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Effect of Conductive, Semi-conductive and Non-conductive Powder-Mixed Media on Micro Electric Discharge Machining Performance of Ti-6Al-4V

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This research was focussed on the effective utilization of the Powder-mixed Micro Electric Discharge Machining (PMEDM) process when using tap water as a dielectric medium for micromachining applications. Micro-holes of diameter 300 µm were drilled over Ti-6Al-4V plates. Firstly, the impact of process parameters on the machining performance was analyzed by using tap water without the additive. The effect of process parameters such as tool material, gap voltage, peak current, pulse on-time and duty factor on the Material Removal Rate (MRR), Tool Wear Rate (TWR), Overcut (OC), Circularity Error (CE) and Taper Ratio (TR) were analyzed by conducting the experiments based on Taguchi's L18 design layout. The optimal parametric setting for multi-objective optimization was figured out through the technique for order of preference by similarity to ideal solution (TOPSIS). Secondly, keeping the process parameters at the optimal setting, the effect of additives in tap water dielectric based micro-EDM was investigated by using non-conductive, semi-conductive and conductive powders, namely Al_2O_3, SiC and Al of different weight concentration and particle sizes. The outcomes reveal that the type of tool has a very significant impact on the micro-EDM performance when using tap water as dielectric without additives. In PMEDM, the conductance of additives has a significant influence on the multi-objective performance characteristic. When using SiC additives in PMEDM, we recorded increase in MRR of 92.18%, decrease in TWR of 28.92%, decrease in OC of 18.99%, decrease in CE of 54.15% and decrease in TR of 24.78%.

Keywords: EDM, PMEDM, Ti-6Al-4V, tap water, Copper tool and Brass tool

1. INTRODUCTION

In microsystems, there is a growing demand for micro-parts made of Ti-6Al-4V due to its excellent physical and mechanical properties [1]. Achieving higher productivity with fine geometrical dimensions is very important while micro-machining Ti-6Al-4V for producing micro-elements and systems [2]. Micro-EDM is one of the non-traditional machining processes. It is highly suitable to perform machining activity on all kinds of electrically conductive materials—of any hardness—to manufacture simple to complex geometrical parts accurately. In EDM, the role of dielectric fluid is very significant, and it serves some principal purposes. It is the insulating medium that facilitates the formation of a plasma channel between tool and workpiece when the applied voltage exceeds dielectric strength. The plasma channel aids the machining activity by melting and vapourization. The dielectric medium helps to flush out the debris from the spark gap which is generated for every electric discharge. It also acts as a coolant and a perfect insulator, thereby creating discharge at different spots on the workpiece for successive electric pulses. Hence, the nature of the dielectric in EDM is a very significant parameter that remarkably influences the material removal process and the quality of the machined surface.

Generally, in the EDM process, hydrocarbon oils are used as dielectric fluids. However, when hydrocarbon oil is employed as a dielectric, certain problems are encountered such as emission of harmful gases (primarily CO and CH_4), operator health issues and decomposition of unwanted products. Thus, the alternate dielectrics fluids such as deionized water and tap water are put forward judicially to accomplish eco-friendly and economic manufacturing [3]. Researchers suggested dry, near-dry and water EDM as alternative processes to oil-based EDM to achieve green manufacturing [4]. Kou and Hun [5] reported that water-based dielectric fluids enhanced the material removal rate to fivefold while performing high-speed machining on Ti-6Al-4V compared to that of conventional oil-based EDM. Tang and Duo [6] proved that tap water can effectively be used as a dielectric in EDM of Ti-6Al-4V with the help of a red copper rod of 10 mm. They found that tap water EDMs yield high MRR and less operating cost and showed no harm to operators or the environment. A review paper has revealed that the best MRR was achieved when tap water was used as a dielectric. It has also pointed out that electrically conductive additives decrease the insulating property of the dielectric at the spark gap, and thus increase the width of an inter-electrode gap that supports better flushing resulting in better MRR and surface finish [7].

