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Effect of Powder-Mixed Dielectric on EDM Process Performance

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ABSTRACT

Electrical Discharge Machining (EDM) is extensively used to manufacture different conductive materials, including difficult to machine materials with intricate profiles. Powder Mixed Electro-Discharge Machining (PMEDM) is a modern innovation in promoting the capabilities of conventional EDM. In this process, suitable materials in fine powder form are mixed in the dielectric fluid. An equal percentage of graphite and silicon carbide powders have been mixed together with the transformer oil and used as the dielectric media in this work. The aim of this study is to investigate the effect of some process parameters such as peak current, pulse-on time, and powder concentration of machining High-speed steel (HSS)/(M2) on the material removal rate (MRR), tool wear rate (TWR) and the surface roughness (Ra). Experiments have been designed and analyzed using Response Surface Methodology (RSM) approach by adopting a face-centered central composite design (FCCD). It is found that added graphite-silicon carbide mixing powder to the dielectric fluid enhanced the MRR and Ra as well as reduced the TWR at various conditions. Maximum MRR was (0.492 g/min) obtained at a peak current of (24 A), pulse on (100 µs), and powder concentration (10 g/l), minimum TWR was (0.00126 g/min) at (10 A, 100 µs, and 10 g/l), and better Ra was (3.51 µm) at (10 A, 50 µs, and 10 g/l).

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1. Introduction

Electro-discharge machining is widely used amongst nontraditional machining used for processing tool mold, medical devices, injector nozzles and die industries. The applications of this process increased due to its ability to machine materials regardless of their hardness and its ability to produce geometrically complex shapes [1]. In recent years, researchers have highlighted increasing EDM machining performance with innovative methods [2]. Among these methods, powder mixed EDM is one of the effective techniques for promoting the capabilities of conventional EDM by improving the material removal rate and surface roughness as both of these responses are mainly considered by the industries [3]. In PMEDM, appropriate materials in fine powder form such as (Graphite, Iron, Aluminum, Titanium, Silicon, Copper, Chromium or Alumina, etc.) are mixed with the dielectric fluid, that decreases the insulating capability of the dielectric and enlarges the spark gap distance among the electrodes to uniformly diffuse the electric discharge in all directions. As a result, the process becomes more effective and thus improves MRR and surface quality [4-6]. Figure 1 shows the principle of powder-mixed EDM [5].

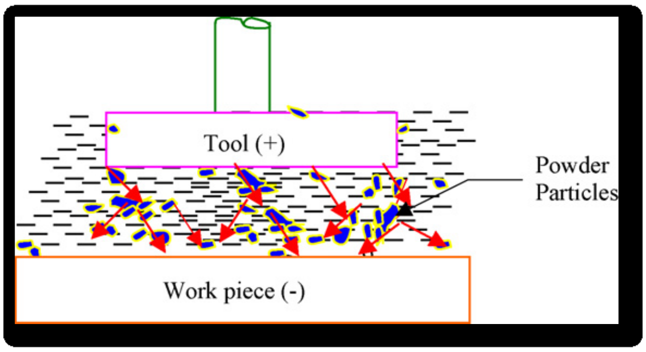

Figure 1: Principle of Powder-Mixed EDM [5].

