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Research Article

Investigation and Modeling of Silicon Powder Mixed EDM using Response Surface Method

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Abstract

Electrical Discharge Machining (EDM) is a thermo-electric process which widely used in the manufacturing process for tool mould and die industries. Mechanism of EDM process is complex and difficult to understand. So, establishing a comprehensive model to predict the performance by correlating the process parameters is a difficult work. In the present work, a Central Composite Design (CCD) for combination of variables and Response Surface Method (RSM) have been used to explore the influence of process parameter such as; peak current, powder concentration and tool diameter on the Material Removal Rate (MRR) on EN-8 steel. Analysis Of Variance (ANOVA) at 95% level of significance was performed to obtain the significant coefficients. Significant process parameters have been identified and optimum process conditions have been obtained. A confirmation experiments has been conducted and verified optimal conditions. Percentage errors of predicted and actual values for developed models was found within 5%.

Keywords: *EDM, PMEDM, MRR, Silicon Powder, ANOVA, RSM*

1. Introduction

EDM is a thermo-electric process in which material removal takes place through the process of controlled spark generation. It is widely used to machine hard and electrically conductive materials for making of mould, die, automotive, aerospace and surgical components (Ho and Newman, 2003). EDM does not make direct contact between the tool and workpiece. So, it can be employed to machine thin and fragile components by eliminating mechanical stresses and vibration problems during machining (Pandey & Shan, 1980). Powder Mixed EDM (PMEDM) has one of the newly developed advanced techniques by mixing suitable powder like aluminum, chromium, graphite, copper, silicon or silicon carbide etc. into the dielectric fluid of EDM (Zhao et al, 2005), (Kansal et al, 2005). The powder particles in the spark gap get energized and accelerated in a zigzag fashion and help to increase the spark gap between tool and the workpiece. Under the sparking area, the particles come closer and form a clusters structures between both the electrodes (Kansal et al, 2005). The interlocking between the different powder particles takes place in the direction of current flow. This cluster chain formation helps in bridging the discharge gap between electrodes thus decreasing the insulating strength of the dielectric fluid and increases the spark gap distance between the tool electrode and workpiece (Mohri et al, 1919), (Wong et al, 1989). The schematic diagram of principle of PMEDM is shown in Fig 1.

Due to bridging effect, the insulating strength of the dielectric fluid decreases and easy short circuit takes place, which causes early explosion in the gap. As a result, a 'series discharge' starts under the electrode area causing faster erosion from the workpiece surface thereby improving material removal rate (MRR). The added powder modifies the plasma channel between tool and workpiece. The plasma channel becomes enlarged and widened (Zhao et al, 2005). The sparking among the powder particles is uniformly distributed, hence electric density of the spark decreases. Consequently, uniform erosion (shallow craters) occurs on the workpiece surface, hence improvement in surface finish at better machining rates.

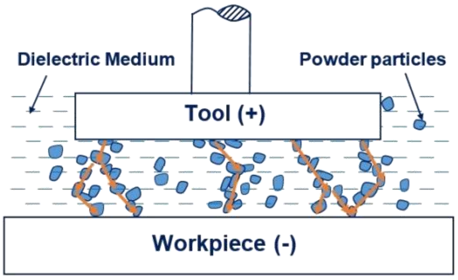

Fig. 1 Principle of powder mixed EDM

First PMED has investigated in the year 1980 by Erden and Bilgin to study the effect of powder particles (copper,

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aluminum, iron and carbon) mixed into dielectric fluid (kerosene) of EDM to MRR. They observed that MRR increases with increase in the concentration of powder and also concluded that at excessive powder concentration machining becomes unstable due to occurrence of short circuits.

