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Performance of electrical discharge machining using aluminium powder suspended distilled water

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Abstract

This paper presents the experimental investigations on addition of aluminium metal powder to dielectric fluid in electric discharge machining (EDM). As more emphasis is given nowadays to the green manufacturing concept, the present investigation uses distilled water mixed with aluminium powder as dielectric fluid instead of conventional hydrocarbon-based oils. The workpiece and electrode materials chosen for the investigation are W300 die-steel and electrolytic copper, respectively. Taguchi design of experiments is used to conduct experiments by varying the parameters peak current, pulse on-time, concentration of the powder, and polarity. The process performance is measured in terms of material removal rate (MRR), electrode wear ratio (EWR), average surface roughness (Ra), and white layer thickness (WLT). The experimental results indicate that the polarity significantly affects the machining performance. Signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) are employed to find the optimal levels for the process parameters to achieve maximum MRR, low EWR, Ra, and WLT values.

Key Words: Aluminium powder, die-steel, distilled water, powder mixed EDM, Taguchi method

1. Introduction

Electrical discharge machining (EDM) is a thermal process with a complex metal-removal mechanism, involving the formation of a plasma channel between the tool and workpiece. For several decades, EDM has been an important manufacturing process for the tool and die industry. To improve the performance of EDM, dielectric fluid suspended with different powders was attempted by several investigators. Powder mixed electric discharge machining (PMEDM) improves the quality of the electric discharge machined surface and reduces the surface defects. The effect of impurities like copper, aluminium, iron, and carbon in dielectric fluid was first studied by Erden and Bilgin (1980). Increase in material removal rate (MRR) was reported due to the addition of certain concentrations of powders to dielectric fluid. Further research revealed that the electrically conductive powder suspended in the dielectric fluid reduces the insulating strength of the dielectric and increases the spark gap between the tool and workpiece. As a result, the process becomes more stable thereby improving MRR and

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surface finish. The improvement in the surface finish depends on the thermo-physical properties, particle size, and concentration of the powder (Yih-fong and Fu-chen, 2005). Furthermore, research in PMEDM reveals that modified waveform of the pulse current and multiple discharge effect are responsible for the improvement in MRR and surface finish. Chow et al. (2008) observed that a single pulse generates several discharging spots, which create smaller crater and smaller debris that will easily flush the gap and accelerate the MRR.

Generally, kerosene and hydrocarbon oil are used as the dielectric fluid in most of the die-sinking EDM systems. Hydrocarbon oil and kerosene decompose at very high temperature of plasma and pollute the air around the machining setup. The adhesion of carbon particles on the work surface also restricts the efficiency and stable discharge, and further reduces the material removal rate (Leao and Pashby, 2004). In view of environmental issues of hydrocarbon oil-based dielectric fluids as mentioned, for the last 3 decades various researchers have tried to use environmentally friendly dielectric fluids (Abbas et al. 2007). These are water, water mixed with organic compounds and commercial waterbased dielectric fluids found to improve the process performance of EDM. Although there has been extensive work on PMEDM using kerosene and hydrocarbon oil to improve the machining performance and surface quality of electric discharge machined parts (Pandey and Singh, 2010; Singh and Bhardwaj, 2010), only limited work has been done using powder suspended deionized water as dielectric fluid.

Jeswani et al. (1981) studied the performance of distilled water and kerosene as the dielectric fluid in EDM. The distilled water resulted in higher MRR compared to kerosene at higher pulse energy (288 mJ) and it was concluded that distilled water can be used as a dielectric fluid in EDM at high pulse energy range. Jilani and Pandey (1984) compared the performance of different dielectrics such as tap water, distilled water, and kerosene with low carbon steel work material. Tap water resulted in higher MRR compared to distilled water and kerosene. A negative electrode during machining produces zero electrode wear and minimum surface roughness. Masuzawa et al. (1983) conducted experiments with SK4 die-steel with copper as tool electrode at 10%, 25%, and 50% concentration of ethylene glycol, glycerine, polyethylene glycol 200, polyethylene glycol 600, dextrose, and sucrose solution in water as dielectric fluid. It was reported that MMR increases with increase in the concentration, and more significantly with increase in the molecular weight. Kagaya et al. (1986, 1990) produced non-tapered straight micro-holes and narrow slit of surface roughness 1 μm using water dielectrics. Water dielectric causes decarburization of recast layer and less cracks on carbon steel work material (Kruth et al., 1995). When compared with kerosene, EDM machining of Ti-6Al-4V using distilled water dielectric produces a TiO layer instead of TiC on the workpiece (Chen et al., 1999). Further work during surface modification of Ti alloy using urea solution in water as dielectric produced a hard TiN layer on the workpiece due to element transfer (Yan et al., 2005). Research work by Ekmekci et al. (2005) with respect to the surface integrity of EDM machined samples in de-ionized water reveals less retained austinite and low intensity of micro-cracks when compared to hydrocarbon oil. Bai and Koo (2006) investigated the effects of kerosene and distilled water as dielectric during electrical discharge surface alloying of superalloys. Chow et al. (2008) compared the effect of water and SiC powder suspended in water as dielectrics during micro-slit EDM machining.