Extensive studies concerning the PMEDM and its optimization are available. Some of the most relevant are listed as a continuation. Erden and Bilgin [7] were the first to introduce the concept of Powder-mixed EDM (PMEDM), they studied the influence of carbon, aluminum, copper, and iron powders mixed in dielectric fluid and conducted improved machining rates and reduced time-lags when the concentration of powders increased in the gap space also reducing the insulation strength of dielectric. Kung et al. [8] made a study under finishing conditions of low-level peak current less than 3 A. The authors analyzed the effect of the concentration of aluminum powder particle, peak current, pulse on time, and grain size on MRR and EWR during the powder-mixed EDM of cobalt-bonded tungsten carbide (WC–Co). Response the surface methodology (RSM) was adopted to plan and analyze the experiments. nevertheless, surface finish criterion, the dominant response of PMEDM application, has not been involved to be considered in this study. Sharma et al. [9] studied the effect of concentration and grain size of aluminum powder on the machining performance, namely material removal rate, tool wear rate, percentage wear rate, and surface roughness, of conventional EDM with reverse polarity. It is concluded experimentally, with the increase in the concentration and changes in the grain size of the powder, the surface roughness, and percentage wear rate decreases continuously, on the other hand, the material removal rate and the tool wear rate increases. Assarzadeh and Ghoreishi [10] demonstrated an effort for modeling and optimizing the input parameters effected on Aluminum oxide (Al_2O_3) powder mixed electro-discharge machining using CK45 heat-treated die steel workpiece and tool electrode of commercial copper. Planned experiments used response surface methodology (RSM). three of the main input parameters (discharge current, pulse-on time, and source voltage) were discussed on MRR and Ra. The results are sets of optimum points that keep the Ra and all machining parameters in their specified ranges and make the MRR as high as possible simultaneously. Rathi and Mane [11] discussed the influence of powder mixed EDM of Inconel 718. The selected machining parameters were current, pulse on time, duty cycles, and powder media (SiC, Al_2O_3, C). Optimization is carried out by (S/N) ratio analysis of the Taguchi method. ANOVA is used to present the effect of process parameters on (MRR) and (TWR). The maximum MRR is obtained at Ip of 18 A, Pon of 5 µs, a duty cycle of 85%, and Graphite as powder media. Low TWR is achieved at Ip of 12 A, Pon of 20 µs, the duty cycle of 90%, and SiC as powder media. Kolli and Kumar [12] focused on optimizing the process parameters such as discharge current, powder, and surfactant concentration mixed in the dielectric when machining Ti-6Al-4V using the Taguchi method. They concluded that when mixed the Graphite powder and surfactant with dielectric fluid can be enhanced the MRR and reduce the EWR, Ra, and RLT at various conditions. Mohanty et al. [13] Conducted a study of the use of Al_2O_3 Nano-powders in EDM process, a copper electrode with 12mm diameter was chosen to machining (AlSiCP12%) metal matrix composite. Pulse on time (30, 60, 90) µs, pulse off time (10, 15, 30) µs, low voltage current (6, 12, 18) A, high voltage current (1, 1.5, 2) A, and flushing pressure (0.2, 0.4, 0.6) kg/m2 were the process parameters on which process performance like MRR, EWR, Ra had been analyzed. RSM with Box Behnken design was adopted to conduct the experiment layout. Results showed that the use of powder had been improved MRR and Ra. Experimental values and predictive results showed good compatibility with each other in low percentage error. Surekha et al. [14] have analyzed the effect of aluminum PMEDM input parameters, namely peak current (6, 8, 10) A, gap voltage (40, 50, 60) V, pulse-on-time (50, 75, 100) µs, and concentration of powder (2, 4, 6) g/l on MRR and TWR of machining EN-19 alloy steel by using brass metal as an electrode. Response surface modeling, adopted central composite design, had been employed to conduct the experiments and established the Non-linear models that represent the MRR and TWR. They concluded when the input parameters changed from their lower-level to higher-level, the TWR value had been raised by more than 50% which is not desirable. Max. MRR was (0.0266 g/min) attained at (IP=10 A, CP=6 g/l, V=60 V, and Ton=100 µs) and Min. TWR was (0.0079 g/min) achieved at (IP=6 A, CP=6 g/l, V=60 V, and Ton=50 µs).

This paper attempted to study the effect of added the powder mixture of Graphite (50%) and Silicon Carbide (50%) with different concentrations of transformer oil. Material Removal Rate, Tool Wear Rate, and Surface Roughness are selected as response parameters to measure the EDM and PMEDM process performance. Response surface methodology (RSM) has been used for modeling and predict the process performance as well as analyzed them by ANOVA to find the most significant factors for each response.

2. Experimental work

The selected M2 High-Speed Steel work piece and the copper (Cu) electrode materials was firstly tested for chemical composition of the central organization for standardization and quality control / Ministry of Planning / Iraq and according to ASTM E415 standard, the results are listed in Tables 1 and 2 respectively.

Table 1: Chemical Composition of M2 High-Speed Steel (HSS).

