Performance Parameters Optimization Of Powder Mixed Electric Discharge Machining (PMEDM) By Taguchi Method

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Electrical discharge machining (EDM) is widely used in the production of dies. This paper describes an investigation into the optimization of the EDM process when silicon powder is suspended into the dielectric fluid of EDM. Taguchi's parameter design approach was adopted to obtain an optimal setting of powder mixed EDM (PMEDM) process parameters (peak current, pulse duration, duty cycle, concentration of silicon powder added into the dielectric fluid) that may yield optimal process performance (material removal rate and surface roughness). A modified powder mixed dielectric circulation system was developed in the laboratory. Experiments have been performed on this newly designed experimental setup. The obtained experimental results indicate significantly improved performance of PMEDM over EDM. The results were verified by conducting confirmation experiments with optimal process conditions.

Keywords: Powder mixed EDM; Material removal rate; Surface roughness; Process optimization.

1. Introduction

Electrical discharge machining (EDM) is a widespread non-conventional material removal process used in the manufacturing industry. It can produce intricate shapes on any conducting metal and alloy irrespective of their hardness and toughness [1]. In addition, it does not make direct contact between the electrode and the workpiece, thus eliminating mechanical stresses, chatter and vibration problems during machining. Inspite of remarkable process capabilities, the limitations like low volumetric material removal rate and poor surface quality restricted its further applications [2]. To address these problems, recently, powder mixed EDM (PMEDM) has emerged as one of the advanced techniques in the direction of enhancement of capabilities of EDM process [2-3]. In this technique, a suitable material in fine powder form is mixed into the dielectric fluid of EDM. The added powder significantly affects the performance of EDM process. The electrically conductive powder reduces the insulating strength of the dielectric fluid and increases the spark gap distance between the tool electrode and workpiece [2-6]. As a result, the process becomes more stable thereby improving material removal rate (MRR) and surface finish.

The process parameters of PMEDM process may include type of powder, its concentration, shape, size, density, electrical resistivity and thermal conductivity etc. along with conventional parameters of EDM [3]. Extensive

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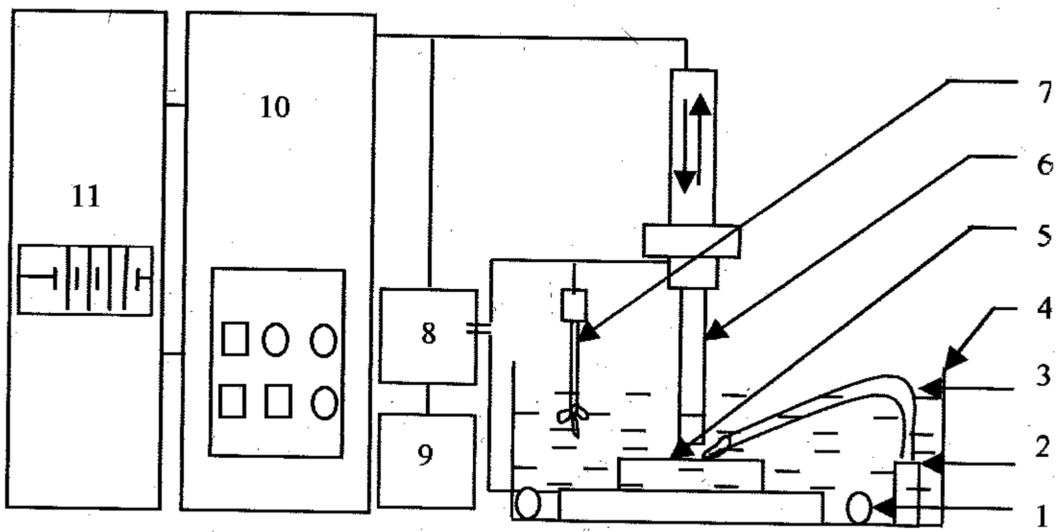
experimental work is therefore needed to study all these parameters. Hence it becomes imperative to select the most influential factors for achieving optimal machining performance. Therefore, this research work has been undertaken to optimize the effect of various process parameters on PMEDM process performance. The process performance is measured in terms of MRR and surface roughness (SR).

2. Literature Review

The effect of powder particles (copper, aluminum, iron and carbon) suspended in dielectric fluid of EDM was first studied by Erden and Bilgin [7]. They reported that the machining rate increased with increase in the concentration of the powder. Later, Jeswani [8] carried out work using graphite powder suspended in the kerosene oil. It was observed that MRR increased by 60% and tool wear ratio decreased by 15%. Mohri et al. [5,9] found that an EDM finishing process using silicon mixed dielectric provides a mirror surface on an area up to 500 cm^2. They further reported that under specific working conditions, aluminum and graphite powders exhibit more improvement in surface finish than caused by silicon powder. By mixing the different additives (silicon, graphite, molybdenum, aluminum and silicon carbide) into the dielectric fluid of EDM, glossy and smooth surface finish can be achieved [6]. The presence of powder increases the gap distance as compared to traditional EDM by at least a factor of two [6]. The enlarged and widened discharge channel lowers the breakdown strength of the dielectric fluid and reduces the electrical density on the machining spot and thus generates shallow craters [10]. Ming et.al. [11] observed that a *bridging effect* is created with the addition of powder, which facilitates the dispersion of discharge into several increments. As a result, several discharge trajectories are formed within a single input impulse and various discharge spots are created. Hence MRR and surface finish improves. Tzeng and Chen [12] applied the optimization strategy in order to reduce the functional variability of EDM process. However, no study has been reported about the identification and optimization of PMEDM process parameters.