This paper presents the experimental investigations of aluminium metal powder mixed in distilled water as dielectric during machining of W300 die-steel to investigate the effect of polarity on the performance. The optimal values of process parameters are obtained using signal-to-noise ratio and ANOVA analysis for improved MRR and surface finish.

2. Experimental details

2.1. Experimental set-up

The experiments were conducted on a die sinking EDM machine, model C-425, manufactured by the Electronica Industries, India. To conduct experiments with water as dielectric, a separate dielectric re-circulating system was fabricated and attached to the machine table. Figure 1 shows the schematic diagram of powder mixed EDM experimental set-up.

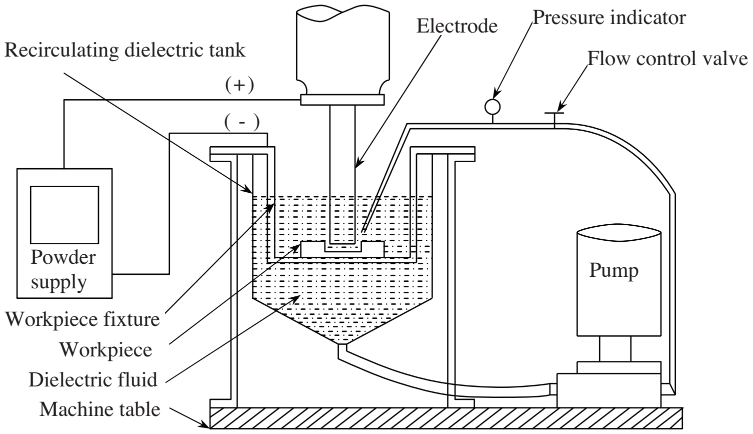

Figure 1. Schematic diagram of PMEDM experimental set-up.

2.2. Work materials

The work material chosen for the present study is W300 steel. It is extensively used in the fabrication of tools and dies. The composition of W300 steel is given in Table 1. The required sizes of workpiece were cut from a blank, and the top and bottom surfaces of the workpiece were ground. Electrolytic copper of diameter 9.5 mm was chosen as the tool electrode material. The experiments were conducted with powder mixed distilled water as dielectric. The metal powder selected was aluminium owing to its better thermo-physical properties (Yih-fong and Fu-chen, 2005) with average particle size of 27 μm. The improvement in the electrical conductivity of distilled water when mixed with different concentrations of aluminium powder is shown in Figure 2. The dielectric was circulated at the work-tool interface by means of an external jet.

Table 1. Typical percentage of composition of W300 (Wt. %).

C	Si	Mn	Cr	Mo	V	Fe
0.32-0.42	0.8-1.2	$<$ 0.5	4.5-5.5	1-1.5	0.3-0.5	Balance

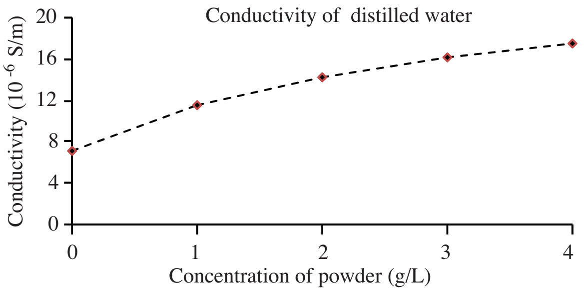

Figure 2. Conductivity of Al powder mixed distilled water.

