roughness. Surface finish deteriorates sharply with increase in setting value of these process parameters due to high energy input to machining zone. Best surface finishing can be obtained at optimum setting of current, pulse on time and duty factor.
- Current and pulse on time are most significant process parameters affecting overcut as in TWR. OC increases significantly with increase in current where as higher pulse on time yields a moderate reduction in overcut. Duty factor is not a significant parameter for OC. Keeping other parameters constant, optimum combination of electrical parameters namely peak current, pulse on time and duty factor gives lowest overcut.
- As per the results of the multi response optimization the values for process parameters that results in optimized value of MRR (optimized), TWR(optimized), OC(optimized) and SR (optimized) are; pulse-on time: 50 μs, discharge current: 6 A and duty factor: .7. The microstructure investigation of the samples machined with SEM at experimental condition corresponding to high energy input rate has revealed a strong co-relation between the surface quality and energy input rate. The samples machined at high energy input condition exhibited rougher surface with lot of built-edge layers, whereas the better surface quality was obtained under low energy input conditions.

7. Limitations and Scope for future work

- Fabrication of aluminium metal matrix composite by other advanced processes like powder metallurgy, diffusion, deposition, etc. may be done to achieve different set of properties.
- Aluminium alloy reinforced with other hard ceramics like TiC, B4C and metallic elements such as molybdenum, vanadium may be used as matrix phase.
- Further work may be concentrated on evaluation of surface characteristics or surface integrity features such as recast layer, crack size, crack density, residual stresses etc.
- Efforts should be made to investigate the effects of parameters on EDM process in a cryogenic cutting condition.

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No potential conflict of interest was reported by the authors.

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