Element	C%	Mo%	Cu%	Cr%	Si%	S%	P%	Mn%
Weight %	0.855	5.83	0.175	4.71	0.305	< 0.001	< 0.001	0.28
Element	Ni%	Ti%	Al%	W%	Co%	Sn%	V%	Fe%
Weight %	0.14	< 0.0005	< 0.005	5.73	0.045	< 0.001	1.88	Rem.

Table 2: Chemical Composition of Cu Electrode.

Element	Zn%	Pb%	Sn%	P%	Mn%	Fe%	Ni%	Si%	Cr%
Weight %	0.0001	0.0005	0.0005	0.0001	0.0002	0.0091	0.0004	0.0373	0.0008
Element	Al%	S%	As%	Ag%	Co%	Bi%	Cd%	Sb%	Cu%
Weight %	0.0024	0.0001	0.0001	0.0024	0.0004	0.0001	0.0001	0.0017	Rem.

The hardness of the work piece was 62 HRC measured by the Rockwell hardness tester (Model HR-150A). The work piece was cut in square specimens with dimensions (25 x 25 x 3) mm by wire electrical discharge machining (WEDM) as shown in Figure 2.

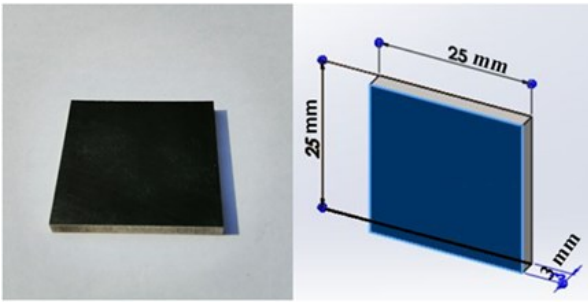

Figure 2: The work piece after cutting by wire EDM and before machining.

The copper electrode was manufactured with a rectangular cross-section of 6×40 mm and 70mm lengths as shown in Figure 3.

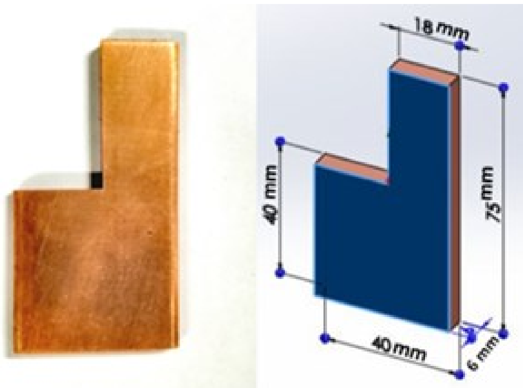

Figure 3: The copper electrode used as a positive pole.

Experiments were done on a CHEMER EDM machine, which is placed at the University of Technology/ Baghdad, shown in Figure 4.

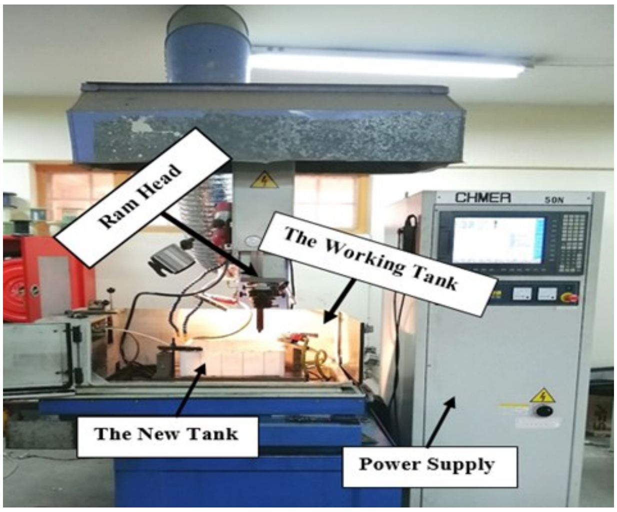

Figure 4: CHEMER EDM machine component.

