Powder additives influence on dielectric strength of EDM fluid and material removal

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Abstract: Electrical discharge machining (EDM) is used to machine difficult-to-machine materials having high hardness and toughness. One of the recent advancements in the EDM process is the powder mixed electrical discharge machining (PMEDM) process, in which the metallic or abrasive additives in the form of fine powders are added to the dielectric fluid. PMEDM was found to improve machinability in terms of higher material removal rate (MRR) and enhanced tool wear index (TWI), by reducing the breakdown strength of the dielectric. In PMEDM process, machining happens with relatively larger spark gap with enhanced machining characteristics. This paper investigates the influence of powder mixing on the breakdown strength of the liquid dielectric and the gap voltage. Determination of dielectric strength was carried out with a specially designed experimental set-up adhering to ASTM standard D1816 – 97. Tests were conducted using silicon carbide, alumina, copper and aluminium powders. The effect of varying the grain size was also studied. An experimental set-up was also designed and realised to measure the influence of powder mixing on the gap voltage and MRR in machining of titanium alloy. The results have shown significant improvement in MRR and TWI.

Keywords: powder mixed electrical discharge machining; PMEDM; metallic and abrasive powders; dielectric strength; gap voltage; material removal rate; MRR; tool wear index; TWI.

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1 Introduction

The use of thermal energy in electrical discharge machining (EDM) to machine electrically conductive materials irrespective of hardness makes it suitable in the manufacture of dies, moulds, tools, surgical components and many components used in aerospace industry (Ho and Newman, 2003). In EDM process, the shape of the electrode defines the spark area resulting in accurate part production, but the rate of machining is fairly slow, which can be called the main limitation of EDM process. As the machining characteristics of EDM process is strongly influenced by the dielectric's performance, substantial consideration has been given to modify the properties of liquid dielectric, so as to accomplish higher productivity. One of the approaches is by adding fine form of metallic and abrasive powders to the dielectric liquid of the EDM processes called powder mixed electrical discharge machining (PMEDM).

Even before the existence of PMEDM process, Erden and Bilgin (1981) studied the effect of natural and artificial impurities in the dielectric fluid and observed that these contaminants increased the machining rate by improving the breakdown characteristics of the dielectric fluid where the concentration was critical or the grain size was critical. Rajurkar and Pandit (1986) carried out a detailed study on the debris formation in EDM and observed the presence of debris to alter the breakdown characteristics of the liquid dielectric up-to a critical value. Goodlet and Koshy (2015) reported that gap flushing played an important role in the productivity of EDM process. Danikas (1990) found that the conditioning, electrode, electrode area, gap spacing, and oil pre-treatment affected the dielectric strength of the liquid dielectric.

Furutania et al. (2001) observed that the powder behaviour under the electric field resulted in chain formation between the electrodes for various powders and concluded that chain like formation promoted the discharge between the electrodes. Researchers experimented the performance of EDM by adding various powders with distinct thermo-physical properties and observed that these powders, when added at different size, concentration, density, affected the machining performance and reported that the presence of debris aided the machinability (Talla et al., 2017; Kung et al., 2009; Kumar, 2015; Tzeng and Lee, 2001). Captured images of the gap debris and the presence of additive particles in insulating fluids were found to reduce the dielectric breakdown strength of the fluid and also it disclosed the presence of debris in the electrode surfaces at extreme range of sizes (Murray et al., 2016). Marashi et al. (2016) observed the addition of powders to reduce the resistivity of the dielectric and enhances the ionisation and spark frequency between the tool and workpiece. Though the presence of gap debris helped in machining, too much presence of debris was observed to be affecting the surface of the material to be machined. Guu and Hocheng (2001) used rotary tool to flush the debris effectively and reported higher material removal rate (MRR) than that of the conventional EDM process.

