Dielectric Fluid Parameter Optimization in Machining of Composite Material using WEDM Process

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Abstract: Wire Electric Discharge Machining (WEDM) has become most popular among the non-conventional machining processes because of precise machining and accuracy of parts. The process is preferable for accurate machining of complex geometries in hard materials such as Aluminium Silicon Carbide metal matrix composite. In this work, an attempt is made to analyze and optimize the dielectric fluid parameters in machining of Al/SiCp 10% work material. The input variables such as volume flow rate, flow velocity and chemical composition of dielectric medium used in the WEDM are chosen for this. Taguchi’s L9 orthogonal array is used to conduct experiments in WEDM machine and ANOVA results have confirmed the influence of chosen parameters on the output responses. Computer simulation model of the WEDM tank with dielectric fluid, work piece and nozzle is presented using Fluent software. The Fluent model is analyzed based on the maximum removal of debris in the work material. Optimization is carried out to maximize the Material Removal Rate (MRR) and minimize surface roughness. The results obtained from Taguchi’s optimization and Fluent analysis have been validated by carrying out tests on WEDM. The study shows that volume flow rate and flow pressure can adequately influence MRR and surface roughness.

Keywords: Composite material, Material Removal Rate, Surface Roughness, Dielectric Fluid, CFD

1. Introduction

WEDM is a non-conventional, thermo-electric process in which the material from work piece is eroded by a series of discharge sparks between the work and tool electrode immersed in a liquid dielectric medium and widely used to produce dies, punches and moulds, finishing parts for aerospace and automotive industry and surgical components [1-3]. The minute arcs created in numerous numbers within very short duration, locally evaporates the metal which are cooled down and flushed away by the flowing di-electric fluid. The method is practised by the industries to produce complex shapes that are either difficult or uneconomical through conventional machining processes. WEDM process is proven its ability in machining hard but conductive materials and reproducing complex shapes [4]. Industries like aerospace, automotive and marine are increasing the usage of aluminium based composite materials which are usually very difficult to machine using turning and milling operations. [5,6]. Such composite materials, even though can be conveniently machined using WEDM process, still needs to be tested for improving the machining efficiency and apply flushing effectively [7].

2. Literature Review

Material removal rate (MRR) increases with increasing flushing pressure and becomes constant. Tool wear reduces to certain extent, up to optimal value is reached, and surface finish also showed the same trend [8]. Various dielectric fluids were used and their effect on EDM was revealed. Study concludes that tap water, as dielectric medium, can enhance MRR. As far the surface quality is considered, hydrocarbon oils performance was inferior to that of deionized water [9].
As water, based dielectrics are economic and environment friendly, they must be investigated further as an option of hydrocarbon oil for performance improvement of EDM with different additives and for machining of materials like composites and carbides [14].

Dhakar et al. [10] have used two-phase dielectrics like water-air, EDM oil-air and Glycerine-air mixtures as dielectric medium in near dry EDM process and discovered that high viscosity fluids perform better than that of low viscosity. They also reported that MRR for glycerine-air mixture was enhanced by 300% compared to other mixtures used in the study.

Boron carbide powder varied from 1-15 gpl and mixed along with EDM oil was tried as dielectric medium in machining Ti-6Al-4V alloy [11]. Results revealed that with an increase in B4C concentration had improved the MRR, tool wear rate and surface finish and however concentration beyond 15 gpl of B4C powder resulted in reduced MRR. The authors have also tried with dielectric fluid of surfactant and graphite powder addition to the EDM oil [12]. They concluded that adding surfactant and graphite powder responded positively as far as MRR and TWR were concerned, whereas the quality of machined surface and Recast Layer Thickness (RLT) had come down. Taguchi method was used to determine the optimal concentration of dielectric mixture.

