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MACHINABLITY OF Al/ 10%SiC/ 2.5%TiB_2 METAL MATRIX COMPOSITE WITH POWDER-MIXED ELECTRICAL DISCHARGE MACHNING

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Abstract

In the present work, a study has been made to optimize the process parameters of powder mixed electrical discharge machining (PMEDM). Response surface methodology has been used to plan and analyze the experiments. Analysis were done to investigate the effects of the process parameters viz. pulse current (I), pulse on-time (Ton) and concentration of the Al powder in kerosene dielectric (C) and its effects on material removal rate (MRR), tool wear rate (TWR) and surface roughness (Ra). Process parameters were optimized for high MRR, low TWR and low Ra using desirability function approach of MINITAB software. Due to frequent short circuiting, addition of Al powder to the dielectric fluid reduces the MRR whereas TWR decreases for low peak current of 2 A with the increase in the concentration of powder. Addition of Al powder further improves the surface roughness to a value of 3.31 μm.

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*Keywords:*Metal matrix composites; MRR, Optimization; Powder-Mixed EDM; Surface roughness; TWR.

1. Introduction

Metal Matrix Composites (MMCs) are key materials in many industrial applications like automotive, structural and aerospace industries. These applications require precise and complex machining. The extensive works on the machining of MMC reveals that, high forces during cutting causes rapid tool wear and loss of dimensional accuracy. For the complex and precise machining, unconventional methods such as electric discharge machining (EDM) are inevitable. EDM is a machining process for eroding and removing materials from an electrically conductive material

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by repeated electric sparks. Each spark will locally melt evaporate or ionize the work piece material. But this machining technique results in reduced surface integrity which reduces the yield strength, ultimate strength also fatigue life of the machined component due to poor surface characteristics. (Ramulu et al., 2001). To enhance the process capabilities of conventional EDM electrically conductive powders are mixed in to dielectric fluid which alters the mechanism of metal removal producing high MRR and better surface quality (S. Singh et al., 2012, Wong et al., 1997).Aluminium-6061 grade is reinforced with 10% silicon carbide and 2.5% titanium diboride. The particle size of the silicon carbide titanium diboride is 30 μm and 12 μm respectively. The density of aluminium based hybrid MMCs is nearly one third that of steel, and offers high specific strength, stiffness, and high resistance to wear as mentioned by Singh S. and M.F Yeh (2010). The chemical properties of aluminium 6061 are shown in table 1.

Table 1. Chemical composition of Aluminium 6061

Material	Magnesium	Copper	Silicon	Iron	Manganese	Chromium	Others
Composition	0.8 -1.2	0.15 - 0.4	0.4	0.7	0.15	0.04 - 0.35	0.4

During PMEDM process, the spark-gap filled up with powder particles suspended in the dielectric fluid, get energized due to the electric field. These charged particles are accelerated by the developed electrical field and act as conductors. As a result, the powder particles arrange themselves under the sparking area and gather in clusters (Zhao et. al., 2002). This results in several discharging paths creating multiple discharges within a single input pulse (Chow et al., 2008). Thus a single input pulse creates several discharging craters causing faster metal removal from the work surface. At the same time, shallow craters create smaller debris and will be flushed away easily from the spark-gap, which results in improved surface finish (Hu et. Al., 2013).

Kumar and Davim (2011) studied about role of powder in PMEDM of Al-10%SiC and stated that with the addition of appropriate amount of silicon powder in to the dielectric will increase the MMR and reduce the surface roughness. They also suggested that concentration of powder, peak current and pulse duration are the significant variables. Suresh Kumar et. al. (2014) conducted EDM in aluminium alloy (6351) reinforced with 5 wt.% SiC and 10wt.% B_4C hybrid composite and optimized the process parameters viz. pulse current, pulse on time, pulse duty factor and voltage using gray relational approach. They concluded that pulse current is the most significant parameter affecting the output response. Velmurugan et. al (2011) conducted EDM in hybrid Al6061 metal matrix composites reinforced with 10% SiC and 4% graphite particles and analyzed the machining characteristics and the surface properties. They used central composite rotatable method for experimentation. PMEDM done on 6061Al/ Al_2O 3p/20p by Singh et. al. (2010) revealed that by adding SiC abrasives, the process effectiveness improves and the surface roughness is reduced as compared with the conventional EDM. The effect of the electrode area on the surface roughness and topography while using PMEDM in AISI H13 is studied by Pecas and Henriques (2008). They concluded that the use of PMEDM conditions promotes the reduction of surface roughness and the white layer thickness. It was confirmed that powder-mixed dielectric significantly reduces surface heterogeneity contributing to increase process robustness.