2.3. Design of experiments

In the present study experiments are planned using Taguchi's experimental design. Taguchi's method is one of the most important statistical tools for designing high quality systems at reduced cost (Krottmaier, 1994). This method uses a special design of orthogonal array to study the entire process parameter space with a smaller number of experiments. A screening test is carried out to identify the parameters that strongly influence the PMEDM process outcomes and it is found that peak current (I), pulse on-time (Ton), and concentration of powder (C) are the important process parameters.

Table 2 shows the process parameters and their levels selected for the present investigation. For the 3 input process parameters L9 orthogonal array was selected. Each experiment was performed for 10 min and replicated 3 times. Table 3 shows the experimental matrix and output responses for the positive and negative polarities. The steps involved in the Taguchi optimisation method in this study are shown in Figure 3.

Table 2. Experimental conditions and process parameters.

Workpiece	W300 steel, 20 mm × 40 mm × 6 mm
Electrode	Electrolytic copper Ø 9.5 mm
Voltage (V)	35
Polarity	Positive and negative
Peak current (A)	6, 9, 12
Pulse on-time (μs)	100, 180, 240
Duty factor (%)	65
Concentration of powder (g/L)	0, 1, 2
Dielectric fluid	Distilled water
Flushing pressure (kPa)	70

Table 3. Experimental plan and output responses.

S. no.	I (A)	Ton (μs)	C (g/L)	Output responses (avg. of 3 replicates)							
				Negative polarity				Positive polarity			
				MRR (mg/min)	EWR (%)	Ra (μm)	WLT (μm)	MRR (mg/min)	EWR (%)	Ra (μm)	WLT (μm)
1	6	100	0	11.00	80.98	2.93	8.33	10.00	13.61	4.32	21.3
2	6	180	1	4.00	727.78	1.83	9.10	21.33	7.88	3.25	22
3	6	240	2	1.00	1466.67	2.99	10.50	18.33	7.11	3.58	22.7
4	9	100	1	12.33	202.38	2.69	9.40	28.50	19.47	3.67	20.7
5	9	180	2	2.00	1294.44	2.60	12.10	20.50	8.66	3.49	20.7
6	9	240	0	9.00	140.10	3.83	22.43	16.33	8.01	4.65	28
7	12	100	2	12.00	217.41	3.08	13.23	33.33	35.39	3.94	20.3
8	12	180	0	26.33	38.70	4.50	13.83	26.67	22.55	4.32	25.3
9	12	240	1	5.00	414.44	3.17	10.37	30.67	10.29	4.30	24

The machining performance of PMEDM was investigated by studying the influence of process parameters on material removal rate (MRR), electrode wear ratio (EWR), average surface roughness (Ra), and white layer thickness (WLT). MRR and EWR were calculated based on the weight loss method. Average surface roughness, Ra, was measured using a TESA-Rugosurf surface roughness tester. To measure the WLT, machined samples were sectioned using wire-EDM and then polished and etched with nital solution. The WLT was measured using a Carlzeiss optical microscope. Figure 4 is a photograph of the PMEDM machined sample.

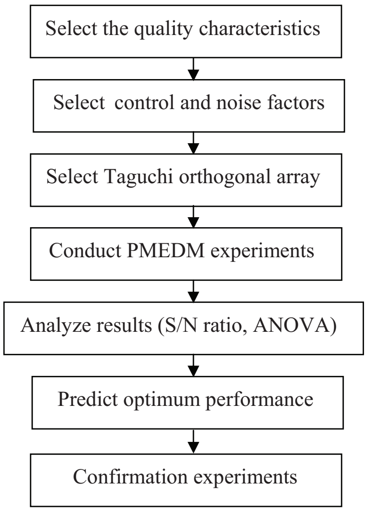

Figure 3. Steps applied in Taguchi optimization method.

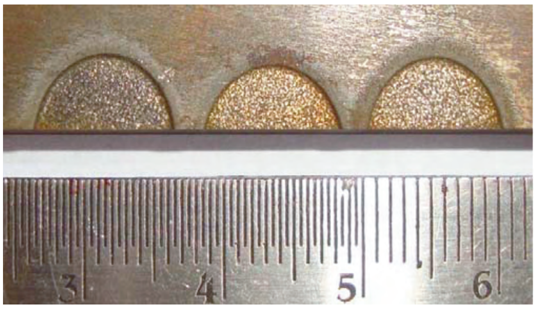

Figure 4. PMEDM machined samples.