3. Technology of PMEDM Process

Powder mixed EDM has a different machining mechanism from the conventional EDM. In this process, a suitable material in the powder form is mixed into the dielectric fluid either in the same tank or in a separate tank. For better circulation of the powder mixed dielectric, a stirring system is employed. For constant reuse of powder in the dielectric fluid, a special circulation system (Figure1) is used. The various powders that can be added into the dielectric fluid are aluminum, chromium, graphite, copper or silicon carbide etc. The spark gap is filled up with additive particles. When a voltage of 80-320 V is applied between the electrode and the workpiece facing each other with a gap of 25μm -50μm, an electric field in the range 10^5 -10^7V/m is created. The powder particles get energized and behave in a zigzag fashion (Figure 2). Under the sparking area, the particles come close to each other and arrange themselves in the form of clusters between both the electrodes. The interlocking between the different powder particles occurs in the direction of flow of current. The chain formation helps in bridging the gap between both the electrodes. Due to *bridging effect*, the insulating strength of the dielectric fluid decreases. The easy short circuit takes place, which causes early explosion in the gap. As a result, a *'series discharge'* starts under the electrode area. The faster sparking within a discharge takes place, which causes faster erosion from the work piece surface and hence increases the MRR. At the same time, the added powder modifies the plasma channel. The plasma channel becomes enlarged and widened [2]. The sparking is uniformly distributed among the powder particles, hence electric density of the spark decreases. Consequently, uniform erosion (shallow craters) occurs on the workpiece surface. This results in improvement in surface finish at better machining rates.



1 - Magnets; 2 - Circulation pump; 3 - Nozzle; 4 - Tank;
5 - Workpiece; 6 - Electrode; 7 - Stirrer; 8 - Oscilloscope;
9 - Recorder; 10 - ZNC generator; 11 - DC Power supply

Figure 1: *Schematic diagram of PMEDM experimental setup*

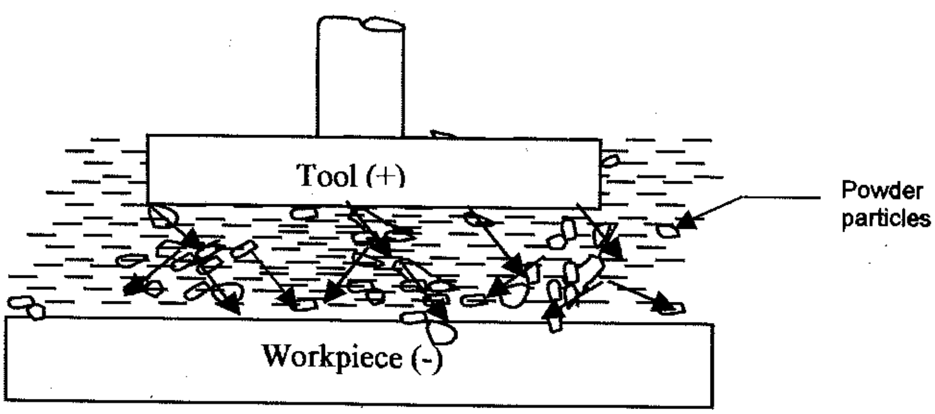


Figure 2: *Principle of Powder mixed EDM*

4. Experimentation

4.1 Setup

Experiment was conducted on a EZNC fuzzy logic Die Sinking EDM machine manufactured by Electronica Machine Tools Ltd. India [13]. It is energized by PS fuzzy logic 50-Ampere working current pulse generator and associated controller to produce rectangular shaped current pulses for discharging purpose. Both the voltage and current waveform on the tool were recorded using a digital storage oscilloscope. Silicon powder is suspended into the commercially available kerosene oil. The powder particle size is in the range of 20-30 μm.

Since the machine needs about 300 liters of kerosene oil for circulation of the dielectric fluid under normal conditions. Utilizing the existing circulating system of the machine tool directly will waste a large amount of kerosene. Therefore, a small working fluid circulating system has been designed (Figure 1). In the modified circulating system, a micro pump is installed for better circulation of the powder mixed dielectric fluid. To avoid particle settling, a stirring system is incorporated. The pump and the stirrer are employed in the same tank in which machining is performed. The circulation and stirring system are designed in such a way that, it can be used at the commercial level. Each trial run is performed for a duration of 40 minutes. The experiments have been are performed with positive polarity. In each test, the MRR is calculated by the weight loss method while SR is measured in terms of arithmetic mean roughness of the evaluated roughness profile (R_a in μm) using a Surf coder SE1200 surface testing analyzer.