In PMEDM process, the added powders under the influence of electrical field are energised and aligned in a zig-zag fashion between the electrodes where chains are formed at multiple places between the sparking area, resulting in bridging effect. This chain alters the gap voltage and in-turn the insulating strength of the liquid dielectric, resulting in early spark. PMEDM process works steadily at low pulse energy, which substantially enhances the performance by lowering the spark gap (Chakraborty et al., 2015).

Tzeng and Lee (2001) portrayed the mechanism of material removal in PMEDM process from normal EDM process, so that adding additive powders into the spark led to an increase in gap width and consequently reduced the explosive gas pressure of the plasma and electrical discharge power density for a single power pulse. This resulted in shallow crater instead of deeper crater as in the normal EDM process. This modified material removal mechanism for the PMEDM process, by which the normal single electrical discharge was interpreted as the collective effect of thrust driven by the gaseous explosion largely from the working fluid evaporation and the impact caused by the powders. Zhang et al. (2012) postulated the mechanism for PMEDM, where the anomaly of the electric field in the discharge gap widened the spark gap. Accumulation of positive and negative charges occurred at the top and the bottom of the powders respectively under the effect of gap voltage resulting in the occurrence of discharge breakdown, where the electric field density was the highest.

Later several researchers (Baseri and Sadeghian, 2016; Batish et al., 2015; Kolli and Kumar, 2017) used various powder additives in the dielectric liquid of the PMEDM process and observed that these powders aids in decreasing the dielectric strength of the EDM fluid causing early explosion of plasma between the electrodes which in-turn resulted in higher MRR. Khosrozadeh and Shabgard (2017) found the addition of nanopowders in the EDM process to widen the plasma channel and subsequently to increase the number of parallel sparks.

Kuffel et al. (2000) postulated that the particles that are suspended in the fluid are polarisable and are of higher permittivity than the liquid and it experiences electrical forces which are directed towards the place of maximum stress. Under the uniform field between the electrodes, presence of surface irregularities on the electrode initiates the movement of particles, which give rise to local field gradients. Kumar et al. (2016b) observed the debris in the spark gap to form a conductive path between the electrodes. This resulted in redundant spark which eventually increased the spark gap. Arora and Mosch (2011) listed the following external factors, viz., electrode configuration, electrode material, size and surface finish, temperature, purity of the liquid dielectric and its condition of ageing affected the formation of bridge resulting in dielectric breakdown. Lately, Mohanty et al. (2017) conducted experiments on Inconel 718 using commercial grade brass electrode and graphite powder mixed kerosene as dielectric. The study revealed a significant increase in MRR as the graphite concentration was increased from 0% to 4%. Ojha et al. (2016) reported an improvement in the surface roughness of the work piece while machining medium carbon steel using copper electrode and chromium powders mixed with the commercial kerosene dielectric. The improvement in the surface finish was attributed to the widening and enlargement of plasma channel due to the powder addition, which made the sparking uniformly distributed.

From the literature reviewed it is learnt that PMEDM enhances the machining characteristics of the material by reducing the spark gap between the tool and the electrode. Various literature citations have presented the evidence of better machining characteristics with the addition of powder into the dielectric fluid, but no comprehensive theory is available to enumerate the evidence of the phenomenon of lowered breakdown strength. The purpose of this work is to augment the concept of change in spark gap when the additives are added into the dielectric fluid of the EDM process and also to produce the quantitative evidence for the change in dielectric strength with the addition of powders into the dielectric fluid.

2 Materials and methods

From the literature reviewed here, it can be established that PMEDM process enhances the machinability in terms of increased MRR though the mechanism of PMEDM is still a haze. Thus, to understand precisely the mechanism of higher MRR in PMEDM, the experimental work was carried out in three phases, namely:

1. experimental determination of dielectric strength of powder mixed dielectric liquid
2. experimental observation of spark voltage
3. PMEDM experiments with powder mixed dielectric.