Non-conductive Al_2O_3 powders were utilized as additives in oil-dielectric and copper tools of 12 mm diameter to machine AlSiCp12% metal matrix composite (MMC) by EDM. It was observed that the addition of Al_2O_3 powders improves the breakdown phenomenon that augments the machining rate and alleviates the surface roughness [8]. Some researchers [9] employed alumina powders of 45 nm size as additives in deionized water-dielectric while performing EDM over Inconel alloy with a copper tool of dimension 5 mm x 15 mm. They observed that the occurrence of arcing was more in conventional EDM when compared to that of PMEDM. They also pointed out that the addition of alumina powders increased the spark gap during machining which eased the flushing of debris, thus resulting in stable machining. Chow et al. [10] compared the effect of SiC and aluminium additives of particle size 1µm in kerosene-dielectric while executing micro-slit EDM over titanium alloy. Their results showed that SiC powders show better effect on MRR than that of aluminium. Kibria et al. [11] substantiated that B_4C-mixed deionized water dielectric resulted, comparatively, in a lower variation of diameteral variance at the entry and exit holes at higher discharge energy compared to pure deionized water during micro-EDM of titanium alloy. Pecas and Henriques [12] used silicon powders as additives in Castrol-fluid dielectric while carrying out EDM on AISI H13 hot work tool steel with copper tool area ranges from 1 to 64 cm^2. The average particle size of the additive was 10 µm and the additive concentration was 2 g/L. They concluded that the addition of semi-conductive silicon powders in the dielectric nearly annihilate the abnormal discharges and paves the way to attain machined surface with mirror polish. Tzeng and Lee [13] performed PMEDM on SKD11 mould steel by employing copper as a tool material of 8 mm diameter and kerosene as a dielectric medium. They analyze the impact of aluminium, chromium, copper and silicon carbide powders on the material removal process. Their experimental outcomes proved that the MRR was higher when the volumetric powder concentration was 0.5 cm^3/L and particle sizes ranged from 10-15 µm. Chromium powder ranked first in yielding better MRR. No significant impact on MRR was noticed when using copper as additives because of its higher density.

Nguyen et al. [14] investigated the effect of titanium powders in oil-dielectric while machining SKD tool steel by EDM. In their experimental investigation, they selected tool materials (copper and graphite), tool polarity, pulse-on time, pulse-off time, current and powder concentration as process parameters. Their results showed that powder concentration was the most significant process parameter. The addition of Ti powder intensifies the material removal process and decreases the surface roughness. Prihandana et al. [15] examined the effect of molybdenum disulphide additives in kerosene dielectric based micro-EDM. They fabricated micro-holes with a depth of 25 µm and a diameter of 1000 µm over Cu, brass and Cu-W workpiece materials with the aid of Cu, Cu-W and Ag-W tools. In their experimentation, the particle size and concentration of MoS_2 additives were 2 µm and 2-5 g/L, respectively. Their results proved that the semi-conductive MoS_2 additives produced black spot-free machined holes and enhanced the MRR.

From the research undertaken in the PMEDM, it can be inferred that the different types of additives, levels of concentration and particle size deliver non-identical and contrasting effects on the performance of the machining—particularly MRR, TWR and surface finish. The literature survey further underscored the scarcity of research in the field of tap water dielectric based PMEDM. Therefore, the following objectives had been set for this present research. First to discern the effect of process parameters in tap water dielectric based micro-EDM of Ti-6Al-4V. Second, to investigate the effect of electrically non-conductive, semi-conductive and conductive powders, namely Al_2O_3, SiC and Al, as dielectric additives, on the machining speed and dimensional accuracy of PMEDM through Material Removal Rate (MRR), Tool Wear Rate (TWR), Overcut (OC), Circularity Error (CE) and Taper Ratio (TR).