Further, the availability of inexpensive sources of SiC and TiB_2 along with ability of discontinuous MMC to be fabricated using conventional stir casting technique increases the relevance of this composition. In the present study, the machinability of Al/ 10%SiC/ 2.5%TiB_2 metal matrix composite material were investigated with powder-mixed electrical discharge machining (PMEDM).

The different process parameters for the experiment are current, pulse on-time and concentration of powder in dielectric. Face-centered CCD scheme, a popular variant of the central composite design involving three levels for each factor, was used to plan the experiments. This design is considered most effective for second order designs capable of handling linear, quadratic, and interaction terms in process modelling. From the literatures it is understood that by the use of PMEDM a very good improvement in process productivity and stability can be achieved. Also finish cut with a thin recast layer can be obtained. A lot of works are being done in the field of using EDM machining of composite materials but the works done on PMEDM of composites are very less in number. Many researches are going on in this field regarding the experimentation and optimization of the process in composite materials. Experimentation and its analysis will be done on the material at different process parameters and optimum value of each parameter for the maximum performance will be determined. To study and to understand about the efficiency of the process in MMCs is of at most importance. In support of this, analyzing the material removal rate, electrode wear rate and surface roughness has to be done to obtain a final result which will be of considerable use in the present industrial conditions and in future.

2. Experimental Procedures

2.1 Workpiece preparation

Stir casting is used for the preparation of the hybrid aluminium metal matrix composite work material. Silicon carbide and titanium diboride of average particle size 30 μm and 12 μm respectively are used as the reinforcements for casting. Silicon carbide 10 wt% and titanium diboride 2.5 wt% were reinforced in to aluminium 6061. The cast specimen of 34 mm diameter is cut using wire-EDM in to circular plates of 10mm thickness.

2.2 Tool preparation

The tool material used for the experimentation is electrolytic copper tool (99.9%). The diameter of the tool electrode is 10mm and its total length is 120mm. Through the centre of the tool a 6 mm hole of 11 mm length is drilled. The remaining 10mm of the tool is drilled with three 2mm holes aligned at an angle of 120^0 apart. The tool drilling is done using modern drilling machine with high precision. Tool rotation is enabled using a DC motor fitted rotating head installed on the EDM machine. The schematic of the tool prepared is shown in figure 1.

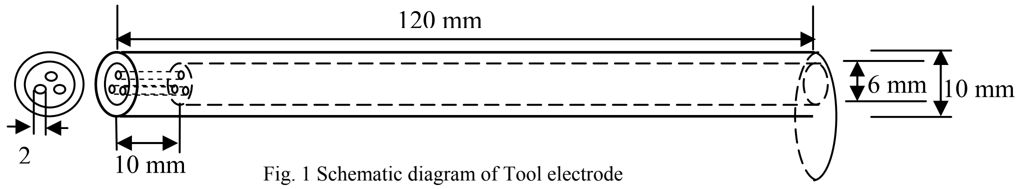

Fig. 1 Schematic diagram of Tool electrode

2.3 Experimental setup

To conduct experiments with Al powder mixed kerosene, a separate dielectric recirculation system was designed, fabricated and attached to the machine. The recirculation system consists of dielectric tank of capacity 6.5 litres, pump and delivery devices. The top portion of the tank is in cylindrical shape and the bottom portion of the tank is in conical shape. The circulation system consists of a 0.25 HP pump. The pump receives the dielectric fluid from the outlet of the conical tank and recirculates to the tool-work inter-electrode gap to flush the debris during machining.

A fixture is fabricated to hold the workpiece of dimensions ø 34 mm × 10 mm in position during the PMEDM experiments. The fixture is preciously fabricated to ensure parallelism of workpiece surface with reference to the machine table.

Rotating head is attached to the EDM machine to give tool rotation. The whole process will be done with the work piece and tool fully immersed in kerosene. The flash point of kerosene is 37 to 65ºc. So at room temperature kerosene can catch fire. So the kerosene at the spark gap which is at high temperature is separated from the atmosphere by sinking it in kerosene. Each experiment will be of 10 minutes duration.