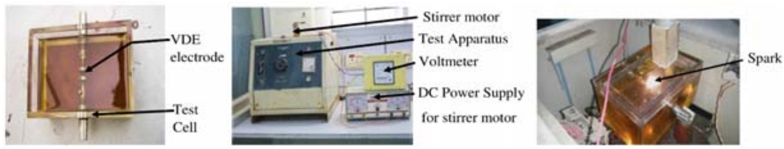
2.1 Experimental determination of dielectric strength of powder mixed dielectric

To validate the concept of reduction of breakdown strength of the liquid dielectric, a test apparatus in conformance with ASTM D 1816 – 97 standard was made to test the dielectric breakdown strength of the EDM oil is shown in the Figures 1(a) to 1(c). The apparatus consisted of a transformer, current-interrupting circuit, voltage-control equipment, Verband Deutscher Electrotechniker (VDE) electrode and a test cell. A brass polished spherically capped VDE electrode was kept in the polymeric test cell of one litre capacity with a lid. A motor driven stirrer was used to prevent the sedimentation of powder additives at the bottom the test cell. The space between the electrodes was precisely adjusted to keep a distance of 2 mm using a slip gauge.

Table 1 Dielectric strength (kV/mm) of various powders at different concentrations with the values of standard deviation (average of six trials)

Powder concentration	*Silica @ 44*		*Silica @ 100*		*Silica @ 254*		*Alumina @ 44*		*Copper @ 44*		*Aluminium @ 44*	
	Silica @ 44 µm	*SD*	*Silica @ 100 µm*	*SD*	*Silica @ 254 µm*	*SD*	*Alumina @ 44 µm*	*SD*	*Copper @ 44 µm*	*SD*	*Aluminium @ 44 µm*	*SD*
0.00	9.000	0.000	9.000	0.000	9.000	0.000	9.000	0.000	9.000	0.000	9.000	0.000
0.25	8.500	0.158	8.250	0.079	7.521	0.026	8.146	0.100	7.708	0.094	7.917	0.065
0.50	8.417	0.094	7.833	0.151	6.917	0.065	7.792	0.065	7.479	0.026	7.625	0.056
0.75	8.125	0.068	7.333	0.171	6.625	0.056	7.646	0.092	7.063	0.110	7.333	0.123
1.00	7.813	0.117	7.313	0.095	6.500	0.068	7.354	0.061	6.458	0.065	6.896	0.128
1.25	7.750	0.088	7.271	0.083	6.250	0.079	6.854	0.047	6.292	0.102	6.521	0.100
1.50	7.688	0.110	6.708	0.094	6.146	0.100	6.688	0.086	6.000	0.105	6.313	0.095
1.75	7.538	0.034	6.646	0.115	6.000	0.088	6.521	0.026	5.813	0.152	6.229	0.100
2.00	7.438	0.167	6.396	0.061	5.792	0.065	6.292	0.051	5.625	0.137	5.958	0.032
2.25	7.292	0.129	6.292	0.085	5.688	0.066	6.063	0.034	5.479	0.128	5.854	0.115
2.50	7.063	0.110	6.146	0.083	5.625	0.079	5.833	0.076	5.313	0.141	5.646	0.061
2.75	6.708	0.116	6.063	0.110	5.500	0.079	5.708	0.051	5.000	0.125	5.542	0.051
3.00	6.417	0.200	5.750	0.068	5.438	0.086	5.667	0.051	4.833	0.076	5.271	0.121

Figure 1 Test apparatus used to measure the breakdown voltage, (a) test cell (b) test apparatus (c) occurrence of spark (see online version for colours)



(a) (b) (c)

Figures 1(a) and 1(b) show the test cell with stirrer and the test apparatus. First, the test cell was filled with EDM oil without adding any powder additives and voltage was applied in steps to notice the breakdown of the EDM oil. For consistency six trials were conducted and the average value was taken as the breakdown strength of the EDM oil for the given powder at a particular concentration, and it is given in the Table 1. Figure 1(c) shows the occurrence of spark between the electrodes indicating the breakdown of the EDM fluid. Break down voltage (BDV) was noted and the dielectric strength of the EDM oil was calculated using the relation (1).

