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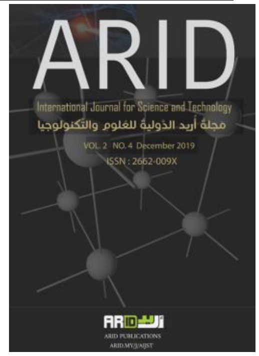

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Influence of Alumina Power –Mixed Dielctric on EDM Process Using Response Surface Methodology

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تأثير مسحوق الألومينا الممزوج بالسائل العازل على عملية القطع بالشرارة الكهربائية بأستخدام منهجية الأستجابة السطحية

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Abstract

Powder mixed electrical discharge machining (PMEDM) is a hybrid machining process where a foreign powder suspended into a dielectric fluid for enhancing the capabilities of EDM. The objective of this manuscript is to study the influence of input parameters like alumina (Al_2O_3) powder concentration (0,10, and 20) g/l, peak current (10,14, and 24) A, and pulse on time (50,75, and 100) µs High-speed steel (HSS) on the material removal rate (MRR), electrode wear rate (EWR) and the of M2 surface roughness (Ra). Response surface methodology (RSM), adopting a face-centered central composite design (FCCD), has been conducted to design and analyses the experimental layout. The experimental results were observed that Al_2O_3 fine powder mixed with the transformer oil significantly improved the MRR and reduces the EWR and Ra at various conditions. Maximum MRR was (0.49966 g/min) obtained when adding (20 g/l) Al_2O_3 at peak current of (24 A) and pulse on (100 µs), minimum EWR and Ra was (0.00092 g/min) and (3.669 µm) respectively at concentration of (20 g/l), peak current (10 A) and pulse on (100 µs).

Keywords: Electro-discharge machining (EDM), Powder-mixed dielectric, Response surface methodology, Alumina fine powder, Surface roughness.

الملخص

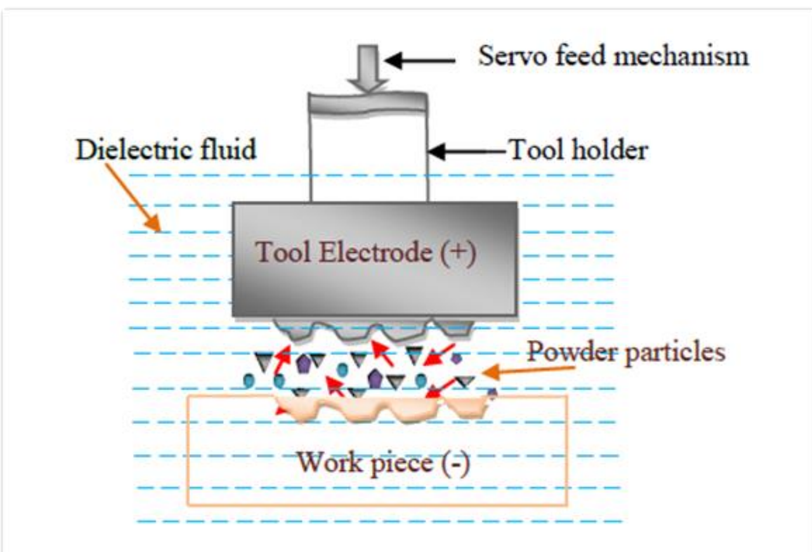
تعتبر عملية القطع بالشرارة الكهربائية الممزوجة بالمسحوق (PMEDM) عملية تصنيع هجينة حيث يتم خلط مسحوق خارجي في السائل العازل لتعزيز أمكانيات عملية القطع بالشرارة الكهربائية (EDM). الهدف من هذا البحث هو دراسة تأثير معاملات الادخال مثل تركيز مسحوق الالومينا (Al_2O_3) (0، 10، 20) غرام/لتر ، قيمة التيار (10، 14، 24) أمبير، وقيمة زمن مكوث النبضة (50، 75، 100) مايكروثانية لتشغيل الفولاذ M2 ذو السرعة العالية (HSS) على معدل ازالة المادة (MRR)، معدل تآكل القطب (EWR) و خشونة السطح (Ra). منهجية الاستجابة السطحية، التي تتبنى تصميمًا مركّزًا مركزيًا محوره الوجه (FCCD)، قد أجريت لتصميم وتحليل المخطط التجريبي. لوحظت النتائج التجريبية أن المسحوق الناعم (Al_2O_3) الممزوج بزيت المحولات قد حسن بشكل كبير من معدل ازالة المادة وقلل كل من معدل تآكل القطب و خشونة السطح تحت ظروف مختلفة. أعلى MRR تم الحصول عليها هي (0.49966 غرام/دقيقة) عند أضافة (20 غرام/لتر) من (Al_2O_3)، قيمة تيار (20 أمبير) و زمن مكوث النبضة (100 مايكروثانية)، و أقل (EWR) و (Ra) كانت (0.00092 غرام/دقيقة) و (3.669 مايكرومتر) على التوالي، عند تركيز 20 غرام/لتر، قيمة تيار (10 أمبير) و زمن مكوث النبضة (100 مايكروثانية).

الكلمات المفتاحية: عملية القطع بالشرارة الكهربائية (EDM)، مزج مسحوق بالسائل العازل، منهجية الاستجابة السطحية، مسحوق الألومينا الناعم، خشونة السطح.