3. Results and discussion

This section discusses the determination of optimal values for the process parameters such as peak current, pulse on-time, and powder concentration for positive and negative polarities for higher MRR, lower values of EWR, Ra, and WLT during PMEDM using S/N ratio analysis. Significant process parameters are identified using ANOVA.

3.1. S/N ratio analysis

In the Taguchi experimental design, S/N ratio is the ratio of signal-to-noise, where signal represents the desirable values (i.e. mean for the output characteristic) and noise represents the undesirable value (i.e. the square deviation for the output characteristic). Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available depending on type of characteristic: lower is better (LB), nominal is best (NB), and higher is better (HB). For the present investigation, higher is better quality characteristic was chosen for MRR, which is calculated according to Eq. (1). Lower is better was chosen for EWR, Ra, and WLT, calculated using Eq. (2).

$$S/N\,ratio = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

$$S/N\,ratio = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{2}$$

where y_i represents the experimental observed value of the ith experiment and n is the number of repetitions of each experiment.

The calculated S/N ratios for all the experiments are listed in Table 4, and Figures 5-8 show the effect of process parameters on S/N ratio for output responses MRR, EWR, Ra, and WLT respectively. The optimum values of process parameters for maximum MRR, low values of EWR, Ra, and WLT with experimental values are tabled in Tables 5 and 6 for positive and negative polarities, respectively.

Table 4. Experimental plan and S/N ratio values.

S. no.	I (A)	Ton (μs)	C (g/L)	Output responses (avg. of 3 replicates)							
				Negative polarity				Positive polarity			
				MRR	EWR	Ra	WLT	MRR	EWR	Ra	WLT
1	6	100	0	20.82	–38.17	–9.33	–18.41	20.00	–22.68	–12.71	–26.58
2	6	180	1	12.04	–57.24	–5.26	–19.18	26.58	–17.93	–10.23	–26.84
3	6	240	2	0.00	–63.33	–9.50	–20.42	25.26	–17.04	–11.08	–27.10
4	9	100	1	21.82	–46.12	–8.60	–19.46	29.09	–25.79	–11.30	–26.30
5	9	180	2	6.02	–62.24	–8.29	–21.65	26.23	–18.75	–10.86	–26.30
6	9	240	0	19.08	–42.93	–11.67	–27.01	24.26	–18.07	–13.35	–28.94
7	12	100	2	21.58	–46.75	–9.76	–22.43	30.45	–30.98	–11.90	–26.16
8	12	180	0	28.41	–31.75	–13.07	–22.81	28.51	–27.06	–12.71	–28.07
9	12	240	1	13.97	–52.35	–10.02	–20.31	29.73	–20.25	–12.67	–27.60

Table 5. Optimum parametric combination in negative polarity.

Requirement	Optimal combinations (I/Ton/C)	Confirmation of results			
		MRR (mg/min)	EWR (%)	Ra (μm)	WLT (μm)
Higher MRR	12 A/100 μs/without powder	23	34.78	2.38	17
Lower EWR	6 A / 180 μs / without powder	2	347.82	2.3	12
Lower Ra	6 A / 180 μs / 1 g/L	2	900	1.4	17
Lower WLT	6 A / 100 μs / 1 g/L	4	225	1.72	11

Table 6. Optimum parametric combination in positive polarity.

Requirement	Optimal combinations (I/Ton/C)	Confirmation of results			
		MRR (mg/min)	EWR (%)	Ra (μm)	WLT (μm)
Higher MRR	12 A / 180 μs / 1 g/L	30	26.66	2.62	31
Lower EWR	6 A / 240 μs / without powder	12	8.22	1.93	29
Lower Ra	6 A / 180 μs / 2 g/L	12	8.22	1.53	17
Lower WLT	6 A / 100 μs / 2 g/L	11	9.09	1.95	19

3.1.1. Effect of parameters on process performance MRR

From the trend of MRR at different levels of the process parameters, it can be observed from Figure 5a that MRR increases with the increase in peak current from 6 A to 12 A, for both PP and NP. The increase in MRR with peak current could be attributed to the dependence of MRR on the product of energy per pulse and pulse frequency. Thus, increasing the pulse current at a constant frequency and voltage increases the energy of the pulse and, ultimately, gives a higher MRR. A similar trend was reported for PMEDM on other materials in the literature (Wong et al., 1998).