$$Dielectricstrength = \frac{BDV}{elctrodeSpacing}\left(kV / mm\right) \tag{1}$$

When no powders were added to the test cell, the breakdown strength was observed to be 9 kV/mm. The same was repeated for adding powders into the test cell at a concentration of 0.25 g/litre. Since at higher concentration, the measurement of BDV was found to be inconsistent for some of the powders, the concentration of the additive powders was limited up-to 3 g/litre. The additive powders used for the experiment were:

1 silicon carbide (SiC)

2 alumina (Al_2O_3)

3 copper

4 aluminium.

Necessary preheating was carried to ensure that the powders were free from volatiles. The properties of the additive powders used are listed in the Table 2. Experiments were conducted by adding these powers by increasing the concentrations from 0 to 3 g/litre in steps of 0.25 g/litre. The effect of grain size in altering the breakdown voltage was also studied separately with silicon carbide powders.

Table 2 Thermo-physical properties of the additive powders

Property	*SiC*	*Al_2O_3*	*Copper*	*Aluminium*
Electrical resistivity (Ω-m)	10	1.43×10^{-5}	1.69×10^{-8}	2.65×10^{-8}
Thermal conductivity (W/mK)	120	30	401	237
Density (g/cc)	3.16	3.986	8.96	2.70
Melting point (°C)	2,830	2,072	1,083	660

2.2 Experimental observation of spark voltage in PMEDM process

Since the experimental determination of dielectric strength of powder mixed dielectric was carried out in an isolated set-up, it was necessary to study the actual influence of the powders in the PMEDM process. A 50 MHz and 1 G sample/sec, agilent digital storage oscilloscope (DSO) was connected to the voltage terminal of the PMEDM experimental set-up to study the effect of powders and to observe the reduction of gap voltage when additive powders were added into the liquid dielectric. Though all the powders affect the BDV of the dielectric, alumina was used in this test to record the gap voltage of PMEDM process. The gap voltage recorded on the DSO was noted for the pure dielectric liquid at gap currents of 25 A and 35 A. These gap voltages were compared with those obtained from alumina powder mixed PMEDM process for a concentration of 4 g/litre and at two different gap currents of 25 A and 35 A.

2.3 EDM experiments in the powder mixed dielectric liquid

The next stage in the experimental investigation was to study the influence of the powders on the machining process itself. Machinability of the PMEDM process was measured in terms of MRR and tool wear rate (TWR). The experimental set-up consists of a pump to feed the alumina powder (44 micron size) mixed dielectric fluid into the spark gap. A stirrer was used to ensure the homogeneity of the powder mixed liquid dielectric in a secondary tank. Circular copper rod of 12 mm diameter was used as the tool, since it is a widely used electrode by the researchers in the EDM process (Raj and Prabhu, 2017). Kumar et al. (2016a) had demonstrated the circular electrode to have better machinability than the square or triangular electrodes, due to the absence of vulnerable sharp corners. ASTM B 348 grade 5 titanium alloy plate of dimension 150 × 50 mm and 5 mm thickness was used as the work piece. During the experiments the following machining conditions were used:

Current	: 25 A and 35 A
Duty factor	: 70%
Dielectric discharge rate	: 6 lpm
Concentration of alumina in dielectric	: 0, 2 and 4 g / litre
Machining time	: 10 min

Six experiments in all were conducted under the machining conditions stated above. The MRR of the work piece was calculated by measuring the difference in the mass of the work piece removed before and after machining per unit time. Similarly, the TWR was also measured by calculating the difference in the mass of the tool removed before and after machining and tool wear index (TWI) was computed using the expression (2).

$$TWI = \frac{MaterialRemovalRate}{ToolWearRate} = \frac{MRR}{TWR} \tag{2}$$

3 Results and discussion

3.1 Experimental determination of dielectric strength of powder mixed dielectric

A large number of external factors and the presence of any form of contaminants significantly affect the breakdown strength. Arora and Mosch (2011) reported that the breakdown strength of the liquid dielectric is distinguished as:

1 intrinsic breakdown – where the secondary sources which may affect the breakdown of the liquid dielectric is neglected

2 practical breakdown strength – in which the secondary sources which affect the breakdown are bound to be present.