The dimensions of the working tank of the CHEMER EDM machine, which contains the dielectric fluid, are (820×500×300) mm. A large amount of dielectric fluid should be available to fill the working tank with these dimensions. Hence, a large amount of powder is required to get the desired amount of powder concentration within the dielectric fluid. So a new tank with a capacity of 8 liters of the dielectric was developed to avoid this problem. Experiments were performed in the new tank filled with the powder mixture of Graphite-Silicon Carbide with the transformer oil and placed in the empty working tank. A small pump was placed inside the new tank to isolate the powder-mixed internally in order to avoid deposition of the powder at the bottom of the tank or accumulating overhead the dielectric surface. The viscosity of the transformer oil dielectric was (28.01 Pa.s) tested at 23oC in the department laboratories and the particle size of both powders Graphite (Gr) and Silicon Carbide (SiC) was (~ 1-2 µm) which examined in the Nanotechnology and Advanced Materials Research Center at University of Technology. The initial and final weight of the work piece and the electrode are measured before and after machining by using the electronic weighing balance with an accuracy of (0.0001g). The surface roughness for each work piece was measured after PMEDM machining by using the portable surface roughness tester with an accuracy of (± 0.05) µm.

3. Design of experiments

The aim of this study is to investigate the influence of powder-mixed dielectric on MRR, TWR, and Ra by selecting different input machining parameters. RSM is an effective statistical and mathematical technique that finding a quantitative formula for the relationship amongst the input and output parameters [15]. The mathematical model is established for predicting the responses, where it explains the correlation between the input parameters and response. The system behaviour is clarified employing the quadratic polynomial equation as follows [16].

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i=0}^{k-1} \sum_{j=2}^{k} \beta_{ij} X_i X_j \quad (1)$$

Three input parameters with three levels for each parameter were selected in this study as shown in Table 3. Whereas Table 4 illustrates the fixed input machining parameters. In order to conduct the experiments, face-cantered central composite design (FCCD) matrices contained from the RSM approach have been employed. The experimental layout and response result are given in Table 5.

Table 3: Machining parameters and their Levels.

Parameters	Units	Levels		
		-1	0	1
Peak current (I_P)	Amp	10	14	24
Pulse-on time (P_{on})	µsec	50	75	100
Powder concentration (C_P)	g/l	0	5	10

Table 4: Fixed input parameters.

Machining Parameters	Fixed values
Work piece polarity	Negative
Electrode polarity	Positive
Dielectric fluid	Transformer oil with Mixture powder of Gr+SiC
High voltage	140 V 1.2 A
Pulse-off time	25 µsec
Servo feed	75 %
Working time	5.0 sec
Jumping time	2.0 mm
Gap code	10
Depth of cut	1 mm

Table 5: Experimental layout and response result.

Run order	C_P g/l	I_P Amp	P_{on} µsec	MRR g/min	TWR g/min	Ra µm
1	0	10	50	0.1829	0.00519	4.535
2	10	10	50	0.190559	0.003397	3.51
3	0	24	50	0.4258	0.095516	5.479
4	10	24	50	0.469714	0.077619	4.311
5	0	10	100	0.1918	0.001928	4.59
6	10	10	100	0.224182	0.001259	3.602
7	0	24	100	0.4173	0.04695	5.947
8	10	24	100	0.492	0.025375	4.866
9	0	14	75	0.2647	0.011824	4.931
10	10	14	75	0.328474	0.007	4.382
11	5	10	75	0.223333	0.002815	3.987
12	5	24	75	0.464328	0.043522	5.479
13	5	14	50	0.27589	0.016128	4.449
14	5	14	100	0.332899	0.00364	5.133
15	5	14	75	0.312424	0.016667	5.01
16	5	14	75	0.277622	0.007784	4.69
17	5	14	75	0.303765	0.007865	4.894
18	5	14	75	0.319167	0.008833	4.815
19	5	14	75	0.277459	0.008722	5.129
20	5	14	75	0.303824	0.016667	4.989

4. Results and Discussion

Based on the experimental results obtained from Table 5, The effect of the process parameters (C_P), (I_P) and (P_{on}) on the three responses, namely MRR, TWR, and Ra were analyzed by analyses of variance (ANOVA) from RSM approach using MINITAB 17 software. Tables 6-8 illustrate the results of ANOVA backward elimination regression for MRR, TWR, and Ra, respectively. ANOVA was conducted to test the significance of the model. Values of "P-Value" less than 0.05 (95 % of confidence interval), indicate these model terms are statistically significant. Furthermore, the Lack-of-Fit term should be insignificant having a P-Value more than 0.05, which is desired[10].