4.2 Electrode and Workpiece Material

The workpiece material used in this study is EN-31 (AISI-52100) die steel. The material is supplied in fully annealed condition. The hardness of the workpiece material is measured on different points and average hardness value was found to be 59HRC. The chemical composition of the workpiece material is given as: 0.9-1.2% C, 0.1-0.3% Si, 0.3-0.7% Mn, 1-1.6% Cr, 0.025% S, and 0.025% P (max.) and balance is ferrous. Copper electrodes with diameter 25mm has been selected to machine the EN-31 die steel.

5. Design of Experiments

Several approaches are available for the design of experiments to investigate the effect of various process parameters on PMEDM performance. They include, simple single-factor-by-single-factor approach, i.e. only one factor is changed for a given trial run, the traditional factorial, fractional factorial approach [14] and the highly-fractional factorial experimental design, namely, the Taguchi method [14-15]. The number of experiments to be conducted decreases rapidly by using Taguchi method. This in turn, reduces the time consumed as well as the overall costs. Compared to the single-factor-by-single-factor approach, Taguchi method can extract information more precisely and more efficiently. In addition, less number of tests is needed even when the number of variables is quite large. Although Taguchi's experimental design and analysis are conducted by highly fractional factorial experimental design (Taguchi Orthogonal Arrays) to determine the influence of the factors and their levels and identify the best combination of parameters. It has been shown that this method yields the same or even better results (in terms of precision) as compared to complete factorial experiment [14-15].

5.1 Taguchi's Approach

The Taguchi experimental design was conceived and developed by Dr. Genichi Taguchi in Japan after World War II. Taguchi method is a simple, efficient and systematic approach for the quality optimization of products and processes. Moreover, this method suggests means to economize experimental work. The Taguchi method uses S/N (Signal to Noise) ratio to quantify the variation in data. There are three categories of S/N ratios depending on the types of characteristics like higher is best (HB), lower is best (LB) and nominal is best (NB). The S/N ratios are calculated by using the following equations [14-15]:

$$HB: S/N\ ratio = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^{-2}\right] \quad (1)$$

$$LB: S/N\ ratio = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^{2}\right] \quad (2)$$

$$NB: S/N ratio = 10\log_{10}\left[\frac{\bar{y}^{2}}{z^{2}}\right] \quad (3)$$

where, $\bar{y}$ and z are respectively the sample mean and sample standard deviation of n observations in each trial.

To estimate the relative contribution of each process parameter on overall measured response, analysis of variance (ANOVA) is performed. The information regarding the significance of parameters can also be obtained by use of ANOVA and F-test [14-15].

5.2 Process Parameters of PMEDM process

In order to identify the process parameters that affect the quality of components processes by PMEDM, an Ishikawa cause-effect diagram is constructed as shown in Figure 3. The process parameters can be listed in four categories as follows:

(a) Electrical parameters: peak current, pulse duration, duty cycle, supply voltage.

(b) Non-electrical parameters: electrode lift time, working time, nozzle flushing, gain.

(c) Powder based parameters: powder type, powder concentration, powder shape, powder size, powder conductivity.

(d) Electrode based parameters: electrode material, electrode size.

The following four parameters were chosen for this study:

1. Concentration of silicon powder, A;
2. Peak current, B;
3. Pulse duration, C;
4. Duty cycle, D.

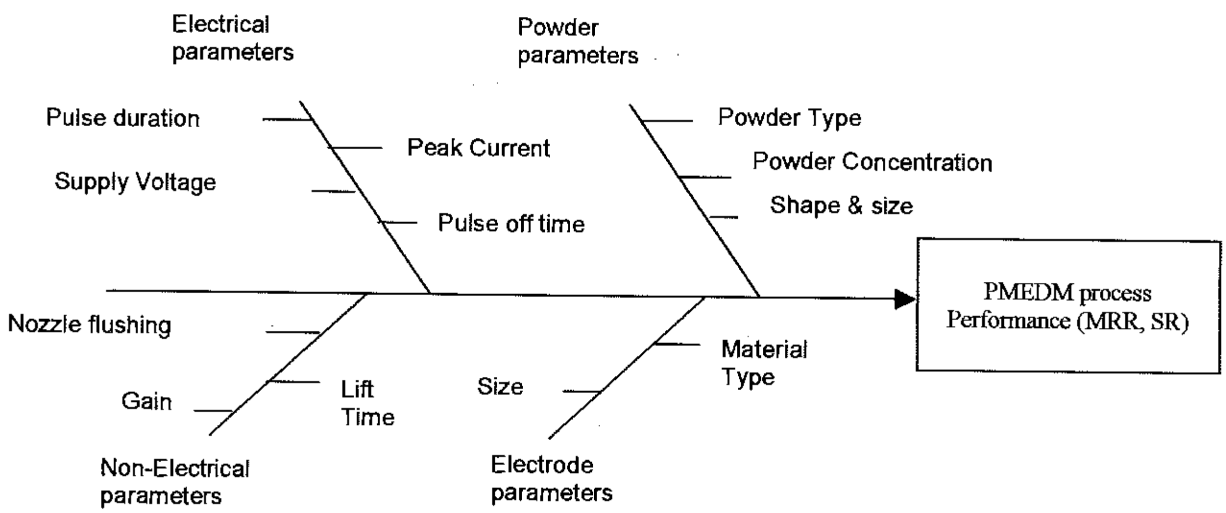


Figure 3: *The Ishikawa cause-effect diagram*

The selected process parameters, their designated symbols and levels are given in Table 1. The ranges of these parameters were selected on the basis of preliminary experiments conducted by using one variable at a time approach. Taguchi recommended various standardized orthogonal arrays (OA's) such as L_4, L_8, L_9, L_{16}, L_{18} and L_{25} etc. Depending upon the number and type of parameters to be studied, a suitable OA is chosen. In the present work, there were total four parameters; each at three levels. For this, L_9 (3^4) OA is the suitable choice for the present work [15]. L_9 (3^4) OA was selected to assign various columns. The experiments were conducted according to the trial conditions specified in L_9 (3^4) OA (Table 2). The observed values of MRR and SR are set to 'higher the best' and 'lower the best' respectively. The complete procedure of optimization of PMEDM process performance is summarized in Figure 4 [15].

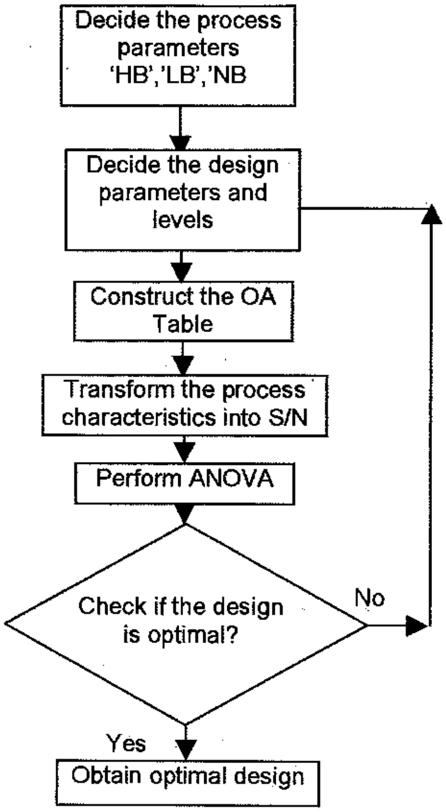
Table 1: *PMEDM process parameters and their levels*

Designation	Process Parameter	Levels		
		1	2	3
A	Powder Concentration (g/l)	0	1	2
B	Peak current (A)	3	6	12
C	Pulse duration (μs)	50	100	150
D	Duty cycle	0.7	0.8	0.9

Table 2: *The L9 (3^4) Taguchi orthogonal array layout*

Trial No.	Process Parameters				Response		
	Powder concentration (A)	Peak current (B)	Pulse duration (C)	Duty cycle (D)	R1	R 2	R 3
1	1	1	1	1	--	--	--
2	2	2	2	2	--	--	--
3	3	3	3	3	--	--	--
4	1	2	2	3	--	--	--
5	2	3	3	1	--	--	--
6	3	1	1	2	--	--	--
7	1	3	3	2	--	--	--
8	2	1	1	3	--	--	--
9	3	2	2	1	--	--	--

Note: R1, R2 and R3 represent repetitions



Note: HB: Higher the better
LB: Lower the better
NB: Nominal the better

Figure 4: *Procedure of Taguchi method*

6. Analysis and Discussion

Since the experimental design is orthogonal, it is possible to separate out the effect of each process parameter at different levels. The raw data collected from the experiments for each trial runs (1 through 9) were converted into their respective S/N ratio by using Software Minitab (Table 3) [16].

6.1 Material Removal Rate:

The raw data for average values of MRR and those of the S/N ratios for each parameter at levels 1, 2 and 3 are calculated from Table 3 and are given in Tables 4 and 5 respectively. The response curves (Figure 5) for the individual effect of four process parameters on the average value and S/N ratio have been plotted by using these data.