2.4 Design of experiments

Design of experiments (DOE) is a structured, organized method for determining the relationship between factors, which affect the process and the output of that process. The basic aim of any DOE is to obtain the maximum information about the process with minimum number of experiments. In this study, a face centered central composite design (FCCCD) technique was selected. The CCD is a popular design in response surface methodology (RSM) approach. The main advantages of this technique as mentioned by Kuppan P et. al (2008) is (1) CCDs can be run sequentially; (2) CCDs are efficient, providing information on experiment variable effect and over all experimental error in minimum number of runs; (3) CCDs are very flexible. DOE was prepared to investigate the effects of process parameters viz. pulse current (I), pulse on-time (Ton) and Al concentration of powder in kerosene dielectric (C) and its effects on material removal rate (MRR), tool wear rate (TWR) and surface roughness (Ra).

2.5 Experimentation

After the work piece, tool and electrolyte preparation the experimentations are done. The input parameters are current (I), pulse on-time (T_{on}) and concentration of the powder in the dielectric (C). The responses parameters are material removal rate (MRR), tool wear rate (TWR) and surface roughness (Ra). Central composite design approach is used for the experimentation. 20 experiments were conducted according to the design of experiments. Before the starting of the experimentation pilot experiments were conducted to fix the value of voltage to 30V which is kept constant throughout the experiment. Machine servo sensitivity, lift time, and mode of flushing were also kept constant throughout the experimentation. The process is done with negative polarity. The duty factor was set at 60% and correspondingly values of T_{on} and T_{off} were found out using the equation 1.

$$\text{Dutyfactor} = \frac{\text{Ton}}{\text{Ton+Toff}} \qquad (1)$$

The range of values of process parameters are shown in the table 2. As per the DOE experiments are conducted on the workpiece using Electronica machine. The kerosene mixed with predetermined amount of Al powder of 27 µm diameter is used as the dielectric fluid. The used kerosene is filtered using a 5 micron filter to remove machining debris present in it to conduct further experiments. The weight of the work piece and tool is measured using a precision balance before and after each experiment using a digital single pan balance (maximum capacity 220 g, precision 0.0001 g). The final machined workpiece is shown in figure 2.

Table 2. Process parameters for the experiment.

Parameters	Range of values
Current (A)	2, 5, 8
Pulse on time (µs)	30, 50, 70
Powder Conc. (g/l)	0, 2, 4

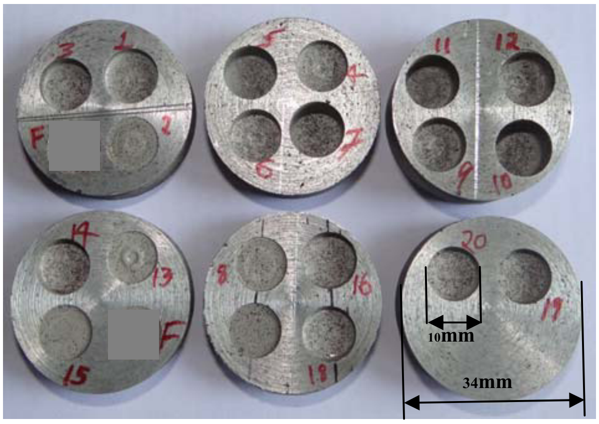

Fig. 2 Machined work piece materials

After carrying out the machining the surface roughness testing was done. The surface texture which is developed by each trial of machining was analyzed using contact profilometry using MahrSurf GD 120 surface roughness tester fitted with a 2 µm probe. A traverse length of 5.60 mm is used according to standards with a 0.80 mm cut off length. For all the specimens the average surface roughness (Ra) is measured and values are noted.

2.6 Optimization experiments

Using the desirability function approach optimized values are obtained which will give maximum MRR, minimum TWR and minimum surface roughness. Using these values one optimization experiment is conducted to check the reliability of optimization. The values obtained from these experiments are compared with that obtained from software

3. Results and Discussion

The experiments are completed and the results are tabulated. The loss of material for the work piece and the tool was obtained from the experiments and the corresponding value of material removal rate and tool wear rate is obtained. The surface roughness values are also measured. The design of experiments followed and the corresponding values of the responses obtained are tabulated in table 3.

Using p test table of ANOVA the regression model equation is developed and significance of each process parameter is analyzed. The model equations will be in second order polynomial form which is best suited for small region of variable space. By performing ANOVA at 95% confidence level, the significance of each coefficient can be obtained and insignificant terms can be eliminated. Using desirability function approach the values of optimal process parameters are obtained by which the maximum process performance can be ensured. Also from the same plot the values of the MRR, TWR and Ra at different input parameters were obtained.