From Figure 5b, it is evident that MRR increases with increase in Ton up to 180 μs and then MRR decreases in PP. It is also noted that Ton is not significant on MRR in PP. It is also observed from Figure 5b that in NP the MRR decreases with the increase in Ton within the range of investigation. The decrease in MRR at high Ton could be due to increasing discharge energy by longer pulse on-times not allowing high discharge frequencies and causing more energy losses by heat conduction. Further, in EDM metal is primarily removed in the liquid and vapour phase from the work material, whereas the long pulse duration causes the plasma channel to expand and this expansion causes less energy density on the workpiece, which is insufficient to melt and/or vaporize the workpiece material. This might have also coupled with the effect of frequent short-circuiting at higher pulse on-time during PMEDM and also excessive formation of gas, which affects the breakdown characteristics of the dielectric. A similar trend of higher MRR at lower values of Ton (10-20 μs) has been reported by Jilani and Pandey (1984). When the tool is positive, the influence of Ton is not significant on MRR. Furthermore, is also noted that pulse on-time is not significant on MRR in PP.

Figure 5c depicts the influence of concentration of aluminium powder on MRR. When 1 g/L powder is added to the dielectric, the PP results in high MRR due to an increase in the discharge gap and dispersion of the discharge energy (Chow et al., 2008). This effect is more dominant in PP than in NP. Further increase in the concentration of the powder leads to unsteady machining conditions, which decrease in MRR as previously established by Erden et al. (1980). Hence for maximum MRR, positive polarity with high peak current of 12 A, moderate Ton of 180 μs, and medium concentration of powder 1 g/L should be selected.

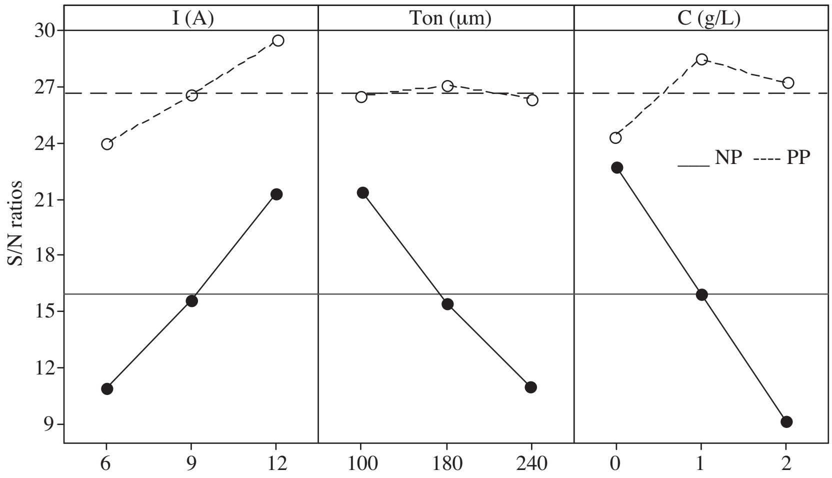

Figure 5. S/N ratio graph of the process performance MRR.

3.1.2. Effect of parameters on process performance EWR

During the EDM, material is removed from the workpiece as well as the tool. The mass loss of the electrode with respect to the mass loss of the workpiece is called the electrode wear ratio (EWR).

From the trend of EWR at different levels of the process parameters, it is evident from Figure 6 that polarity plays a vital role in PMEDM. It is seen from Figure 6a that EWR increases with increase in peak current during PP. If pulse current is increased, the amount of debris in the gap becomes too high. The particle could then form an electrically conducting path between the electrode and work material, causing unwanted discharges, which become arcs and reduce the sparking efficiency. Since EWR is the ratio of electrode erosion and work material removal it increases with peak current. However, EWR decreases with increase in the peak current during NP. The reason for the trend is explained with the help of Figure 5a. The increase in MRR is highly significant when the peak current is varied from 6 A to 12 A in NP compared to that of PP. Further, it is also observed during the experiments that tool wear is very low in NP. Since EWR is the ratio of tool wear to material removal in the workpiece, the ratio decreases with the increase in peak current.

The effect of Ton on EWR for NP and PP is depicted in Figure 6b. The EWR decreases with the decrease in pulse on-time during PP. The phenomenon may be attributable to long pulse on-time, which provides better heat removal around the surface of the copper electrode, which is normally a good thermal conductor. The decrease in temperature on the surface of the electrode causes less wear on the electrode. However, at the same time due to increased pulse on-time there is an increase in MRR (as seen in Figure 5b). As EWR is the ratio between tool wear and mass of material removed in the workpiece, the slope of EWR decreases for the increment in pulse on-time. Furthermore, in NP, it is found that EWR increases with the increase in Ton. This trend could be explained with the help of Figure 5b; MRR decreases with the increase in Ton. As the EWR is the ratio of tool wear to material removal in the workpiece, the ratio increases with the increase in Ton.