Table 3: *Experimental results for the PMEDM performance characteristics*

Exp. Number	Observed values			
	MRR		SR	
	Mean	S/N Ratio	Mean	S/N Ratio
1	0.31	-10.17	0.93	0.63
2	0.60	-4.43	1.53	-3.69
3	1.07	0.58	1.98	-5.93
4	0.78	-2.15	0.89	1.01
5	0.99	-0.08	1.56	-3.86
6	2.29	7.19	1.96	-5.84
7	0.96	-0.35	0.66	3.60
8	1.40	2.92	1.16	-1.28
9	3.07	9.74	1.22	-1.72

Table 4: *Average values of raw data (MRR) at different levels*

Process parameter designation	Average values, MRR			Main effects, MRR	
	L1	L2	L3	L2-L1	L3-L2
A	0.66	1.35	1.81	0.69	0.46
B	0.68	0.99	2.14	0.31	1.15
C	1.33	1.48	1.00	0.15	-0.48
D	1.45	1.28	1.08	-0.17	-0.20

Note: L1, L2 and L3 represent levels 1, 2 and 3 respectively

Table 5: *Average values of S/N data (MRR) at different levels*

Process parameter designation	Average values, MRR			Main effects, MRR	
	L1	L2	L3	L2-L1	L3-L2
A	-4.67	1.65	4.10	6.32	2.45
B	-4.22	-0.53	5.84	3.69	6.37
C	-0.018	1.05	0.049	1.07	-1.00
D	-0.17	0.80	0.45	0.97	-0.35

Note: L1, L2 and L3 represent levels 1, 2 and 3 respectively

From the trend of variation of MRR at different levels of the process parameters, it can be noted that when silicon powder is suspended into the dielectric fluid of EDM, improves the MRR. Level 1 indicates the case of simple EDM while levels 2 and level 3 represent PMEDM. The reason for enhancement of MRR is mainly that the conductive powder particle when added into the dielectric fluid of EDM lowers the breakdown strength of the dielectric fluid. The powder particle tries to bridge the discharge gap between both the electrodes. This facilitates the dispersion of discharge into several increments (sparking frequency increases) and hence enhances the MRR. Another observation from the present experiment is that the increase in peak current improves the MRR. This may be due to its dominant control over the input energy. It is representative of the energy per pulse expended in the spark gap region. It thus controls the material removal rate. This result is in line with the findings of [7,11]. The pulse duration is another factor that shows the variation in mean and S/N ratio. The MRR increases with increase in pulse duration, reaches an optimum value at 100μs pulse duration. Further increase in pulse duration decreases the MRR. This can be due to the fact that the short pulse duration may cause less vaporization on the surface of the workpiece, whereas the long pulse duration may cause an expansion of the plasma channel, thereby decreasing the energy density in the machining process. It is further noticed from the response curves that the duty cycle does not produced a pronounce effect on MRR.

From Figure 5, it can be observed that the parameters: concentration of silicon powder (A), peak current (B) and pulse duration (C) appreciably affect both the mean and variation in MRR values (S/N ratio). The trend of variation of the response curves suggested that the 3rd level of parameters A (A_3) and B (B_3) and 2nd level of parameter C (C_2) may provide maximum MRR from workpiece when machined by PMEDM. It can be further noticed that in the case of parameters A, B and C, the highest value of average response corresponds to highest value of S/N ratio. However this is not the case with the parameter D. The best average response for D would be obtained at 1st level but S/N ratio for D is best at 2nd level. In order to make final decision, the relative contribution of mean value and S/N ratio has been considered from ANOVA. The pooled version of ANOVA for average values of raw data as well as S/N data is given in Table 6 and 7 respectively. It can be observed from Table 6 and Table 7 that the relative contribution of factor D towards mean value of MRR (12.98%) is higher than that for S/N ratio (2.06%).

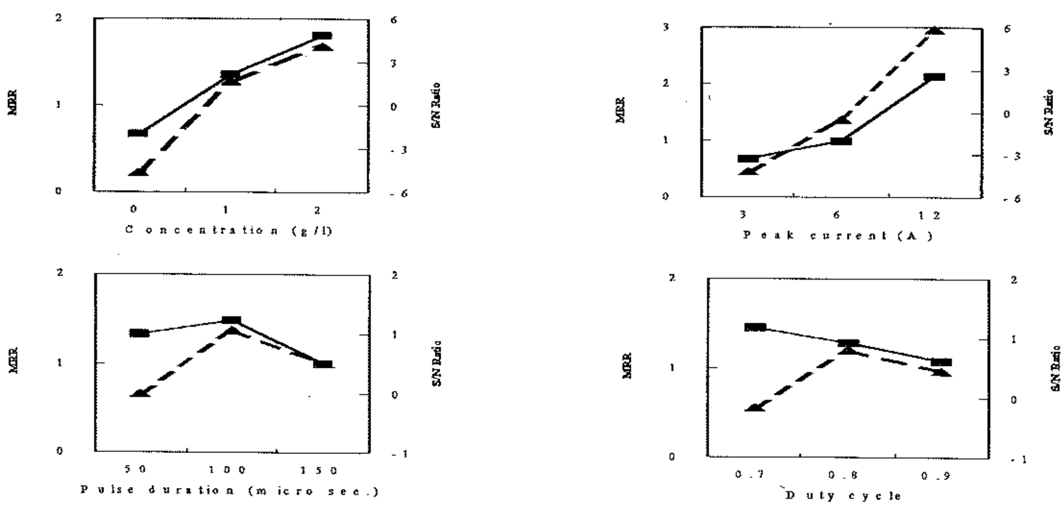


Figure 5: *The effect of process parameters on MRR and S/N data(■- Mean MRR; ▲—S/N ratio)*