Table 6: Results of ANOVA backward elimination regression for MRR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	0.168159	0.042040	139.15	0.000
Linear	3	0.164078	0.054693	181.03	0.000
C_P	1	0.004947	0.004947	16.38	0.001
I_P	1	0.157846	0.157846	522.46	0.000
P_{on}	1	0.001284	0.001284	4.25	0.047
Square	1	0.002925	0.002925	9.68	0.007
I_P*I_P	1	0.002925	0.002925	9.68	0.007
Error	15	0.004532	0.000302		
Lack-of-Fit	10	0.002978	0.000298	0.96	0.556
Pure Error	5	0.001554	0.000311		
Total	19	0.172691			
Model Summary	S	R-sq	R-sq(adj)	R-sq(pred)	
	0.0173817	97.38%	96.68%	95.07%	

Table 7: Results of ANOVA backward elimination regression for TWR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0.012520	0.002087	74.39	0.000
Linear	3	0.009436	0.003145	112.13	0.000
C_P	1	0.000256	0.000256	9.11	0.010
I_P	1	0.007529	0.007529	268.43	0.000
P_{on}	1	0.001651	0.001651	58.86	0.000
Square	1	0.000299	0.000299	10.67	0.006
I_P*I_P	1	0.000299	0.000299	10.67	0.006
2-Way Interaction	2	0.001394	0.000697	24.85	0.000
C_P*I_P	1	0.000183	0.000183	6.52	0.024
I_P*P_{on}	1	0.001211	0.001211	43.18	0.000
Error	13	0.000365	0.000028		
Lack-of-Fit	8	0.000270	0.000034	1.79	0.269
Pure Error	5	0.000094	0.000019		
Total	19	0.012885			
Model Summary	**S**	**R-sq**	**R-sq(adj)**	**R-sq(pred)**	
	0.0052962	97.17%	95.86%	92.17%	

Table 8: Results of ANOVA backward elimination regression for Ra.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	6.3139	1.57848	39.70	0.000
Linear	3	6.0899	2.02997	51.05	0.000
C_P	1	2.3146	2.31457	58.21	0.000
I_P	1	3.4316	3.43162	86.30	0.000
P_{on}	1	0.3437	0.34373	8.64	0.010
Square	1	0.9805	0.98052	24.66	0.000
I_P*I_P	1	0.9805	0.98052	24.66	0.000
Error	15	0.5965	0.03976		
Lack-of-Fit	10	0.4752	0.04752	1.96	0.237
Pure Error	5	0.1212	0.02425		
Total	19	6.9104			

Model Summary	S	R-sq	R-sq(adj)	R-sq(pred)
	0.199410	91.37%	89.07%	84.51%

Equations (2), (3), and (4) demonstrated the mathematical link among the process parameters and the responses MRR, TWR, and Ra, respectively, which obtained from nonlinear regression equation in RSM approach. These equations are employed to estimate the predicted values of these responses.

$$MRR = -0.1848 + 0.00445C_P + 0.03943I_P + 0.000453P_{on} - 0.000632I_P * I_P \quad (2)$$

$$TWR = -0.0434 + 0.001265\, C_P + 0.00290\, I_P + 0.000658\, P_{on} + 0.000202\, I_P * I_P - 0.000134\, C_P * I_P - 0.000069\, I_P * P_{on} \quad (3)$$

$$Ra = 0.357 - 0.0962\, \mathrm{C_P} + 0.4770\, \mathrm{I_P} + 0.00742\, P_{on} - 0.01157\, \mathrm{I_P} * \mathrm{I_P} \quad (4)$$

From the main effects plot and the surface plots of the material removal rate (MRR), which shown in Figures 5 and 6 respectively, it observed that the MRR improves with the increase in powder concentration (C_P) from 5 to 10 g/l compared with the low MRR for pure EDM with a concentration of 0 g/l. When the powder is mixed with the insulating dielectric, it becomes conductive and hence enhancement in sparking occurs that results in more material removal from the surface. Higher current (I_P) results in higher MRR This is due to the controlling of the input discharge energy when the current increase generates a strong spark that caused a higher temperature resulting in melting and evaporation of materials and the formation of craters on the workpiece. Similarly, with increases in Pulse-on time (P_{on}) from 50 to 100 µs the MRR increases moreover, this increase becomes more evident when the I_P value increased for the same reason. It can be noticed that the maximum MRR value is obtained at the higher levels of C_P, I_P, and P_{on}.