The regression model equation to obtain MRR, TWR and Ra values is given below:

$$MRR = -22.18 + 1.03I + 0.67T_{on} - 2.20C + 1.10I^2 - 0.01T_{on}^2 + 0.32C^2 + 0.22I \times T_{on} - 0.73I \times C + 0.03T_{on} \times C$$

$$TWR = 3.53 + 0.94I - 0.17T_{on} - 0.56C + 0.12I^2 + 0.001T_{on}^2 - 0.006C^2 - 0.02I \times T_{on} + 0.06I \times C + 0.008T_{on} \times C$$

$$Ra = 8.61 + 0.83I - 0.21T_{on} - 0.22C - 0.07I^2 + 0.001T_{on}^2 - 0.19C^2 + 0.005I \times T_{on} + 0.02I \times C + 0.01T_{on} \times C$$

The R^2 value achieved for MRR, TWR and Ra models are 99.5%, 97.84% and 75.23% respectively. These values indicate that the predictors very well explain the amount of variation in the observed response values. Using these model equations the values of MRR, TWR and Ra corresponding to each combination of I, T_{on} and C can be obtained. Using these obtained values graphs are plotted with responses in vertical axis and process parameters in horizontal axis. From these graphs the effect of process parameters on responses can be analysed.

3.1 Effect of process parameters on Material Removal Rate

Observing the trend of MRR from different levels of the process parameters, it can be observed from figure 3.a, that MRR tend to increase with increase in peak current for any value of pulse on-time. Hence, maximum MRR is obtained at high peak current (18 A). The increase in the MRR with peak current could be due to the dependence of MRR on the energy per pulse which increases with increase in pulse current at constant frequency and voltage. A similar trend also observed by Wong et al. (1998) during machining of other material with PMEDM.

Figure 3.b shows the variation of MMR with pulse on-time for the three values of concentration of powder. From the graph it is evident that MMR tend to increase with increase in pulse on-time. Hence, maximum MRR is obtained at high pulse on-time (70 µs). The increase in MRR at higher T_{on} could be due to increasing the discharge energy by longer pulse on-time.

It can also be inferred from the Figure 3.c, that with increase in the concentration of the powder, MRR tends to decrease. The addition of the powder into the dielectric fluid at 2 A current has negligible influence on MRR whereas, the reduction in MRR is more notable when powder is added to the dielectric at high values of current (8 A). This is due to unsteady machining conditions prevailed because of frequent short circuiting which decrease the MRR as earlier established by Erden and Bilgin, 1980. Thus, the maximum MRR is obtained at high peak current of 8 A, with high pulse on-time of 70 μs without Al powder addition to the kerosene.

Table 3. Design of experiments and the corresponding values of MRR and TWR.

Sl. No.	Process Parameters			Responses		
	I (A)	T_{on} (µs)	C (g/l)	MRR (mg/min)	TWR (mg/min)	Average Ra (µm)
1	5	50	2	59.23	2.17	5.49
2	2	30	4	4.60	0.30	3.79
3	5	50	2	70.45	1.35	6.61
4	5	30	2	45.34	4.79	6.56
5	8	30	0	119.03	9.81	7.55
6	5	50	2	66.62	2.84	5.59
7	8	70	4	156.99	5.52	8.45
8	2	50	2	8.07	0.17	5.21
9	5	50	0	76.06	2.53	6.71
10	8	70	0	171.41	3.55	6.91
11	8	50	2	141.06	7.02	6.72
12	8	30	4	95.44	10.19	5.85
13	2	30	0	6.29	0.97	5.03
14	5	70	2	75.55	1.81	8.01
15	2	70	4	9.50	0.42	4.18
16	5	50	2	72.40	2.61	5.97
17	2	70	0	10.73	0.07	4.21
18	5	50	4	55.80	2.54	4.96
19	5	50	2	59.39	1.38	6.04
20	5	50	2	60.46	1.37	8.45

3.2 Effect of process parameters on Tool Wear Rate

Figure 4.a shows the variation of TWR with current at different values of pulse on-time. It can be observed that, TWR increases with increase in pulse current different pulse on-time. From figure 4.b it is evident that TWR decreases with the increase in the pulse on-time. The decrease in TWR at high T_{on} could be due to increasing the discharge energy by longer pulse on-times, not allowing high discharge frequencies and causing more energy losses by heat conduction. Similar trend was also reported by Lee et al. (2001). Also for higher pulse on-time values and lower currents there is an increased possibility of carbon deposition on the tool electrode which results in a lower TWR as mentioned by Hu et al. (2013). Hence low TWR can be obtained at high pulse on-time (20 µs).