Singh et al. [13] have reviewed the effect of different dielectric fluids on MRR and TWR. Effects of gaseous, liquid, liquid plus powder particles, vegetable oil based dielectrics were reviewed and reported that vegetable-based oil dielectric had comparatively good sustainability index. Further, it was suggested that Jatropha oil could be a best alternative for hydrocarbon based dielectric fluids. The review which was considering researches of past 36 years in this field, have not reported a good number of works carried out to know the effect of dielectric fluid parameters on MRR and TWR. From the above literature survey, it is understood that a gap exists in predicting the effect of controlling parameters of dielectric medium on the common outputs of machining. Even there is a very short report on wire EDM, a variant of EDM process. Hence, an effort was made to study how the dielectric fluid parameters such as fluid pressure, volume flow rate, ion exchanger resin composition effect on MRR and surface quality in wire EDM of aluminium matrix composites.

3. Experimental Design

This research is carried out on machining of composite material in WEDM with brass electrodes. Dielectric parameters such as volume flow rate, flow pressure and resin composition are varied to investigate their effects on the Material Removal Rate (MRR) and finish of the cut surface. De-ionized water, used as dielectric fluid and injected through nozzle, enhances debris ejection in the gap up to a certain extent. Work materials are prepared by reinforcing 10% SiC particles in Al6061 alloy matrix, through stir cast route and design of experiments is applied to conduct the experiments. This section elaborates these in detail.

3.1 Preparation of work materials

Induction furnace is used to melt the Al6061 alloy at 700°C. Preheated (800°C) SiC particles of 40 µm are presented into the vortex of molten aluminium, created by rotating stirrer at 110 rpm. Stirring is continued for 10 minutes before pouring into the preheated (350°C) metal mould and allowing it to solidify. The microstructure of the work material cast shows that SiC reinforcement is mixed with aluminium matrix (Fig. 1)
3.2 Design of Experiments

From the literature and opinion of the experts in this filed, dielectric fluid parameters namely fluid pressure, flow rate and ion exchanger resin composition are selected for the analysis. Levels of each variable are fixed with the fluid circulation system capabilities. Since three levels are decided (Table 1) for each parameter a total of 3 x 2 = 6 degrees of freedom (dof) is needed to conduct the experiments. Taguchi’s L9 orthogonal array, which can accommodate up to four parameters at three levels has 8 DOF is the suitable design to conduct the experiments. Three trials on each trial is conducted to reduce the experimental error.

After deciding the factors and their levels (table1), L9 orthogonal array (OA) was chosen to plan the experimental layout as shown in table 2. This OA can accommodate up to four three level factors. The levels for each factor are selected based on the past researches and the equipment capability. Material removal rate (MRR) and the surface roughness are the response variables used. All the nine experiments are replicated two times (totally three times) and complete randomization is followed in the order of conducting the trials. The optimization of the observed values was determined by comparing the standard analysis and analysis of variance (ANOVA) which was based on the taguchi method.

Table 1. Dielectric medium parameters and levels.

| Control Parameter                  | Level       | Response measured       |
|-----------------------------------|-------------|-------------------------|
|                                   | 1           | 2           | 3           |                          |
| Volume Flow Rate (lpm)            | Minimum     | Intermediate | Maximum     |                          |
| Pressure (bar)                    | 10          | 12          | 14          | Material Removal Rate (g/min) |
| Ion exchanger resin composition (kg) | 10          | 15          | 20          | Surface Roughness (µm)   |
Design of experiments for volume flow rate, Pressure and resin composition were done by using MINITAB V16 software. Table 3 indicates the work conditions of EDM used while conducting experimental tests.