The effect of adding powders on the breakdown strength of the dielectric liquid is discussed below.

3.1.1 Effect of powders on breakdown voltage of the liquid dielectric

Measurement of the breakdown strength of the dielectric was carried out in the test cell as described in the previous section. The effect of adding the additive powders and the effect of varying the grain size on the breakdown voltage of the liquid dielectric are given in Figures 2 and 3 respectively. It was observed that the breakdown strength of liquid dielectric decreased when the concentrations of additive powders were increased. The trend holds good for all the additive powders regardless of their properties at same grain size (Figure 2). From Figure 2, it was observed that at 44 microns the effect of alumina powder on BDV was steeper with a slope of –52.72° for a linear trend line. Also at higher concentration, effect of alumina was greater in reducing the BDV of the liquid dielectric. Higher electrical resistivity of silicon carbide makes it have a relatively lower effect on BDV of the liquid dielectric even at higher concentration. Also the angle of slope of silicon carbide on BDV was least among these powders.

The mechanism of reduction in breakdown voltage can be explained in the following terms. During the breakdown of liquid dielectric, a gas channel was found to be formed within the liquid in the form of bubble (Huan et al., 2016), which multiplies and results in non-homogeneity electric field under the applied voltage leading avalanche breakdown resulting in lowering of its BDV, this effect will increase at higher concentration. Thus the addition of impurities in the form of powders aids in lowering the BDV for the given dielectric fluid. The result will be much better at higher concentrations. The results of the effect of these powders on BDV were found to be appreciable as the least R^2 values for these powders for a linear trend line stood at 95.94%. Among the metal powders, the angle of slope of aluminium was found to be –37.7°, which was less than that of copper powder.

Figure 2 Effect of powder concentration on dielectric strength – curve with R^2 value and slope (see online version for colours)

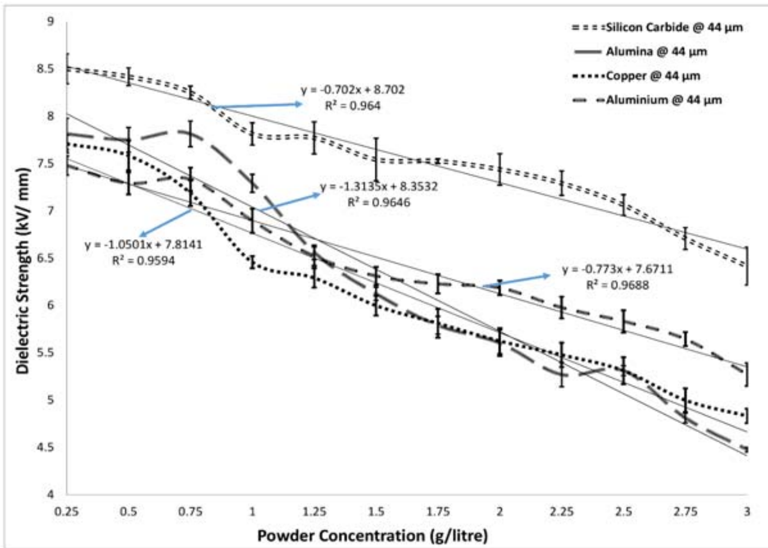
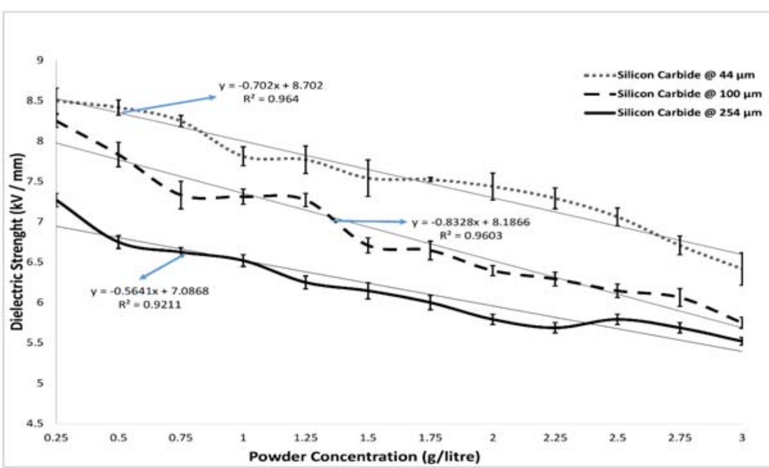