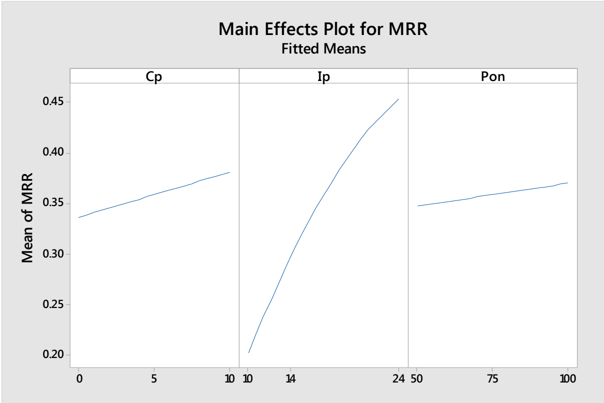

Figure 5: Main effects plot for MRR using Gr+SiC powder.

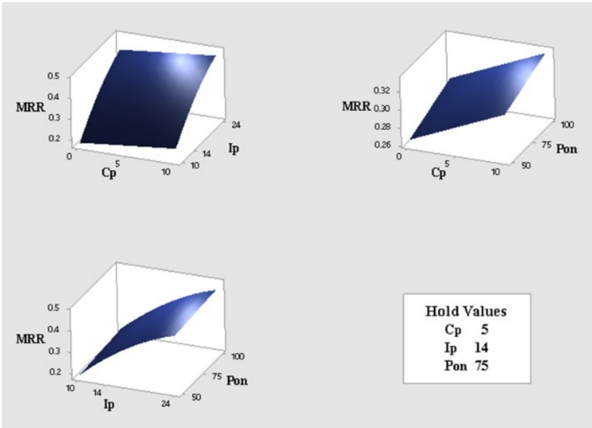

Figure 6: Surface plots for MRR.

Figures 7 and 8 illustrate main effects plot and surface plots of the tool wear rate (TWR), It demonstrated that the TWR reduced with the addition of the mixture Gr+SiC powder to transformer oil as dielectric in comparison with the pure transformer oil and with increasing the powder concentration TWR keep on decreased due to the fact that when adding the powder to the dielectric it disturbs the adherence of nuclides attached to the tool surface and hence the TWR decreased. TWR also reduced with the increase of (P_{on}) from (50 to 100) µs that is because the pollution increasing of dielectric fluid with increases P_{on} where the number of sparks drops this results to reduced TWR. Conversely, the TWR increases with increasing (I_P). When I_P increased the pulse energy also increased and hence high heat energy is created at the work piece-tool interface which results in increased evaporation and melting of the tool causing in raised TWR.

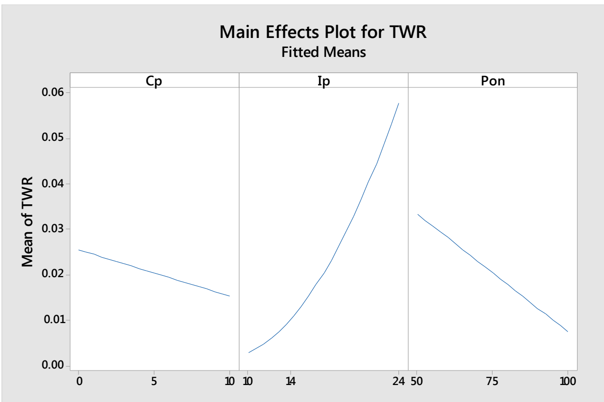

Figure 7: Main effects plot for TWR using Gr+SiC powder.