2. EXPERIMENTAL SECTION

2.1 Experimental set-up and materials

The machine tool ELTECH D300 manufactured by Electronica Hightech (Figure 1) was used to conduct the experimental work. A special tank was designed and fabricated with pump, proper filtration and stirring mechanism to circulate the tap water dielectric fluid mixed with additives. Side flushing was applied at the spark gap, and its pressure was maintained constantly at 0.5 kg/cm^2.

Electrically non-conductive (Al_2O_3), semi-conductive (SiC) and conductive (Al) powder of three various particle sizes and weight concentrations were used in PMEDM. Table 1 lists the physical properties of the powder-type additives.

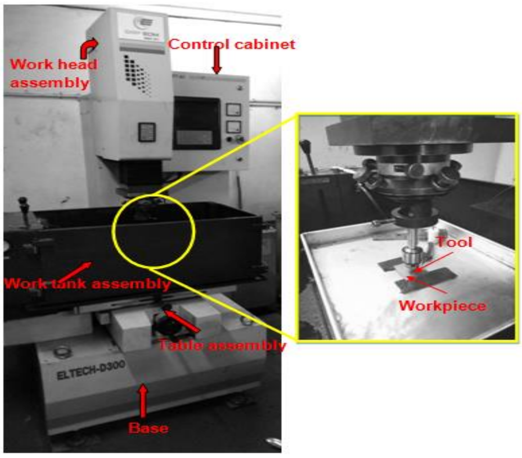

Figure 1. Photograph of machine tool

Table 1. Physical properties of powder-type additives

Powder-type	Density (g cm^{-3})	Electrical resistivity (μ Ω cm)	Thermal conductivity (W cm^{-1} $^{\circ}$C^{-1})	Melting point ($^{\circ}$C)
Al_2O_3	3.98	1 x 1020	0.18	2277
SiC	3.16	1 x 1011	0.2	2700
Al	2.70	2.65	2.38	660

Table 2. Experimental details of PMEDM

Factors	Descriptions
Workpiece	Ti-6Al-4V (Thickness : 550 µm)
Tool material 'T'	Brass tube and Copper tube (OD: 300 µm, ID: 120 µm)
Dielectric fluids	tap water without Additives and tap water with additives
Polarity	Tool: Positive and Workpiece: Negative
Gap voltage 'V' (V)	30, 40, 50
Peak current 'I' (A)	0.5, 1, 1.5
Pulse on-time 'T_{on}' (µs)	100, 200, 300
Duty factor 'DF'(%)	55, 65, 75
Powder-type 'P'	Al_2O_3, SiC, Al (Non-conductive, Semi-conductive, Conductive)
Concentration 'C' (g/L)	1, 2, 3
Size 'S' (µm)	2, 5, 8

The commercially available EDM tube tools, i.e., brass tubes and copper tubes, having an outer diameter of 300 µm and an inner diameter of 120 µm, were used as micro-tools for machining. The workpieces were Titanium alloy Ti-6Al-4V plates of thickness 550 µm. Machining was conducted by setting the tool as an anode. Considering the tool wear, the depth of machining at Z-axis was set as 1 mm. The experimental details are summarized and displayed in Table 2. The ratio of weight loss of the workpiece to the machining time was used to calculate the MRR. The weighing of the workpiece was accurately done by using microbalance of 0.01 mg resolution. TWR was found by reading the Z-axis length before and after machining. The profile of the machined hole both at the entrance and exit sides was analyzed by using a metallurgical microscope at the magnification of X100.