In PMEDM, machining process stability was improved 60% in MRR and tool wear ratio decreased by 15% by using the kerosene oil mixed with 4 g/l graphite powder (Jeswani, 1981). Experimental comparison on the near-mirror-finish phenomenon using graphite, silicon (Si), aluminium (Al), crushed glass, silicon carbide (SiC) and molybdenum sulphide powder with different grain size was carried out to obtain near-mirror-finish (Wong et al., 1989). It was reported that Al powder has better finishing for SKH-51 work pieces, but not on SKH-54 work pieces. To produce superior surface finish, it is important to know the correct combination of powder and work piece materials. EDM process by adding SiC and aluminum powders into kerosene was carried out for the micro-slit machining of titanium alloy for better material removal (Chow et al, 2000). SiC powder in kerosene could give better material removal depth than Al powder. PMEDM machining can clearly improve machining efficiency at the same time surface roughness by selecting proper discharging parameters (Zhao et al, 2002). The size, density, electrical resistivity, concentration and thermal conductivity of Al, Cr, Cu and SiC powders significantly affected the machining performance (Tzeng and Lee, 2001). The smallest size of the particle led to highest MRR for a fixed concentration. The silicon powder positively influenced the reduction of the operating time and also helped to achieve a specific surface quality allowing the generation of mirror-like surfaces (Pecas and Henriques, 2003).

The response surface methodology was used to identify and optimize the most important parameters of PMEDM for maximum material removal rate and minimum surface roughness (Kansal et al, 2005). The concentration of added silicon powder, peak current and pulse duration significantly affect the MRR and SR in PMEDM (Kansal et al, 2007). A study on the effect of Nickel Micro Powder Suspended Dielectric on EDM Performance of EN-19 Steel was carried out and observed that MRR and TWR shows increasing trend for increase in powder concentration up to a maximum limit (Ojha et al, 2011).

From the literature it is revealed that material removal mechanism of PMEDM process is very complex and theoretical modeling of the process is very difficult. In present research work, a prediction model of PMEDM on MRR has been developed. A Central Composite Design (CCD) for combination of variables and Response Surface Method (RSM) have been used to analyze the effect of these three process parameters like Peak Current, Powder Concentration and Tool Diameter on the performance of PMEDM process.

2. Experimental Setup

The experiments were conducted on an Electric Discharge Machine, Savita-Economy (India makes). To conduct experiments a separate dielectric re-circulating system was fabricated and attached to the machine table. Commercial kerosene has been chosen as dielectric fluid. To avoid filtering of powder particles, the powder should not go into the main dielectric tank. Experiment have been conducted by choosing EN-8 steel material as workpiece. Commercial copper with 99% purity is used as tool electrode. The chemical properties of copper tool and EN-8 steel workpiece have been shown in Table 1.

For mixing Silicon powder of 300 mesh size to kerosene dielectric, a small tank made of thin mild steel sheet was placed in the main machining tank to isolate it from the filtering system of the machine. A stirrer was provided the tank to prevent settling and to maintain uniform concentration of the powder in the dielectric throughout the machining cycle. Levels for various process parameters and their selected levels are shown in Table 2. The selected response variables for this study are the MRR and TWR.

Table 1 Chemical properties of copper and EN-8 Steel

Material	Copper	EN-8 Steel
Composition	Copper (99%)	(C + Si + Mn + S + P) = 0.40 + 0.25 + 0.80 + 0.05 +0.05
Hardness	40 BHN	255 BHN
Density	8.90 g/cm^3	7.8 g/cm^3
Melting Point	1083 ^{0}C	1370 ^{0}C

Table 2 Process parameters and their levels

Factors	Unit	Levels		
		-1	0	+1
Peak Current	A	170	190	210
Powder Concentration	gm/l	2	4	6
Tool Diameter	mm	8	10	12

The experimental plans were designed on the basis of the central composite design (CCD) technique of RSM by using Design Expert Software (DOE). In this study, the experimental plan was conducted using face-centered CCD and involved a total of 20 experimental observations at three independent input variables. The machining time for each experimental specimen is 15 min. Experimental settings for the study is shown in table 3.