From the trend of TWR, it is evident from the figure 4.c that, effect of powder addition to the dielectric is not significant on TWR. However TWR tend to decrease with the addition of powder at low current but increases at high currents. This may be due to the deposition of carbon on the surface of the tool at lower value of current as mentioned earlier. Whereas at high value of powder concentration at high pulse current increases TWR. This is due to the fact that presence of powder particles will remove the layer of carbon deposited on the surface of the tool electrode which in turn leads to a faster erosion of the tool electrode. Hence to reduce tool wear low peak currents of 2 A at low pulse on-time 30 μs with high concentration of Al powder 4 g/l in the dielectric should be selected.

3.3 Effect of process parameters on Surface Roughness

The variation of surface roughness for different values of pulse current is shown in figure 5.a. It can be observed that, at high pulse current (8 A) the roughness value is increasing. This is due to the fact that, higher pulse energy available at high values of pulse current creates deeper and larger craters on the workpiece. This will lead to higher irregularities in the machined surface and so a higher surface roughness. It is clear that the best surface finish is obtainable at the low levels of peak current (2 A). Figure 5.b shows the variation of surface roughness for different values of the pulse on-time. It can be observed that surface roughness increases with the increase in the pulse on-time for the powder mixed dielectric when compared to pure dielectric. This is due to the fact that, at constant current, increase in the pulse on-time increases the pulse energy which will produce larger craters. Hence in order to obtain better surface finish low values of pulse on-time (20 µs) should be used.

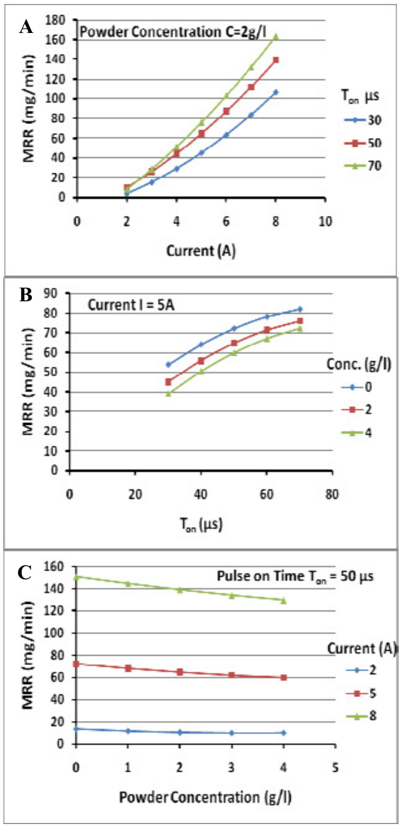

Fig. 3 (A) Current vs MRR at three values of pulse on time, (B) Pulse on time vs MRR at three values of powder concentration, (C) Powder concentration vs MRR at three values of current.

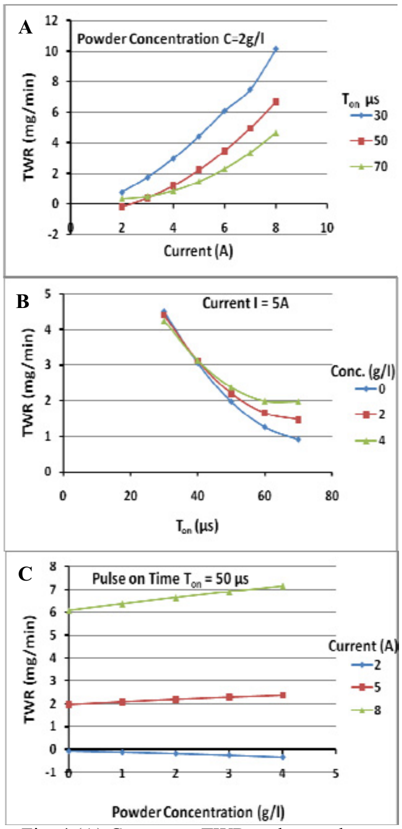

Fig. 4 (A) Current vs TWR at three values of pulse on time, (B) Pulse on time vs TWR at three values of powder concentration,(C) Powder concentration vs TWR at three values of current.