The influence of addition of Al powder is shown in Figure 6c. The addition of Al powder to the dielectric has a less significant effect on EWR during PP compared to that of NP. The quality characteristic for EWR is smaller the better. The minimum EWR is observed at 1 g/L in PP and without powder addition in NP. Further investigations are needed to understand the role of polarity in PMEDM to reduce tool wear.

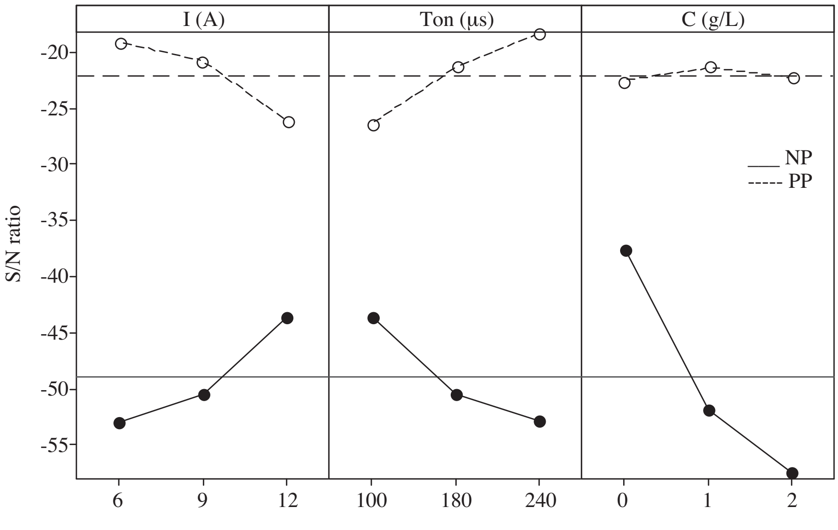

Figure 6. S/N ratio graph of the process performance EWR.

3.1.3. Effect of parameters on process performance Ra

Figure 7 indicates that both NP and PP will have a similar effect on surface roughness with respect to the process parameters. This result is in line with that obtained by Konig et al. (1987) with respect to polarity. Figure 7a shows that average surface roughness increases with increase in the peak current from 6 A to 12 A. This is due to an increase in the spark energy, which leads to large impulsive forces removing more molten material and creating deeper and larger craters, increasing the surface roughness (Yan et al., 2005).

From Figure 7b it is observed that the surface roughness improves with the increase in the pulse-on time from 100 μs to 180 μs and further increase leads to an increase in the surface roughness. This is due to the fact that at constant current setting an increase in pulse on-time results in a proportional increase in spark energy and consequently the melting boundary becomes deeper and wider, and hence increases the roughness value. Therefore, to obtain the minimum Ra value the Ton around 180 μs can be selected.

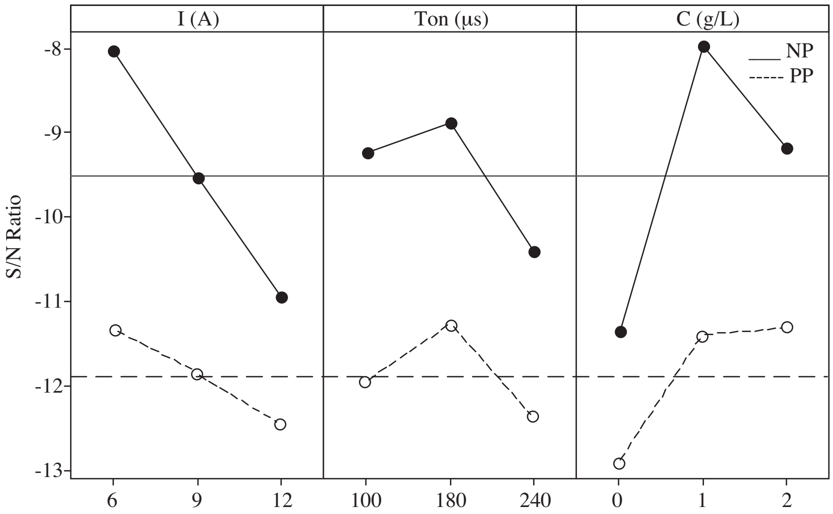

Figure 7. S/N ratio graph of the process performance Ra.