**Table 2. Layout of experiments with L₀ OA.**

| Trial No | Volume Flow Rate (lpm) | Pressure (bar) | Ion exchanger resin composition (kg) |
|----------|------------------------|----------------|-------------------------------------|
| 1        | 1                      | 1              | 1                                   |
| 2        | 1                      | 2              | 2                                   |
| 3        | 1                      | 3              | 3                                   |
| 4        | 2                      | 1              | 2                                   |
| 5        | 2                      | 2              | 3                                   |
| 6        | 2                      | 3              | 1                                   |
| 7        | 3                      | 1              | 3                                   |
| 8        | 3                      | 2              | 1                                   |
| 9        | 3                      | 3              | 2                                   |

**Table 3. Working Conditions**

| Work Condition | Description |
|----------------|-------------|
| Work piece     | Aluminium 6061 MMC with SiC (10%) |
| SiC Particle size | 40 (µm) |
| Tool Material  | Brass       |
| Wire Diameter  | 0.25 mm     |
| Dielectric fluid | Deionized water |

**Figure 2.** Surface roughness measurement using surftest meter

The weight of the work piece before \(w_{j_b}\) and after \(w_{j_a}\) conducting each trial are measured and time taken for each trial \((t)\) is also noted down and finally the MRR is computed as below [4]:
MRR = (w_j - w_j)/t  --------------------- (1)

Surface roughness is measured with Mitutoyo tester (figure 2) with 0.8 mm cut off length. Experiments are conducted and data are obtained from experiment. Table 4 shows the L9 Orthogonal array with replaced parameters and levels and output result after conducting experiments. MRR are taken as outputs and signal to noise ratios were calculated individually.

Table 4. L9 Observed data and S/N ratio for material removal rate.

| S.NO | Parameters | | | | |
| --- | --- | --- | --- | --- | |
| | Volume Flow Rate (lpm) | Pressure (bar) | Ion exchanger resin composition (kg) | Material removal rate (g/min) | Signal to noise ratio (db) |
| 1 | 10 | 2.0 | 10 | 1.300 | 2.279 |
| 2 | 10 | 2.5 | 15 | 1.567 | 3.900 |
| 3 | 10 | 3.0 | 20 | 1.733 | 4.778 |
| 4 | 12 | 2.0 | 15 | 2.500 | 7.959 |
| 5 | 12 | 2.5 | 20 | 2.300 | 7.325 |
| 6 | 12 | 3.0 | 10 | 1.177 | 1.413 |
| 7 | 14 | 2.0 | 20 | 3.633 | 11.206 |
| 8 | 14 | 2.5 | 10 | 2.167 | 6.716 |
| 9 | 14 | 3.0 | 15 | 2.400 | 7.604 |

Table 5 shows the L9 Orthogonal array with replaced parameters and levels and output result after conducting experiments. Surface roughness is taken as output and signal to noise ratio were calculated individually.

Table 5. Observed data and S/N ratio for surface finish

| S.No. | Parameters | Surface Roughness (µm) | Signal to noise ratio (db) |
| --- | --- | --- | --- |
| | Volume Flow Rate (lpm) | Pressure (bar) | Ion exchanger resin composition (kg) | |
| 1 | 10 | 2.0 | 10 | 2.610 | -8.3328 |
| 2 | 10 | 2.5 | 15 | 2.540 | -8.0967 |
| 3 | 10 | 3.0 | 20 | 2.730 | -8.7233 |
| 4 | 12 | 2.0 | 15 | 2.513 | -8.0050 |
| 5 | 12 | 2.5 | 20 | 2.710 | -8.6594 |
| 6 | 12 | 3.0 | 10 | 2.450 | -7.7833 |
| 7 | 14 | 2.0 | 20 | 2.503 | -7.9704 |
| 8 | 14 | 2.5 | 10 | 2.297 | -7.2220 |
| 9 | 14 | 3.0 | 15 | 2.397 | -7.5922 |
4. Analysis of Data

In order to understand the influence of selected factors, that is to know the main effects of parameters, an analysis of variance (ANOVA) is done. Further the observed data are subjected to optimization using Taguchi’s technique.