Table 3 Experimental Machine Setting

Polarity	Discharge Current	Duty Factor	Gap Voltage	Machining time
Straight	15 A	70%	60 V	15 min

Actual amount of material removed and tool wear during EDM is calculated by weight loss method as given in equations 1 & 2 respectively

$$\mathrm{MRR} = \frac{[\text{workpiece weight loss in gms] X 1000}}{\left[\text{Density in}\frac{\text{gm}}{\text{cc}}\right]\text{x[Machining time in mins]}} \quad \text{---- 1}$$

$$\mathrm{TWR} = \frac{[\text{Tool weight loss in gms] X 1000}}{\left[\text{Density in}\frac{\text{gm}}{\text{cc}}\right]\text{x[Machining time in mins]}} \quad \text{---- 2}$$

2.1. Experimental design

RSM is a collection of mathematical and statistical procedures that are useful for the modelling and analysis of problems in which response of demand is affected by several variables and the objective is to optimize the response. In statistics, RSM explores the relationships between several explanatory variables and one or more responses. The RSM is to use a set of designed experiments to obtain an optimal response. RSM uses the model to make contour plots of predicted behaviour. Using these plots one can actually predict the best combination of factors to meet experimental goals.

The RSM is an empirical modelling approach for determining the relationship between various process parameters and responses with the various desired criteria and searching the significance of these process parameters on the coupled responses (Myers and Montgomery, 1995). Design Expert 8.0.4 software was used for design of experiments, and regression and graphical analysis of data to obtain the optimum conditions

The relationship between desired responses and independent process parameters in RSM can be represented as:

$$Y= f(X_1, X_2, X_3, \ldots\ldots\ldots\ldots X_n)$$

where Y is the desired response, f is the response function and X_1, X_2 ... are independent parameters. Response surface is obtained by plotting the expected responses. RSM aims at approximating f by using the fitted second order polynomial regression model which is called the quadratic model. The quadratic model can be represented as follows:

$$Y = C_O + \sum_{i=1}^{n} C_i X_i + \sum_{i=1}^{n} d_i {X_i}^2 + €$$

3. Results and Analysis

Twenty experimental runs have been conducted and values of MRR and TWR along with design matrix are given in Table 4. Analysis of variance (ANOVA) is performed on collected data for testing significance of regression model and model coefficients.

The fit summary for MRR is shown in table 5. It is clearly recommended quadratic model as statically significant for MRR analysis. The Model F-value of 6.01 implies the model is significant. There is only a 0.67% chance that a "Model F-Value" this large could occur due to noise Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. From Table 6, it was observed that Powder concentration (B) has shown the most significant factor affecting the MRR. The "Lack of Fit F-value" of 4.72 implies there is a 7.90% chance that a "Lack of Fit F-value" this large could occur due to noise. Lack of fit is bad, hence require the model to fit. This relatively low probabiity (<10%) is troubling.

Table 4 Process parameters and their levels

Std	Block	A:A	B:B	C:C	**MRR** (mm^3/min)
1	Block 1	170	2	8	3.506
2	Block 1	210	2	8	5.785
3	Block 1	170	6	8	5.853
4	Block 1	210	6	8	10.693
5	Block 1	170	2	12	6.380
6	Block 1	210	2	12	8.345
7	Block 1	170	6	12	7.874
8	Block 1	210	6	12	11.058
9	Block 1	190	4	10	4.960
10	Block 1	190	4	10	4.977
11	Block 1	190	4	10	4.498
12	Block 1	190	4	10	4.757
13	Block 2	156.364	4	10	6.224
14	Block 2	223.636	4	10	6.233
15	Block 2	190	0.6364	10	9.546
16	Block 2	190	7.3636	10	10.563
17	Block 2	190	4	6.636	4.813
18	Block 2	190	4	13.364	7.828
19	Block 2	190	4	10	6.050
20	Block 2	190	4	10	4.087