Table 6: *Pooled analysis of variance (ANOVA)for raw data*

Note: SS′ = Sum of squares due to the sole factor eliminating

Source	D.O.F	SS	V	SS′	F ratio	P (%)
A	2	2.01	1.00	1.81	10.0	29.57
B	2	3.54	1.77	3.34	17.7	54.57
C	2	0.36	0.18	0.16	1.8	2.61
D	(2)	(0.20)	Pooled			
Error	2	0.20	0.10			12.98
Total	8	6.12	0.77			100

the effect of error
V = Variance; P = Percentage contribution; F = Fisher test factor

Table 7: *Pooled analysis of variance (ANOVA) for S/N ratio*

Source	D.O.F	SS	V	SS′	F ratio	P (%)
A	2	123.06	61.53	121.60	84.29	43.06
B	2	155.73	77.87	154.27	106.67	54.62
C	2	2.14	1.07	0.68	1.47	0.24
D	(2)	(1.46)	Pooled			
Error	2	1.46	0.73			2.06
Total	8	282.40	35.3			100

Note: SS′ = Sum of squares due to the sole factor eliminating the effect of error
V = Variance; P = Percentage contribution; F = Fisher test factor

Therefore, considering the level corresponding to higher relative contribution, the optimum combination of input parameters for best MRR is A_3, B_3, C_2 and D_1.

6.2 Surface Roughness:

The average values of raw data of SR and that of S/N ratios for each parameter at levels 1,2 and 3 are given in Table 8 and 9 respectively. The individual effect of each of the four process parameters on the average value of SR as well as on S/N ratio for SR is shown in Figure 6.

From the trend of response curves for SR (Figure 6) at different levels of the process parameters, it can be observed that silicon powder when suspended into dielectric fluid lowers SR. The reason for the lowering in SR is that the added powder modifies the plasma channel. The plasma channel becomes enlarged and widened. The sparking is uniformly distributed among the powder particles, hence electric density of the spark decreases.

Table 8: *Average values of raw data (SR) at different levels*

Process parameter designation	Average values, MRR			Main effects, MRR	
	L1	L2	L3	L2-L1	L3-L2
A	1.48	1.45	1.01	-0.03	0.44
B	0.82	1.41	1.72	0.59	0.31
C	1.35	1.21	1.40	-0.14	0.19
D	1.23	1.38	1.34	0.15	-0.04

Note: L1, L2 and L3 represent levels 1, 2 and 3 respectively

Table 9: *Average values of S/N data (SR) at different levels*

Process parameter designation	Average values, MRR			Main effects, MRR	
	L1	L2	L3	L2-L1	L3-L2
A	-2.99	-2.88	0.19	0.11	3.07
B	1.75	-2.94	-4.50	-4.69	-1.56
C	-2.17	1.47	-2.06	3.64	-3.53
D	-1.65	-1.97	-2.07	-0.32	-0.10

Note: L1, L2 and L3 represent levels 1, 2 and 3 respectively

Consequently, uniform erosion (shallow craters) takes place on the workpiece surface. This results in improvement in surface finish. Another observation from this figure is that the increase in peak current increases the SR. This may be due to that the energy per pulse expended in the spark gap region will increases. A high discharge energy associated with high current is capable of removing a chunk of material leading to the formation of deep and wide craters. The pulse duration is another factor that also shows the variation in mean and S/N ratio. The SR decreases with increase in pulse duration, reaches the minimum value at 100μs pulse duration. Further increase in pulse duration increases the SR. The reason is similar to that explained in the case of MRR. The optimum SR can