Figure 3 Effect of powder size on dielectric strength – curve with R^2 value and slope (see online version for colours)



3.1.2 Effect of grain size of silicon carbide powder on BDV of the liquid dielectric

As the effect of silicon carbide on BDV of the liquid dielectric at all concentrations was relatively less among the selected powders, it was decided to study the effect of grain size of silicon carbide on BDV. Silicon carbide at the grain sizes of 44, 100 and 254 microns was considered for the test. As mentioned earlier, the concentration of the silicon carbide at these grain sizes also varied from 0.25 g/litre to 3 g/litre with a step size of 0.25 g/litre. The effect of grain size of silicon carbide on BDV is shown in Figure 3. When the grain size of silicon carbide was varied as 44, 100 and 254 microns, the breakdown voltage was significantly lowered by increasing the size of the silicon carbide at all the levels of concentration. This is in accordance to the finding that increase in particle size within a critical size enhances better conductivity and reduces the surface tension of the dielectric fluid, resulting in lowered BDV of the liquid dielectric (Kumar and Davim, 2010). The slope angle was found to be larger for 254 μm of silicon carbide, which showed that the higher the size of the grains of the powders, the earlier the spark occurred in EDM with lower BDV. Silicon carbide powders having same electrical property but with various grain sizes lower the BDV by quickly forming a bridge between the electrodes.

Generally, it was found that the breakdown voltage reduced when:

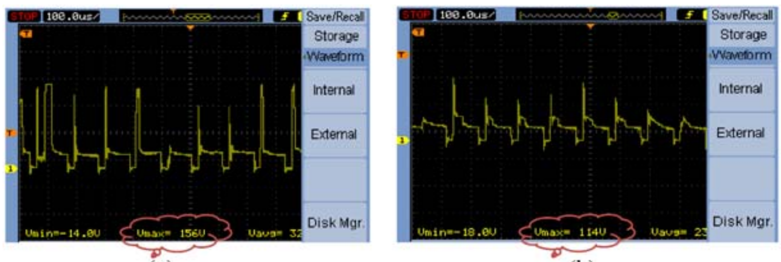
a the concentration of the powders was increased

b the grain size of the powders was increased.

Among ceramic-based abrasives, alumina showed a greater reduction in dielectric strength when the concentration was increased as its electrical resistivity was lower than that of the electrical resistivity of silicon carbide. From the perspective of metallic powers, copper showed a greater reduction in dielectric strength, when the concentration of the powders was increased.

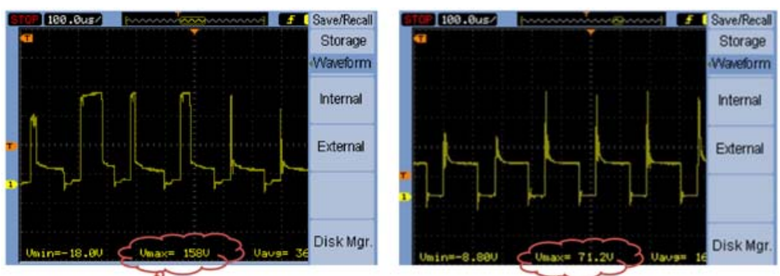
3.1.3 Effect of gap current and powder concentration on spark voltage of PMEDM process