The maximum difference between the diameter of the machined hole and the tool was used to determine the overcut. The roundness error of the machined hole was proposed in terms of circularity, which is a radial distance between the minimum circumscribing circle and the maximum inscribing circle. The difference in diameter of the entrance and entry holes was gauged by finding the TR as per the Equation (1):

$$\mathrm{TR} = \frac{\text{Entry diameter} - \text{Exit diamter}}{2 \text{ x thickness of the workpiece}} \qquad (1)$$

2.2 Experimental set-up design

With the idea gained from literature survey and some trial experiments, the process parameters and their working range were identified. The selected process parameters were tool material, gap voltage, peak current, pulse on-time and duty factor. Taguchi's experimental design had successfully been implemented to carry out experimental investigation in micro-EDM with a minimum number of experiments, less cost and time [16 & 17]. Therefore, it was used to design the experimental layout for the present research work. In view of the number of process parameters and their levels, Taguchi's L18 orthogonal array was found to be the apt experimental layout to conduct the experiments, and it is shown in Table 3. The technique for order of preference by similarity to ideal solution (TOPSIS)—a proven tool to identify the optimal parametric setting for multi-objective optimization [14 &18]—was implemented. It was used to normalize and convert the multi-performance characteristics (MRR, TWR, OC, CE and TR) with different units into single performance characteristic. It helps to figure out the optimal parametric setting that has the foremost relative closeness (CC, or Closeness Coefficient) to the ideal solution. Equal weightage of 0.2 was assigned to MRR, TWR, OC, CE and TR while calculating the CC value. Finally, ANOVA was performed over the CC values to scrutinize the significance and the contribution of the process parameters on the multi-objective performance characteristic.

Table 3. Experimental layout for micro-EDM without additives

Run	Tool Material	Gap Voltage (V)	Peak Current (A)	Pulse On-time (μs)	Duty Factor (%)
1	Brass Tube	30	0.5	100	55
2	Brass Tube	30	1	200	65
3	Brass Tube	30	1.5	300	75
4	Brass Tube	40	0.5	100	65
5	Brass Tube	40	1	200	75
6	Brass Tube	40	1.5	300	55
7	Brass Tube	50	0.5	200	55

8	Brass Tube	50	1	300	65
9	Brass Tube	50	1.5	100	75
10	Copper Tube	30	0.5	300	75
11	Copper Tube	30	1	100	55
12	Copper Tube	30	1.5	200	65
13	Copper Tube	40	0.5	200	75
14	Copper Tube	40	1	300	55
15	Copper Tube	40	1.5	100	65
16	Copper Tube	50	0.5	300	65
17	Copper Tube	50	1	100	75
18	Copper Tube	50	1.5	200	55

While analyzing the effect of additives on the tap water EDM, the researchers were keen on divulging the effect of the electrically conductive nature of the additives on the performance of PMEDM. Hence, non-conductive Al_2O_3, semi-conductive SiC and conductive Al powders had been employed as additives in tap water dielectric. Keeping the machine at the multi-objective optimal setting, another set of L18 experiments were conducted with various levels of control factors of PMEDM, namely the type of powders, weight concentration and average particle size of the additives. The implications of additives on multi-objective performance characteristic of PMEDM were examined. Finally, a comparison of the performance of the tap water micro-EDM with and without additives was made.

3. RESULTS AND DISCUSSION

3.1 Effect of process parameters on pure tap water based micro-EDM

Table 4 exhibits the outcome of the experiments conducted by using pure tap water as a dielectric fluid. The main effects plot for means of multi-objective performance characteristic and the ANOVA results are displayed in Figure 2 and Table 5, respectively. It can be observed that the tool material emerged as the most significant process parameter. In micro-EDM, current passes through the thin tool, and hence, it should possess good thermal conductivity to remove the massive heat energy generated during each pulse discharge. In addition, a good electrically conductive tool creates a stable plasma channel, thereby facilitating stable machining. Copper, which has better electrical and thermal conductive properties than brass, produces a very significant impact on the multi-objective performance characteristic.