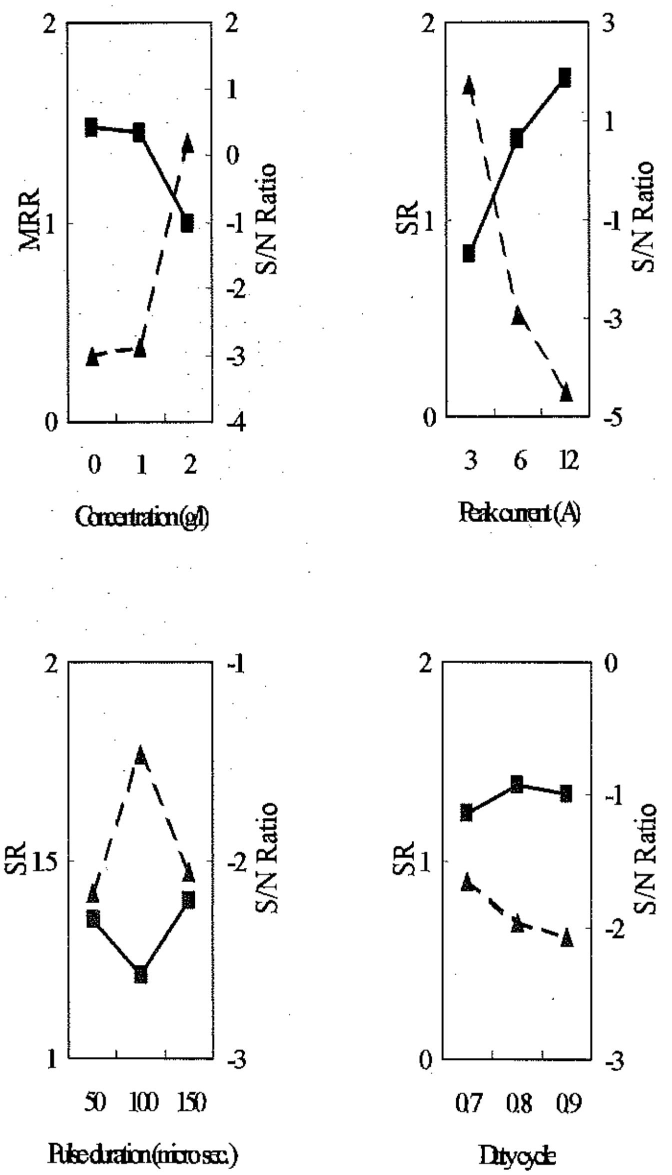


Figure 6: *The effect of process parameters on SR and S/N data (▪- Mean SR; ▲—S/N ratio)*

be produced at minimum level of duty cycle. The reason behind this is that at high duty cycle, there are chances of short-circuiting because of shorter time period available for deionization of dielectric fluid.

Figure 6 indicates that all the parameters A, B, C and D affect both the mean and the variation in S/N ratio. The 3rd level parameter A (A_3), 1st level of parameter B (B_1), 2nd level of parameter C (C_2) and 1st level of parameter D may provide minimum SR. It may be further noticed from this figure that in the case of parameters A, B, C and D, the highest values of the mean response corresponds to the highest values of S/N ratio.

The pooled ANOVA for raw data of SR and S/N data is given in Tables 10 and 11 respectively. These Tables indicate that the parameters A, B, and C significantly affect both the mean value and the S/N ratio. The percentage contribution of parameters indicates that A and B are highly significant parameters in controlling the mean values of SR and S/N ratio. The other parameters are almost equally significant.

Table 10: *Pooled analysis of variance (ANOVA) for raw data (SR)*

Source	D.O.F	SS	V	SS'	F ratio	P (%)
A	2	0.43	0.22	0.40	22.00	22.73
B	2	1.24	0.62	1.21	62.00	68.75
C	2	0.05	0.02	0.02	2.00	1.14
D	(2)	(0.03)	Pooled			
Error	2	0.03	0.01			6.82
Total	8	1.76	0.22			100

Note: SS' = Sum of squares due to the sole factor eliminating the effect of error
V = Variance; P = Percentage contribution; F = Fisher test factor

Table 11: *Pooled analysis of variance (ANOVA) for S/N ratio (SR)*

Source	D.O.F	SS	V	SS'	F ratio	P (%)
A	2	19.81	9.90	19.53	70.71	23.10
B	2	63.58	31.79	63.30	227.07	74.88
C	2	0.85	0.43	0.57	3.07	0.67
D	(2)	(0.28)	Pooled			
Error	2	0.28	0.14			1.33
Total	8	84.54	10.56			100

Note: SS' = Sum of squares due to the sole factor eliminating the effect of error
V = Variance; P = Percentage contribution; F = Fisher test factor

7. Optimum performance predictions

Based on the objective of the process performance under study, the mean and S/N ratios for each run are found for MRR and SR. Although S/N ratio is more objective towards the target, the physical meaning of the S/N ratio (in dB) is not as straightforward as the simple mean (raw data). Therefore, the prediction of the performance at optimum conditions is done based on mean data.

The optimum value of MRR and SR are predicted at selected levels of significant parameters. The estimated mean of the response characteristics (MRR, SR) can be computed as follows [14-15]:

Y_{opt} = Average performance of response + Contribution of significant factors to response at optimum level

Where, Y_{opt} is the optimum value of response (MRR, SR). for MRR,

$$MRR_{opt} = \bar{T} + (\bar{A}_3 - \bar{T}) + (\bar{B}_3 - \bar{T}) + (\bar{C}_2 - \bar{T}) \quad (4)$$

where, $\bar{T}$ = average of the results for MRR (Table 3). $\bar{A}_3$ is average value of MRR at third level of silicon powder concentration. $\bar{B}_3$ is average value of MRR at third level of peak current and $\bar{C}_2$ is average value of MRR at second level of pulse duration (Table 4).