Table 5: Fit summary for MRR

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Mean vs Total	898.2246	1	898.2246			Suggested
Block vs Mean	0.623325	1	0.623325			
Linear vs Block	35.91942	3	11.97314	2.784198	0.0769	
2FI vs Linear	3.432847	3	1.144282	0.224836	0.8773	
Quadratic vs 2FI	46.75069	3	15.58356	9.792562	0.0034	Suggested
Cubic vs Quadratic	12.24534	4	3.061334	7.369712	0.0251	Aliased
Residual	2.07697	5	0.415394			
Total	999.2732	20	49.96366			

Table 6 ANOVA table for MRR (before backward elimination)

Source	Sum of Squares	DF	Mean Square	F Value	p-value Prob > F	
Block	0.623325	1	0.623325			
Model	86.10296	9	9.566995	6.011808	0.0067	significant
A-A	11.0471	1	11.0471	6.941889	0.0271	
B-B	12.70616	1	12.70616	7.984429	0.0199	
C-C	12.16616	1	12.16616	7.645096	0.0219	
AB	1.785596	1	1.785596	1.122052	0.3171	
AC	0.485231	1	0.485231	0.304914	0.5943	
BC	1.16202	1	1.16202	0.730202	0.4150	
A^2	2.482412	1	2.482412	1.559924	0.2432	
B^2	45.01221	1	45.01221	28.28524	0.0005	
C^2	2.887689	1	2.887689	1.814596	0.2109	
Residual	14.32231	9	1.591368			
Lack of Fit	12.24582	5	2.449164	4.717904	0.0790	not significant
Pure Error	2.076485	4	0.519121			
Cor Total	101.0486	19				

Table 7 ANOVA table for MRR (after backward elimination)

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Block	0.623325	1	0.623325			
Model	77.78665	4	19.44666	12.02606	0.0002	significant
A-A	11.0471	1	11.0471	6.831663	0.0204	
B-B	12.70616	1	12.70616	7.857649	0.0141	
C-C	12.16616	1	12.16616	7.523704	0.0159	
B^2	41.86724	1	41.86724	25.89122	0.0002	
Residual	22.63861	14	1.617044			
Lack of Fit	20.56213	10	2.056213	3.960948	0.0984	not significant
Pure Error	2.076485	4	0.519121			
Cor Total	101.0486	19				

Std. Dev.	1.27	R-Squared	0.7746
Mean	6.70	Adj R-Squared	0.7102
C.V. %	18.98	Pred R-Squared	0.5775
PRESS	62.52	Adeq Precision	11.469

The improvement of the model can be done by reducing the insignificant model terms (not counting those required to support hierarchy), To fit the quadratic model for MRR appropriate, the non-significant terms are eliminated by backward elimination process.

After eliminating the non-significant factors (Table 7), the adjusted R^2-squared (Adj R^2-squared) is greater than 0.7 as part of the conditions for model adequacy. Further checking on the model adequacy is that the difference between adjusted R^2-squared and predicted R^2-squared is less than 0.2 and models adequate precision is 11.469 (which is greater than 4) also indicates that the model is adequate.

Fig. 2 shows the normal probability plot residuals for MRR. It is observed that the residuals are falling on a straight line, which means that the errors are normally distributed. Thus, the regression model is fairly well fitted with the observed values.