Table 4. Experimental outcome of micro-EDM without additives

Run	MRR (mg/min)	TWR (mm/min)	OC (μm)	CE (μm)	TR	CC	Rank
1	0.0175	0.0638	71.4	30	0.0168	0.6667	9
2	0.0246	0.0829	82.4	38.1	0.0520	0.5833	12
3	0.0475	0.1338	113.4	54.5	0.1422	0.2521	17

4	0.0237	0.0768	88.1	42	0.0306	0.6236	11
5	0.0399	0.1019	110.5	53	0.0968	0.3961	14
6	0.0400	0.1131	100.4	47.5	0.1303	0.2819	15
7	0.0276	0.0881	93.2	44.5	0.0696	0.5079	13
8	0.0448	0.1219	109.8	51	0.1628	0.2201	18
9	0.0474	0.1170	114.8	54	0.1449	0.2612	16
10	0.0501	0.0582	82.9	38.5	0.0575	0.7118	6
11	0.0417	0.0474	63.8	28.5	0.0272	0.8110	1
12	0.0427	0.0531	88.6	41	0.0205	0.7563	5
13	0.0440	0.0606	72.5	33	0.0329	0.7825	3
14	0.0560	0.0822	83.4	39	0.0194	0.7703	4
15	0.0486	0.0678	71.1	32.5	0.0347	0.7918	2
16	0.0592	0.0753	90.2	42	0.0637	0.6660	10
17	0.0548	0.0742	83.1	38.5	0.0543	0.7094	7
18	0.0636	0.0870	89.9	42	0.0475	0.6982	8

Table 5. Results of the ANOVA for micro-EDM without additives

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
T	1	0.4686	0.4686	163.0	0.000	63.5
V	2	0.0486	0.0243	8.5	0.011	6.6
I	2	0.0701	0.0350	12.2	0.004	9.5
T_{on}	2	0.0900	0.0450	15.7	0.002	12.2
DF	2	0.0375	0.0188	6.5	0.021	5.1
Error	8	0.0230	0.0029			
Total	17	0.7379				

Pulse on-time happens to be the second most significant factor. The increase in pulse on-time aids the growth of the plasma channel at the spark gap; however, this should be restricted, considering that the micro-tool diameter, otherwise, leads to unstable machining and rapid tool wear. The generation of the smaller crater for every discharge seems to be the favourable machining condition, which is offered by the lower pulse duration machine setting. The lower levels of peak current and gap voltage prove to be advantageous for better machining performance. Though the increase in peak current and gap voltage maximizes the spark discharge energy that leads to greater material removal, the larger debris thus generated may tend to produce secondary discharges between the side gap of the micro tool and the machined cavity while moving out of the spark gap. This deteriorates the dimensional accuracy of the machined hole.

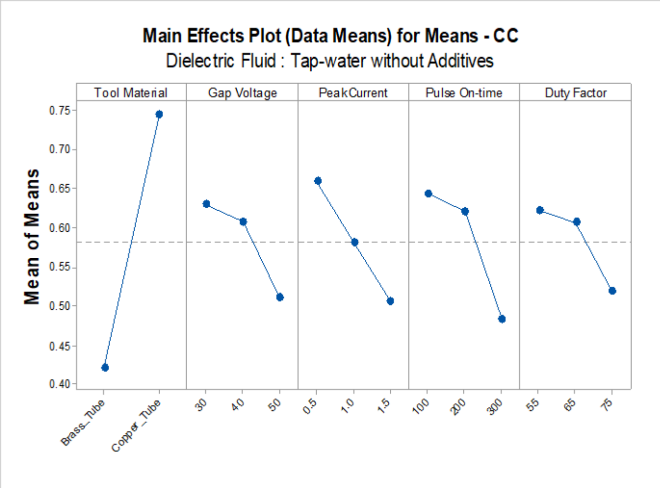

Figure 2. Main effects plot for means of CC of micro-EDM without additives

Moreover, higher spark energy would accelerate the electrolytic reaction at the spark gap when using tap water as a dielectric that imparts unstable machining [18]. Considering the effect of duty factor, its increase in value degrades the machining performance. Larger the duty factor, lesser is the off time in a cycle. So, if sufficient pulse-off time is not provided, the dielectric will not be able to regain its insulating property before the subsequent discharge. This incites arcing instead of EDM sparking at the spark gap that eventually leads to unstable machining. It can be construed that lesser discharge energy and ample off time bolster stable machining at the spark gap. Hence, the lower levels of gap voltage, peak current, pulse on-time and duty factor were found to be the optimal machine setting.