As the addition of various powders at different powder concentration reduced the breakdown strength, the rational explanation for the lowering of breakdown voltage when additive powders were added in the liquid dielectric was evidently captured using agilent DSO. The actual or practical breakdown characteristics in terms of spark voltage of alumina mixed PMEDM process are shown in Figures 4 and 5, which make it clear that the gap voltage of PMEDM process, when alumina is added as additive, is lower than that of the normal EDM process. From Figures 4(a) and 4(b), it is evident that the spark gap voltage significantly reduces from 156 V to 114 V when the concentration of alumina is increased from zero to 4 g/litre at a gap current of 25 A. Similarly, at a gap current of 35 A, the spark gap voltage decreases from 158 V to 71.2 V when the concentration of alumina varies from zero to 4 g/litre [Figures 5(a) and 5(b)]. This further reinforces the concept of bridging of powders in the gap under the influence of electrical field resulting in the machining of materials at lower breakdown voltage. The results are in agreement with the findings of Fontes et al. (2015). The study by Fontes et al. demonstrated the raise in thermal conductivity of the liquid dielectric because of added powders that led to lowering the spark gap of the EDM process. The spark gap is much lowered at higher gap current. It could also be inferred that higher current and powder concentration under controlled condition could lower the gap voltage.



(a) (b)

Figure 4 Breakdown voltage of Al_2O_3 at 25 A current, (a) zero powder (b) 4 g/litre powder (see online version for colours)



(a) (b)

Figure 5 Breakdown voltage of Al_2O_3 at 35 A current, (a) zero powder (b) 4 g/litre powder (see online version for colours)

3.1.4 EDM experiments for computing MRR and TWI

Subsequent to the lowering of gap voltage captured in alumina PMEDM experiments, establishing the enhancement of machinability of PMEDM process becomes necessary. The PMEDM experiments with titanium grade 5 alloy shows that there is a substantial improvement of machining characteristics of PMEDM process as shown in Figures 6 and 7. It was obvious from the experiments that alumina mixed PMEDM process significantly improved the machinability of titanium alloy by increasing the MRR. There was a marked rise in MRR as the machining was done from zero concentration to 2 g/litre to 4 g/litre at a gap current of 25 A. For the similar machining conditions of PMEDM at 35 A, the enhancement of MRR was even higher for those level of powder concentrations. The trend for the MRR rise is in alignment with the findings of Kumar and Davim (2010) that the powders additives lowers the BDV, bridges the spark gap and lead to in higher sparking frequency. From Figure 6, it is clear that the increase in gap current and powder concentration results in higher MRR, Also the machinability of

PMEDM indicates that the higher concentrations of powder at lower gap current results in better machinability as if it was achieved at higher gap current with lower powder concentrations. This possibly could save the energy required for achieving higher MRR.

Figure 6 Enhancement of MRR in PMEDM process (average of six experiment trials) (see online version for colours)