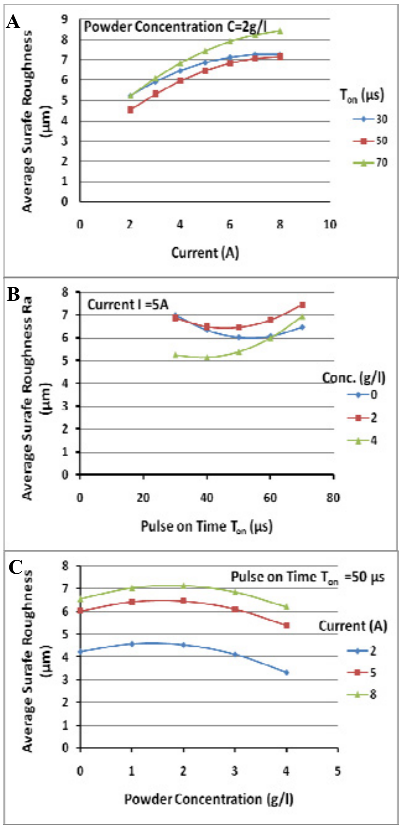

Fig. 5 (A) Current vs Surface roughness at three values of pulse on time, (B) Pulse on time vs Surface roughness at three values of powder concentration (C) Powder concentration vs Surface roughness at three values of current.

Figure 5.b shows the variation of surface roughness for different values of the pulse on-time. It can be observed that surface roughness increases with the increase in the pulse on-time for the powder mixed dielectric when compared to pure dielectric. This is due to the fact that, at constant current, increase in the pulse on-time increases the pulse energy which will produce larger craters. Hence in order to obtain better surface finish low values of pulse on-time (20 µs) should be used.

Figure 5.c shows the variation of surface roughness with increase in concentration of powder for different values of pulse current. It can be observed that surface roughness reduces with increase in concentration of powder from (0 - 4 g/l) for any value of the pulse current. The thermo-physical properties of the Al powder will cause a better spark distribution, thus producing shallow craters on the machined surface (Assarzadeh et al., 2013).

In this way, low values of peak current of 2 A, at low value of pulse on-time 30 µs and high concentration of Al powder 4 g/l produced a surface of roughness value 3.79 µm (sample - 2). This proves that powder addition to the dielectric fluid plays a significant role in modifying the plasma channel. The plasma channel creates several discharging paths causing shallow craters which results in improved surface finish. Using the desirability function approach a values of optimum combination of process parameter are obtained. Verification experiments are conducted and tabulated in the Table 4. The results show that MRR is reproduced within range of ± 12 %, TWR were reproduced within range of ± 11 %, and Ra were reproduced within range of ± 0.15 %.

Table 4. Comparison of optimized values.

I (A)	T_{on} (µs)	C (g/l)	Predicted			Obtained			Error		
			MRR (mg/min)	TWR (mg/min)	Ra (µm)	MRR (mg/min)	TWR (mg/min)	Ra (µm)	MRR (%)	TWR (%)	Ra (%)
7.4	56	0	140.17	4.19	6.63	123.91	4.64	6.64	11.6	10.7	0.15

4. Conclusion

The aim of the research work was to investigate the machinability of hybrid aluminium metal matrix composite using aluminium powder mixed EDM. In this study three process parameters are varied viz. peak current, pulse on-time and concentrations of powder in the dielectric to study the influence on the responses MRR, TWR and Ra. Based on the experimental results the following conclusions are drawn:

- The factors such as peak current, pulse on-time and concentration have significant contribution in MRR, TWR and Ra model.
- High MRR of 171.41 mg/min is obtained at a high peak current of 8 A, high pulse on-time of 70 μs, and low concentration of 0 g/l Al powder (pure kerosene).
- Low TWR of 0.3 mg/l is obtained at low peak current (2 A) and low pulse on-time (30 μs) and high concentration of aluminium powder (4 g/l) mixed kerosene.
- To produce low Ra values, a low peak current of 2 A, low pulse on-time of 30 μs, and higher concentration of powder of 4 g/l should be selected.

Multi-objective optimization using desirability function approach with MINITAB was performed to produce high MRR, low TWR and low Ra values. Experiments were conducted to validate the predicted results and were found within 10% error.

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