3.2 Effect of process parameters on pure tap water based PMEDM

The experimental layout and the outcome of each run are shown in Table 6. The main effects plot for means of multi-objective performance characteristic of PMEDM is displayed in Figure 3. The results of the ANOVA are presented in Table 7. It can be seen that the electrical conductive property of the additives has a huge impact on the multi-objective performance characteristic of PMEDM. The additives, particularly conductive and semi-conductive powders, are able to form a chain-like structure in between the micro tool and the workpiece, which is commonly called bridge formations [19]. The bigger advantages of this bridge formation are the initiation of quicker breakdown without much ignition delay and the creation of multiple sparks over the machining zone for a single current pulse. This amounts to the dispersion of discharge energy that yields stable machining, a commending condition for better micro-EDM performance. Moreover, the conductive and semi-conductive additives provide a larger gap between the tool and the workpiece compared to that of pure tap water EDM for the same gap voltage setting. This aids the easier removal of debris at the machining gap. However, it can be noticed that Al additives ranked after SiC and Al_2O_3 on delivering positive impact over multi-objective performance characteristic of PMEDM. This is because the addition of Al powders greatly raises the conductivity of tap water dielectric at the spark gap. This provokes arcing and short-circuiting between the tool and the workpiece. Furthermore, the micron-sized Al powders actively oxidize in the water at a temperature above 296°C [20], an expected temperature near the plasma channel whose temperature ranges from 8000 to 10,000 °K [21].

Table 6. Experimental layout and outcome of PMEDM

Run	Powder-type	Conc. (g/l)	Size (μm)	MRR (mg/min)	TWR (mm/min)	OC (μm)	CE (μm)	TR	CC	Rank
1	Al_2O_3	1	2	0.0301	0.0127	51.9	15.6	0.0145	0.6430	4
2	Al_2O_3	2	5	0.0305	0.0178	55.1	23.4	0.0554	0.5340	9
3	Al_2O_3	3	8	0.0371	0.0259	78.1	26.3	0.1019	0.3590	15
4	SiC	1	2	0.0732	0.0204	47.6	11.5	0.0156	0.8276	1
5	SiC	2	5	0.0448	0.0343	63.9	21.3	0.0312	0.5790	7
6	SiC	3	8	0.0570	0.0461	68.5	27.5	0.0697	0.4284	11
7	Al	1	5	0.0417	0.0443	81.1	31.0	0.0655	0.3718	14
8	Al	2	8	0.0643	0.0473	86.6	38.0	0.1067	0.2725	18
9	Al	3	2	0.0972	0.0488	86.0	41.5	0.1087	0.3884	12
10	Al_2O_3	1	8	0.0274	0.0193	53.2	19.7	0.0329	0.5826	5
11	Al_2O_3	2	2	0.0358	0.0148	61.7	19.8	0.0490	0.5820	6
12	Al_2O_3	3	5	0.0381	0.0169	66.4	31.1	0.1077	0.3838	13
13	SiC	1	5	0.0445	0.0245	59.1	20.5	0.0187	0.6437	3
14	SiC	2	8	0.0351	0.0333	63.4	22.2	0.0321	0.5473	8
15	SiC	3	2	0.0614	0.0307	57.6	14.9	0.0261	0.6962	2
16	Al	1	8	0.0436	0.0454	86.8	37.5	0.0785	0.2912	17
17	Al	2	2	0.0705	0.0477	67.6	30.0	0.0767	0.4332	10
18	Al	3	5	0.0864	0.0502	90.1	42.5	0.1296	0.3174	16

Table 7. Results of the ANOVA for PMEDM

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
P	2	0.2301	0.1150	50.6	0.000	56.1
C	2	0.0516	0.0258	11.4	0.002	12.6
S	2	0.1032	0.0516	22.7	0.000	25.2
Error	11	0.0250	0.0023			
Total	17	0.4099				