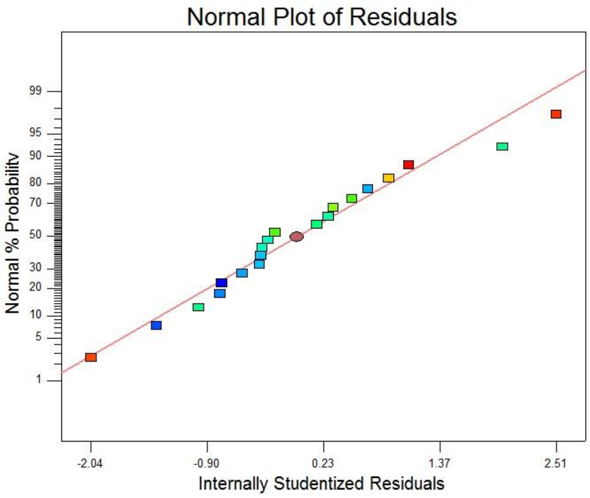

Fig. 2 Normal probability plot residuals for MRR

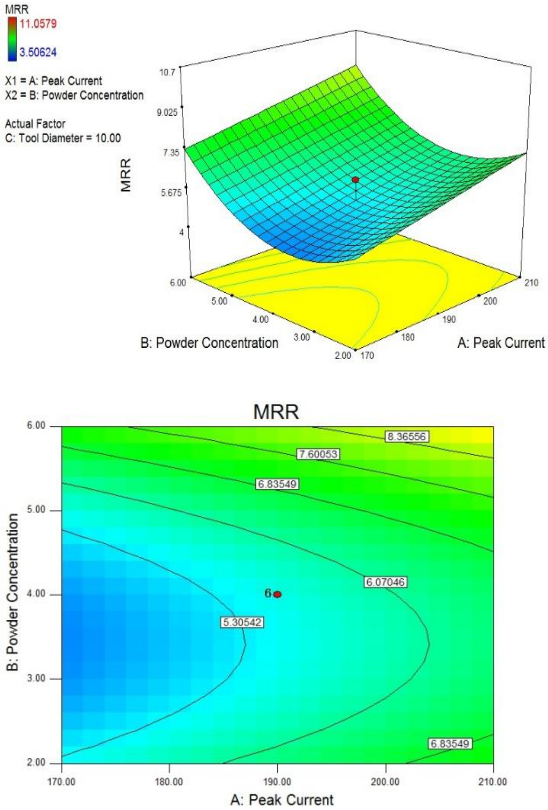

Fig. 3 3D surface and contour plot for MRR

After eliminating the non-significant factors, the final response equation for MRR is found as follows:

Final equation in terms of coded factors:

$$MRR = +5.58 + 0.90A + 0.96B + 0.94C + 1.69B^2$$

Final Equation in Terms of Actual Factors:

$$MRR = -2.85729 + 0.044970 \times \text{Peak Current} - 2.89682 \times \text{Powder Concentration} + 0.47192 \times \text{Tool Diameter} + 0.42239 \times \text{Powder Concentration}^2$$

Fig. 3 shows the 3D surface and contour plot for MRR. The model indicates that the MRR increases with increase in Peak Current and Powder Concentration.

4. Confirmation test

In order to verify the adequacy of the models developed, confirmation experiments were carried out to validate the models developed for MRR.

Table 8 Confirmation test table for MRR

Runs	Parameter Setting			MRR		
	A	B	C	Exp.	Pred.	Pred. Error (%)
1	190	3	9	4.743	4.985	4.85%
2	200	6	10	7.446	7.862	5.29%
3	180	4	9	4.112	4.334	4.94%

This was carried out by using the models to predict the response at a particular point. The results of the confirmation test for MRR is presented in Table 8.

It can be observed that the calculated prediction error is small and tolerable. The prediction error for MRR is within ±5.5 %. This confirms excellent reproducibility of the experimental conclusions.

Conclusions

In this study, quantitative analysis of machinability of EN-8 steel in PMEDM process has been carried out by mixing Silicon powder in the dielectric medium. MRR model was developed using response surface method for three different parameters namely Peak Current, Powder Concentration and Tool diameter of the electrode. Analysis of variance was performed to validate the second-order response models. It is found that powder concentration have more significant effect on MRR. The adequacy of the developed models was checked by performing confirmation runs. The variation in prediction errors for MRR was found within ±5.5%. It can be concluded that the model is valid to predict the machining responses within the experimental region.

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