4.1 ANOVA for material removal rate

The ANOVA for MRR is formulated as shown in Table 6 and the percentage contribution of each of the process parameter is used to understand the degree of influence of various factors.

| Factor                      | DOF | SS   | Adj SS | MSS  | F Test  | P (%) |
|-----------------------------|-----|------|--------|------|---------|-------|
| Volume flow rate (lpm)      | 2   | 2.2156 | 2.2156 | 1.078 | 39.8800 | 46.4627 |
| Pressure (bar)              | 2   | 0.7622 | 0.7622 | 0.3811 | 13.7200 | 15.2008 |
| Ion exchanger resin composition (kg) | 2   | 1.6156 | 1.6156 | 0.8078 | 29.0800 | 33.5564 |
| Error                       | 2   | 0.0556 | 0.0556 | 0.0278 |         | 4.780  |
| Total                       | 8   | 4.6489 |        |       |         | 100    |

From the results it is evident that volume flow rate of the dielectric fluid influences highly in the removal of material followed by ion exchange resin composition and fluid pressure. This supports the principle of wire EDM in which the material removal is due to movement of ionized particles.

4.2 ANOVA for Surface Roughness

ANOVA for surface roughness is also formulated as shown in then Table 7 and found that the flow rate of the dielectric fluid highly influences the surface roughness.

| Factor                      | DOF | SS   | Adj SS | MSS  | F Test  | P (%) |
|-----------------------------|-----|------|--------|------|---------|-------|
| Volume flow rate (lpm)      | 2   | 0.2571 | 0.2571 | 0.1285 | 84.4543 | 84.354 |
| Pressure (bar)              | 2   | 0.0271 | 0.0271 | 0.0135 | 8.8947  | 10.521 |
| Ion exchanger resin composition (kg) | 2   | 0.0018 | 0.0018 | 0.0009 | 0.5861  | 0.912  |
| Error                       | 2   | 0.0030 |        |       | 4.213   |       |
| Total                       | 8   | 0.2890 |        |       |         | 100    |

From the data obtained from the experiments, result was analyzed using ANOVA method. The ANOVA results for various parameters for SR were shown in table 7. The analysis of the above ANOVA results show that the calculated F values and percentage contribution of each factor were obtained are as volume flow rate influences majorly for SR, secondly flow pressure and finally Ion exchanger resin ratio which influences the surface roughness in the work piece. For SR in the above rank table for SR is validated by percentage contribution in ANOVA table and optimized parameters from Taguchi are validated by ANOVA.

Delta and rank table formulated for MRR and surface finish supplements the ANOVA results (refer table 8 & 9).
| Level | Volume flow rate (lpm) | Pressure (bar) | Resin Composition (kg) |
|-------|-----------------------|----------------|-----------------------|
| 1     | 3.652                 | 7.148          | 3.469                 |
| 2     | 5.535                 | 5.950          | 6.488                 |
| 3     | 8.509                 | 4.598          | 7.739                 |
| Delta | 4.857                 | 2.550          | 4.270                 |
| Rank  | 1                     | 3              | 2                     |

| Level | Volume flow rate (lpm) | Pressure (bar) | Resin Composition (kg) |
|-------|-----------------------|----------------|-----------------------|
| 1     | -8.384                | -8.103         | -7.779                |
| 2     | -8.149                | -7.993         | -7.898                |
| 3     | -7.595                | -8.033         | -8.451                |
| Delta | 0.789                 | 0.110          | 0.672                 |
| Rank  | 1                     | 3              | 2                     |

### 4.3 CFD Analysis

CFD analysis had done for parameters such as volume flow rate and pressure of dielectric medium in WEDM. Fluent software is used for analysis.

#### 4.3.1 Geometric Modeling

Geometric models of WEDM tank with dielectric fluid shown in figure 3, work piece and nozzle shown in figure 4 were modeled by using Pro-E software. Geometric models were modeled based on the actual size of tank, work piece and nozzle for debris analysis.

#### 4.3.2 Meshing of Model

Geometric model is meshed by using ANSA software. Triangular mesh is used to create surface mesh of the model and total count of triangular mesh is 116100 shown in figure 3. After surface meshing, T- Grid software is used to create triangular volume mesh in the model. Outer boundary and inner boundary of model are connected by using prism mesh and prism mesh used is to capture the perfect physics in model. Finally, it is simulated by CFD software for maximum removal of debris.
4.3.3 Flushing Analysis in Fluent.