This oxidation would liberate extra heat energy that prompts stray machining in the tap water dielectric, which is an undesirable condition for stable micro-EDM. In Al_2O_3 based PMEDM, their addition in tap water dielectric increases the electrical resistivity at the spark gap. Although the formation of bridges to expedite the breakdown may not be facilitated by the insulated Al_2O_3 particles as that of other conductive and semi-conductive additives, it mitigates the burning of tap water dielectric when operating with higher discharge energy, i.e., larger gap voltage, peak current, pulse on-time and duty factor machine settings. It also disturbs the interference of multiple bridges (discharges), paving the way for stable machining. Hence, their addition in dielectric has a constructive impact when using tap water as a dielectric fluid in PMEDM.

It can be observed that a smaller particle size has a very good impact on the multi-objective performance characteristic in PMEDM. If the particle size is small, the suspensions of powders at the spark gap would be more, which facilitates the change in breakdown characteristics that enhance the performance of PMEDM. It can be learnt that increase in additive concentration has a negative effect on PMEDM. It is due to the fact that large accumulation of particles at the spark gap leads to arcing and short-circuiting, which degrades the machining performance.

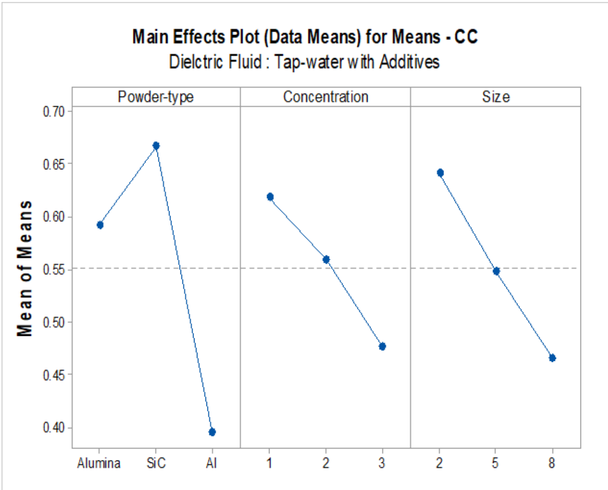

Figure 3. Main effects plot for means of CC of PMEDM

3.3 Comparative analysis of the micro-EDM and PMEDM

From the main effects plot for means of multi-objective performance characteristic (CC) of micro-EDM without additives, the optimal setting of process parameters was identified as copper tube tool, gap voltage of 30 V, peak current of 0.5 A, pulse on-time of 100 µs and duty factor of 0.55. Similarly, from the mean graph of multi-objective performance of PMEDM, the optimal control factors of additives were discovered as SiC additives of concentration 1 g/L and the average particle size of 2 µm. The experimental outcome of the optimal process parametric setting for micro-EDM without additives have MRR of 0.0397 mg/min, TWR of 0.0434 mm/min, OC of 59.6 µm, CE of 25.5 µm and TR of 0.0175. On the other side, the PMEDM have MRR of 0.0732 mg/min, TWR of 0.0204 mm/min, OC of 47.6 µm, CE of 11.5 µm and TR of 0.0156. There can be seen an increase in MRR of 84.38%, reduction in TWR of 53%, decrease in OC of 20.13%, decrease in CE of 54.90% and decline in TR of 10.86%. Hence, the addition of powders in tap water micro-EDM proves to be highly beneficial in improving machining performance.