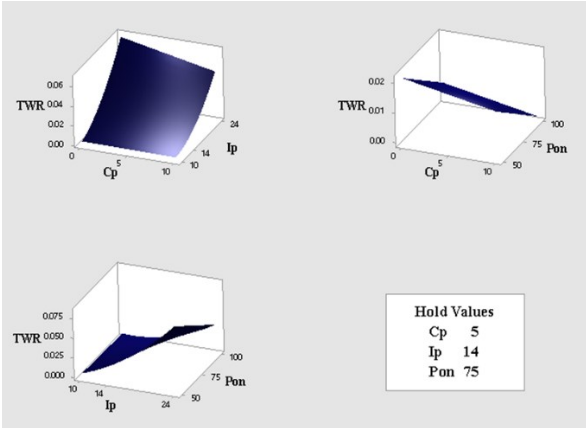

Figure 8: Surface Plots for TWR.

The main effects plot and the surface plots of the surface roughness are shown in Figures 9 and 10 respectively, it reveals that even with high I_P, the value of Ra keeps on decreasing when C_P increased compared with pure EDM (C_P = 0 g/l). This is due to the particles of the suspended powder lead to the uniform dispersion of discharge energy in all directions, which causes small and shallow craters on the machining surfaces resulting in reduced Ra. High Pon means spark energy is obtainable for a longer time and high I_P means more heat input, which creates a rough surface with increasing in both I_P and P_{on}.

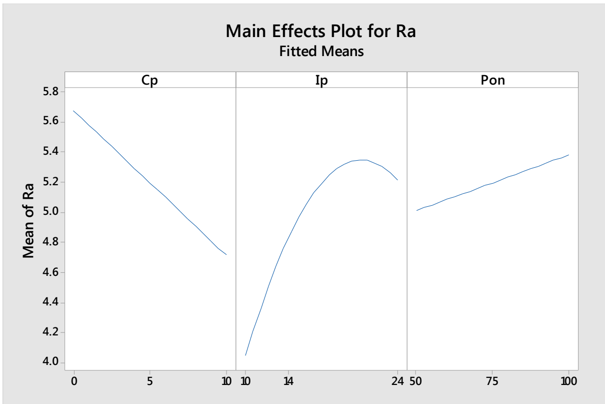

Figure 9: Main effects plot for Ra using Gr+SiC powder.

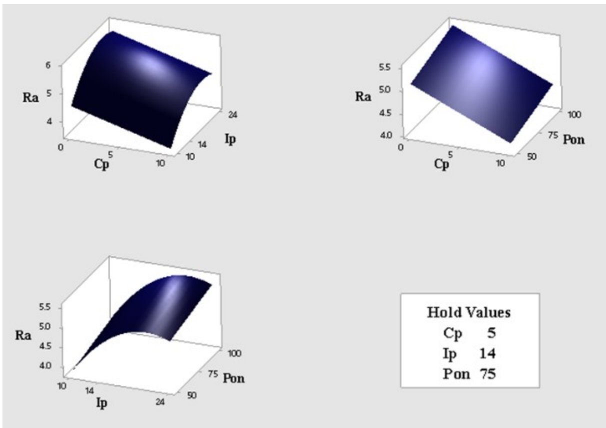

Figure 10: Surface Plots for Ra.

5. Conclusions

In this study, the performance of powder mixed electrical discharge machining has been analyzed for MRR, TWR, and Ra using mixed with transformer oil for HSS/(M2). Furthermore, the effects of powder concentration, pulse-on time, and current have been estimated for the process performance and the following conclusions can be summarized:

1. The addition of mixture Gr+SiC powder to the dielectric improving the MRR, and reducing the TWR, and Ra in comparison with pure dielectric.
2. For the best sitting of MRR, TWR, and Ra must be considered that yields the best values for MRR of (0.492 g/min) are (C_P=10 g/l, I_P=24 A, and P_{on}=100 µs), for TWR of (0.00126 g/min) are (C_P=10 g/l, I_P=10 A, and P_{on}=100 µs), and for Ra of (3.51 µm) are (C_P=10 g/l, I_P=10 A, and P_{on}=50 µs).
3. Peak current (I_P) followed by Powder concentration (C_p) and the quadratic term of (I_P*I_P) were the most significant effected terms on MRR and Ra.
4. The most influential terms on TWR were found are the linear terms of (I_P) followed by (P_{on}) and the interaction effect of (I_P*P_{on}).

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