Addition of powder at a low level of 1 g/L in NP and even at a high level of 2 g/L in PP improves the surface roughness to a value of Ra = 1.53 μm. The combined effect of low electrical resistivity, low density, and higher thermal conductivity of the aluminium powder causes better spark distribution, thus producing shallow craters on the machined surface (Yih-fong and Fu-chen, 2005). Hence for low Ra in both polarities a low peak current of 6 A, a moderate Ton of 180 μs, and a 2 g/L concentration of powder should be selected. However, more improvement in the surface roughness is still expected at higher concentration of aluminium powder in positive polarity.

3.1.4. Effect of parameters on process performance WLT

During EDM not all the workpiece material melted by the discharge is expelled into the dielectric. The remaining melted material is quickly chilled, primarily by heat conduction into the bulk of the workpiece, resulting in an exceedingly hard surface known as a white layer or recast layer. The thickness of the white layer varies from 1 to 25 μm depending on the spark energy.

From the trend of WLT at different levels of process parameters, it can be observed that WLT can be reduced effectively by varying the process parameters in NP rather than in PP. It is observed from Figure 8a that the WLT increases with the increase in the peak current. However, at NP the WLT decreases at high current values. The observations are consistent with the results reported previously (Zhang et al., 2011). This is due to the fact that an increase in pulse current leads to an increase in the rate of heat energy, which is subjected to both of the electrodes, and in the rate of melting and evaporation. Therefore, more heat is transferred into the workpiece as the pulse current increases, and the dielectric is increasingly unable to clear away the molten material, causing it to build upon the surface of the parent material. During pulse off-time, this molten material resolidifies to form a white layer and the thickness of the white layer depends on the volume of molten material. The minimum value of WLT is obtained at a low level of peak current of 6 A.

From Figure 8b, it is evident that an increase in the Ton increases the tendency of formation of WLT. In EDM metal is primarily removed in the liquid and vapour phase. At low pulse on-time the short pulses may cause less vaporization of the work material, whereas a long pulse duration causes the plasma channel to expand and this expansion causes less energy density on the workpiece, which is insufficient to melt and/or vaporize the workpiece material, which ultimately results in a thick white layer.

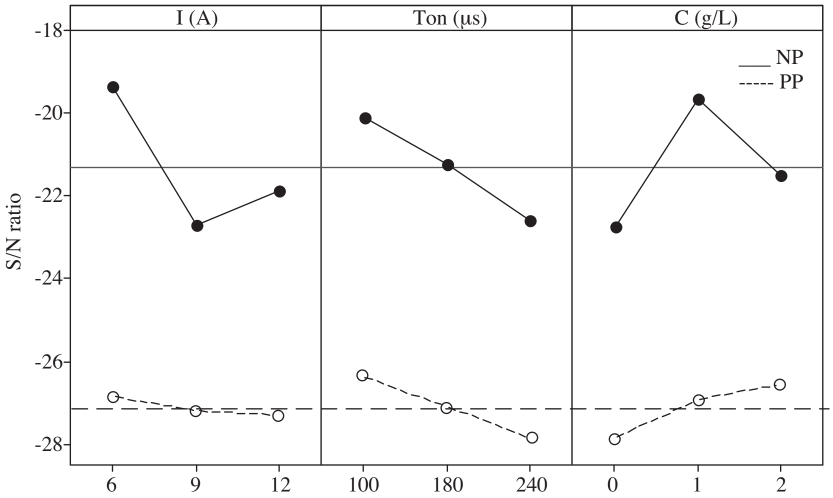

Figure 8. S/N ratio graph of the process performance WLT.

The addition of aluminium powder to the dielectric generates a more homogeneous and thinner white layer. The distribution of the white-layer thickness with the powder concentration is shown in Figure 8c. The increase in the discharging rate due to the increase in the process stability and the reduction in the impulsive forces mentioned by Uno and Okada (2000) contribute to the formation of a denser and smooth white layer. Addition of powder at a low level of 1 g/L in NP and even at a high level 2 g/L in PP reduces the WLT.