Here,

$$\bar{T} = \frac{11.47}{9} = 1.27,\ \bar{A}_3 = 1.81, \bar{B}_3 = 2.14, \bar{C}_2 = 1.48$$

Substituting the values of various terms in equation (4).

$$MRR_{opt} = 1.27 + 0.54 + 0.87 + 0.21$$
$$= 2.89\ mm^3/min$$

Similarly, the estimation of optimum SR is done using the data from Table 8. The estimated average value at the optimum conditions for SR is 0.4μm (As indicated in the following).

Estimation of optimum value for SR [14-15]:

$$SR_{opt} = \bar{T} + (\bar{A}_3 - \bar{T}) + (\bar{B}_1 - \bar{T}) + (\bar{C}_2 - \bar{T})$$

$$= \bar{A}_3 + \bar{B}_1 + \bar{C}_2 - 2\bar{T}$$

where, $\bar{T}$ = average of the results for SR (Table 3). $\bar{A}_3$ is average value of SR at third level of silicon powder concentration. $\bar{B}_1$ is average value of SR at first level of peak current and $\bar{C}_2$ is average value of SR at second level of pulse duration (Table 8).

Substituting the values of various terms in above equation from Table 8.

$$SR_{opt} = 1.01 + 0.82 + 1.21 - 2 \times 1.32$$
$$= 0.4\mu m.$$

8. Confidence Interval around the Estimated Mean of response

The confidence interval of conformation experiments (CI_{CE}) and of population (CI_{POP}) were computed by using the following expression [14-15]:

$$CI_{CE} = \pm\sqrt{F_{\alpha}(1, f_e) \times V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad (5)$$

$$CI_{POP} = \pm\sqrt{\frac{F_{\alpha}\ (1,\ f_e)\times V_e}{n_{eff}}} \qquad (6)$$

where, $F_{\alpha}\ (1,\ f_e)$ is the F-ratio at a confidence level of (1- α) against DOF one and error degree of freedom f_e. Here, f_e = 2 and the error variance risk, V_e = 0.10 (from Table 6); with

$$n_{eff} = \frac{N}{1+\begin{pmatrix} d.o.f.\ of\ all\ factors\ used \\ in\ the\ estimate\ of\ mean \end{pmatrix}} \qquad (7)$$

where, N (number of trials) = 9,
R (number of repetitions) = 3,
n_{eff} = 1.28 (calculated), and
$F_{0.05}$ (1, 2) = 18.51 (tabulated f-value).

From equations (5) and (6), CI_{CE} = ± 1.43 and CI_{POP} = ± 1.20. The predicted optimal range for the confirmation run of three experiments is:

Mean MRR - CI_{CE} < MRR < mean MRR + CI_{CE}
or
1.46 mm^3/min. < MRR < 4.32 mm^3/min.

The 95% confidence interval of the predicted mean is

1.69 mm^3/min. <MRR < 4.09 mm^3/min.

Similarly, the confidence interval around the estimated mean for SR is

Mean SR - CI_{CE} < SR < mean SR + CI_{CE}
or
0μm < SR < 0.8μm

The 95% confidence interval of the predicted mean is

0.04μm <SR < 0.76μm

To verify the obtained optimum performance of PMEDM process in terms of MRR and SR, three confirmation experiments were conducted at the optimum setting of the process parameters. The average MRR and SR value was found to be 2.80 mm^3/min and 0.44μm, which falls within the confidence interval of the predicted optimum of MRR and SR respectively.

9. Conclusions

Based on the experiments performed on a newly developed experimental setup for the PMEDM process, the following conclusions can be drawn:

1. The concentration of added silicon powder, peak current and pulse duration significantly affect the MRR and SR in PMEDM.
2. Concentration of added silicon powder and peak current are the most influential parameters on MRR and SR. The addition of appropriate amount of silicon powder into the dielectric fluid of EDM enhances the material erosion rate.
3. For maximum MRR, the recommended optimal parameter combination is A_3, B_3, C_2, D_1 and for minimum surface roughness, the recommended parameter combination is A_3, B_1, C_2, D_1.
4. The predicted optimal range (for confirmation run of three experiments) for MRR and SR is given by 1.46 < MRR < 4.32 mm^3/min. and 0 < SR < 0.8 μm respectively.
5. The 95% confidence interval of the predicted mean for MRR and SR is 1.69 <MRR < 4.09 mm^3/min and 0.04 <SR < 0.76 μm respectively.
6. The confirmation tests showed that the average values of MRR and SR fall within the confidence interval of the predicted optimum MRR and SR respectively.

Acknowledgements
The authors would like to thank the support of department of Mechanical Engineering,

SLIET, Longowal, India and M/S Electronica Machine Tools Ltd. Pune, India. We are thankful to Mr. Kulwinder Singh deptt. of Mech. Engg; SLIET, Longowal. We are also grateful to Prof. P.L. Bali, LIET, Jalandhar and Er. Baljit Singh, PSEB for their guidance and expert comments in response to our queries and problems.

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