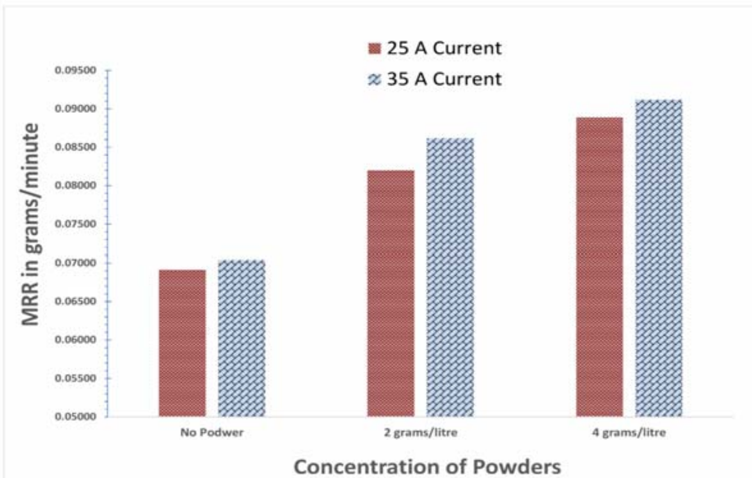
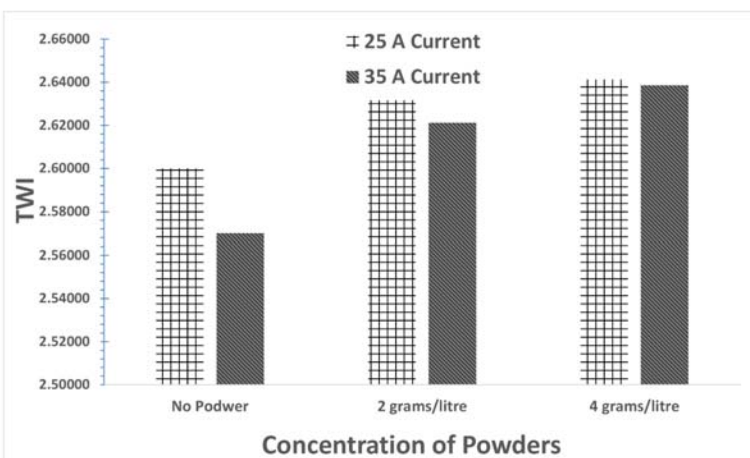


Figure 7 Enhancement of TWI in PMEDM process (average of six experiment trials) (see online version for colours)



Enhancement of machinability was verified with another parameter, namely TWI. Measurement of TWI (Figure 7) indicates that at 25 A gap current increase in the powder concentration from zero to 4 g/litre has resulted in better TWI. The trend holds good under similar machining conditions and at 35 A of gap current.

4 Conclusions

The work attempted to understand the mechanism of material removal in PMEDM process by adding metallic and abrasive powders into the dielectric liquid with an experiment set-up adhering to the ASTM D 1816 – 97 standard. The following conclusions are drawn:

- Both metallic and ceramic powder additives were found to lower the dielectric strength of the medium. This is primarily because of the drop in BDV due to the addition of powders.
- With the addition of 3 g/litre of powders, the reduction in dielectric strength was most pronounced with alumina (50.23% reduction) followed by copper (46.30%), aluminium (41.43%) and finally, silicon carbide (28.70%).
- Reduction of dielectric strength was found to be greater with larger grain size of the silicon carbide. This is because of the higher particle size enabling the formation discharge column. Addition of SiCat 44 μm grain size was found to reduce the dielectric strength of EDM liquid by a factor 0.713, whereas the 100 and 254 μm grains reduced the dielectric strength by factors 0.638 and 0.613. The reported values pertain to the powder concentration of 3 g/litre.
- The dielectric strength was found to reduce progressively as the powder concentration was increased from 0 to 3 g/litre for all additives. The reduction in dielectric strength was due to the formation of a discharge column of additive powders which formed a sort of bridge between the anode and the cathode through the dielectric.
- The capture of voltage plots using a high frequency DSO, pertaining to alumina mixed EDM, at 25 A and 35 A gap current, showed a substantial drop in gap voltage. This is because of the drop in dielectric strength due to powder addition.
- The primary mechanism of increased MRR in PMEDM process was through the reduction in the dielectric strength of the medium, leading to reduction of gap voltage and increased spark gap.
- Under the controlled working conditions, the MRR and the material removed per unit tool wear were found to increase with increasing concentration of powders up to 4 g/litre.
- With the addition of 4 g/litre of alumina an increase of 29.49% in MRR was observed. This also led to a marginal increase in the TWI.

- With the addition of alumina as additive in the PMEDM process, enhancement of machinability of PMEDM process was pronounced through higher MRR and better TWI, under similar machining conditions, both the MRR and the TWI were found to be better with increased powder concentration.

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