The optimal parametric combination of low peak current 6 A, low value of Ton of 100 μs, and addition of a 1 g/L concentration of powder is suitable to produce lower WLT for both NP and PP. This is also evident from Figures 9 and 10, which show different WLT obtained when machined at the optimal combination of process parameters.

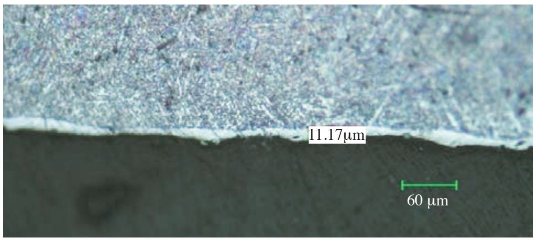

Figure 9. WLT obtained at I-6 A, Ton-180 μs, and C-1 g/L in NP.

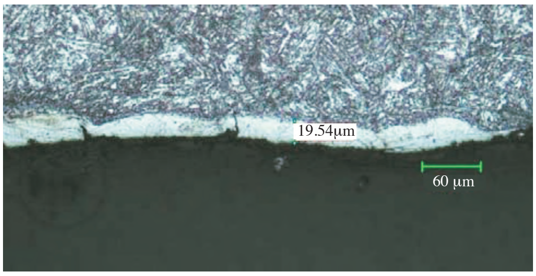

Figure 10. WLT obtained at I-6 A, Ton-180 μs, and C-1 g/L in PP.

3.2. Analysis of variance (ANOVA)

The significant parameters influencing the MRR, EWR Ra and WLT in the PMEDM with water as dielectric fluid are determined using analysis of variance (ANOVA). It helps in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels.

The ANOVA results for MRR, EWR, Ra and WLT are illustrated in Table 7. The F-values for MRR, EWR, Ra and WLT in positive polarity and the contribution of the process parameters peak current, pulse-on time and concentration of the powder were calculated. Peak current had a significant effect of 75% on MRR, EWR, and Ra. Concentration of powder had a significant effect on Ra of 95%.

Table 7. ANOVA for MRR, EWR, Ra, and WLT in positive polarity.

Factor	DOF	For MRR		For EWR		For Ra		For WLT	
		F value	% contribution	F value	% % contribution	F value	% contribution	F value	% contribution
I	2	10.07	62.29	4.22	41.10	6.82	18.34	0.86	5.13
Ton	2	0.25	1.55	4.61	44.92	7.52	20.23	7.98	48.04
C	2	4.68	29.24	0.44	4.23	21.84	58.73	6.77	40.76
Error	2		6.25		9.73		0.268		6.02
Total	8								

$F_{0.25,2,2} = 3.0$; $F_{0.1,2,2} = 9.0$; $F_{0.05,2,2} = 19.0$; $F_{0.025,2,2} = 39.0$; $F_{0.01,2,2} = 99.0$.

Significant effects of I, Ton, and C on MRR, EWR, Ra, and WLT at different confidence intervals were verified in negative polarity.

4. Conclusions

The present work on addition of aluminium metal powder in distilled water resulted in high MRR, good surface finish, and minimum white layer thickness when compared with pure distilled water. The result obtained from the present investigation is extremely helpful for selecting the optimum machining conditions for W300 die-steel work material, which is extensively used in tool and die industries. Within the range of parameters selected the following specific conclusions are drawn from the experimental results.

1. Maximum MRR is obtained at a high peak current of 12 A, a moderate Ton of 180 μs, and a low concentration of powder 1 g/L in positive polarity.
2. Low EWR is achieved in positive polarity with low values of peak current of 6 A, higher values of Ton of 240 μs, and low concentration of powder of 1 g/L.
3. To produce low surface roughness values, a low peak current of 6 A, a moderate Ton of 180 μs, a low concentration of powder of 1 g/L, and positive polarity should be selected.
4. The minimum value of white layer thickness is obtained with low values of peak current 6 A, lower values of Ton of 100 μs, and low concentration of powder of 1 g/L in negative polarity.
5. Polarity plays an important role in PMEDM. Higher productivity, i.e. high MRR, is obtained in positive polarity, whereas better surface quality (surface roughness and white layer thickness) is achieved in negative

polarity. Hence for rough machining positive polarity can be selected to achieve higher MRR and during finishing a better surface is achieved by changing the polarity.

6. These experimental results prove that distilled water can be used as dielectric fluid instead of hydrocarbon oil and moreover the performance can be improved considerably by the addition of aluminium powder.

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