A simulation is made to simulate the behaviour of dielectric fluid in the working gap during the machining process with the aid of commercially available FLUENT V13. The volume removal rate of debris, which is an indirect measure of material removal rate, is notified for each trial with different parameter settings. Then, their results were compared with all the parameters and the parameters those influence maximum removal of debris, are presented.

5. Results and Discussion

In this section, results obtained from the ANOVA for MRR, ANOVA for surface roughness and CFD analysis by Fluent are discussed with analysis results. Taguchi analysis had done for WEDM dielectric parameters, graphs and rank of parameters are discussed below

5.1 Signal to Noise (S/N) ratio graph

The main effects plot on S/N ratios of MRR and surface roughness are shown by figures 4 and 5 respectively. Regardless of the output response variable the maximum S/N is preferred always. In that aspect, by comparing figures 4 and 5 it could be understood that the optimal process parameter values those produce a better MRR with minimum roughness are 14 lpm for volume flow rate, 2.0 bar pressure and 20 kg for ion exchanger resin composition.
5.2 CFD Analysis by Fluent

In Fluent software, analyses were done for various dielectric medium parameters. Parameters such as volume flow rate and flow pressure are taken as input boundary conditions. According to the input boundary conditions the analyses were done by Fluent for all parameters and the best parameter, which has maximum removal debris, are 14 lpm volume flow rate and 2 bar pressure. For this parameter the amount of debris, which was removed from work piece, are 599.0 kg/m² as depicted in figures 6 and 7. Debris removal time from work piece for the best parameter is also shown in figure 8. This result coincides with that of Taguchi’s S/N ratio analysis results as far as the volume flow rate and pressure of the dielectric fluid are concerned. It means that the parameter values those are responsible for maximizing MRR has resulted in maximum debris removal.

5.3 Confirmation experiment:

The prediction of the response values can be done using the following relation:

\[ P = \mu + (A_3-\mu) + (B_1-\mu) + (C_3-\mu) \]  

(2)

\[ P = 2.631 \text{ g/min for MRR} \]

\[ P = 2.533 \mu \text{m for surface roughness} \]
Where ‘P’ is the predicted value of the concerned response and ‘µ’ is the mean value of total responses. A confirmation test is conducted with the optimum values to ensure the reliability of results obtained through the above methods. Three trials are conducted with the parameters values of 14 lpm volume flow rate, 2.0 bar pressure and with 20 kg ion-exchange resin. An average material removal rate of 2.756 g/min and surface roughness value of 2.62 µm are obtained. These values are closely matching with the predicted values.

6. Conclusion

In this work wire electro discharge machining of Al based composite with 10% SiC is carried out. WEDM dielectric medium parameters such as volume flow rate, flow pressure and ion exchanger resin composition are taken as input variables and analysis of data is done for maximizing MRR and minimizing surface roughness. Taguchi optimization method and fluent analyzed model of WEDM dielectric tank are applied to the data collected.

Optimized results of dielectric medium parameters for maximizing MRR and minimizing surface roughness are as follows:

- Maximum MRR is obtained for a volume flow rate of 14 lpm (which contributes 46.46%), ion exchanger resin composition of 20 kg (33.55%) and fluid flow pressure of 2 bar (15.20%)
- Minimum surface roughness is obtained for a volume flow rate of 14 lpm (which contributes 84.35%) followed by fluid flow pressure (10.52%) and ion exchanger resin composition
- CFD analysis by fluent showed the optimized debris removal concentration of 599.0 kg/m$^3$ happens at 14 lpm volume flow rate and 2 bar pressure which also results with a minimum time (0.034 seconds) of debris removal in work piece.
- Confirmation test is conducted to verify the same and the results were found to be satisfactory.
- Results also reveal that volume flow rate of dielectric fluid plays a vital role in maximizing the removal of material and minimizing surface roughness.

7. References

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