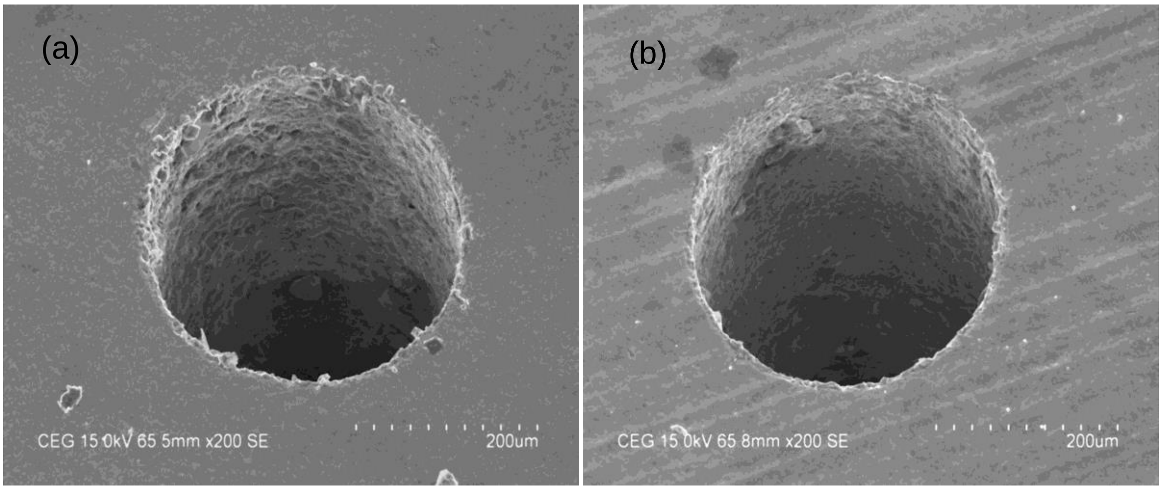

Figure 4. (a) Micro-hole of EDM without additives (b) Micro-hole of PMEDM

The Scanning Electron Microscopy (SEM) photographs of the machined hole at the optimal parametric setting for micro-EDM without additives (Copper tube, 30 V, 0.5 A, 100 µs, 55%) and PMEDM (SiC, 1 g/L, 2 µm) are shown in Figures 4(a) and 4(b), respectively. It can be seen that a much smoother machined surface was obtained in SiC-based PMEDM compared to that of the micro-hole acquired through EDM without additives. The reason is that in pure tap water dielectric based micro-EDM, rapid decomposition of tap water takes place at the spark gap, which gives rise to an increase in the level of oxygen that reacts with molten Ti-metal and forms metal oxides over the machined surface. This has been alleviated by using additives in tap water dielectric.

4. CONCLUSIONS

In this paper, experiments were conducted in order to investigate the influence of tap water dielectric in micro-EDM, with and without additives. Electrically non-conductive Al_2O_3, semi-conductive SiC and conductive Al powders were used as additives in PMEDM. The following conclusions have been drawn:

1. The selected tool material and electrical process parameters proved to be significant in affecting the multi-objective performance of micro-EDM without additives. The descending order of significance was tool material, pulse on-time, peak current, gap voltage and duty factor.
2. Copper tube tool produced the best results compared to brass tube tool.
3. The optimal setting of electrical process parameters for micro-EDM without additives was gap voltage of 30 V, peak current of 0.5 A, pulse on-time of 100 µs and duty factor of 0.55.
4. In PMEDM, semi-conductive powder SiC ranked first in influencing the multi-objective performance characteristic, followed by Al_2O_3 and Al powders.
5. It was found that the conductive additives Al tend to increase arcing and short-circuiting during machining, which adversely affect the dimensional accuracy compared to that of SiC and Al_2O_3 additives.
6. The optimal additive factors in PMEDM was found to be SiC additives, weight-concentration as 1 g/L and average particle size as 2 µm.

7. On comparing the experimental outcomes of the optimal setting attained for micro-EDM with and without additives. SiC-based PMEDM tends to increase the MRR from 0.0397 to 0.0732 mg/min and reduce the TWR from 0.0434 to 0.0204 mm/min. It improves the dimensional accuracy of the machined hole by reducing the overcut from 59.6 µm to 47.6 µm, the circularity error from 25.5 to 11.5 µm and the taper ratio from 0.0175 to 0.0156.

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