1. Introduction

Electro-discharge machining is a widely used amongst nontraditional machining used for processing small deep diameter hole and various complicated holes, die cavity with large components, and other precision parts. 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, 2]. Nevertheless, low machining efficiency and poor surface finish limits its additional applications [3].

Lately, EDM technology has developed significantly, and smooth surface can be obtained with very small surface roughness such as a mirror by controlling the energy of the discharge pulse accurately or by using powder mixed working fluids [4]. This process is called powder mixed electrical discharge machining (PMEDM). Suitable materials in fine powder form like graphite, iron, aluminum, titanium, silicon, copper, chromium or alumina, etc. are mixed in the dielectric fluid, which decreases the insulating capability of the dielectric and raises the spark gap distance between 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 [5-7]. Principle of PMEDM is shown in Figure (1) [8].



. Figure (1): Principle of PMEDM [8].

Extensive studies concerning the PMEDM and its optimization are available. Some of the most relevant are listed a continuation**. Erden and Bilgin (1980)** [9] studied the Powder-mixed EDM (PMEDM) for the first time, they studied the influence of carbon, aluminum, copper and iron powder mixed in dielectric fluid and conducted improved machining rates and reduced time-lags because of the powder particles in gap space and reducing insulation strength of dielectric. **Yan and Chen (1993 and 1994)** [10-12] examined the effect of addition silicon carbide and aluminum powders to dielectric in the machining of Ti–6Al–4V and SKD11. It has been found that the SR increases whereas the MRR improve significantly **Kansal *et al.* (2005 and 2007)** [13, 14] studied the influence of silicon powder mixed EDM on EN-31 tool steel and AISI D2 Die steel on machining rate. The results identify the most important parameters to maximize material removal rate and minimize surface roughness. **Assarzadeh and Ghoreishi (2013)** [15] demonstrated an attempt to model and optimize the machining parameters effected in Aluminum oxide (Al_2O_3) powder-mixed dielectric using heat-treated CK45 die steel workpiece and electrode of commercial copper. The experiments were Planned using (RSM). Three of the main process parameters (discharge current, pulse-on time, and source voltage) were discussed on MRR and Ra. The results are sets of optimal points that makes the MRR as high as possible and maintain the Ra and all machining parameters in their specified ranges simultaneously. **Rathi and Mane (2014)** [16] discussed the influence of machining Inconel-718 by powder mixed EDM. Selected machining parameters were current, pulse on time, duty cycles and powder media (SiC, Al_2O_3, and C). Optimization is carried out by (S/N) ratio analysis of taguchi method. (ANOVA) is used to present the effect of process parameters on (MRR) and (TWR). The maximum MRR is obtained when used Graphite as powder media at Ip of 18 A, Ton of 5 µs, duty cycle of 85% and. Low TWR is attained at I_P of 12 A, Ton of 20 µs, duty cycle of 90% and SiC as powder media. **Tripathy and Tripathy (2017)** [17] tested the influence of current, powder concentration, gap voltage, pulse on time, and duty cycle on MRR, Ra, recast layer thickness (RLT) and the micro-hardness (HVN) when machining H-11 die steel during PMEDM. Taguchi method with orthogonal array of L27 was used to carry out the experiments with SiC powder suspended in dielectric fluid. Results have shown that machining without addition powder most cracks, pores, holes, and surface pits are found to occur with more non-uniform surfaces which increase the SR however, when powder is mixed with the dielectric fluid, the surface texture showed tremendous improvement due to increased MRR, reduced SR and RLT, improved HVN and superior surface quality with less micro-crack**. Bhaumik and Maity (2017)** [18] made an attempt to investigated the influence of SiC PMEDM for machining (AISI 304) stainless steel on Ra. RSM had been adopted to design the experiments. It had been conducted that, the most suitable parametric combination which produces the best value of Ra (6.7 µm) was: I_P=4 A, Ton=50 µs, C_P=10 g/l, gap voltage=65 V, and duty cycle=65%. Results had shown that I_P was the most significant factor for Ra and with the increase of C_P the Ra decreased. **Sahu *et al.* (2018)** [19] found that Among the investigated parameters (powder concentration, pulse-on time and peak current); peak current has performed as the greatest significant parameter followed by powder concentration. Results show when mixing 4g/l of SiC powder into kerosene dielectric, at low energy input, has appeared beneficial for achieving maximum material removal rate, and decreased surface roughness, surface crack density, as well as white layer thickness. **Sahu and Datta (2019)** [20] conducted investigations of graphite PMEDM with various peak current on the material removal rate and tool wear rate. Some of the topographical and morphology features of the machined surface were also examined. The outcomes, as compared with the pure EDM, are estimated to be capable of improving MRR, decreasing TWR, reducing surface finish, less micro-hardness and residual stress at the machined surface and reduced severity of surface cracking as well as intensity.

The aim of this study is to Investigate the influence of alumina powder-mixed dielectric on MRR, EWR, and Ra using response surface methodology (RSM) to modeling and predict the process performance by selecting different input machining parameters and Analyzed the responses by ANOVA to find the most significant factors for each .

2. Experimental Work:

2.1 Machine tool

Experiments were done on a CHEMER EDM machine, which is placed at the University of Technology / Baghdad, shown in Figure (2). The dimensions of the working tank of CHEMER EDM machine, that 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 Al_2O_3 fine 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 that filled of the transformer oil mixed with Al_2O_3 fine powder 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.

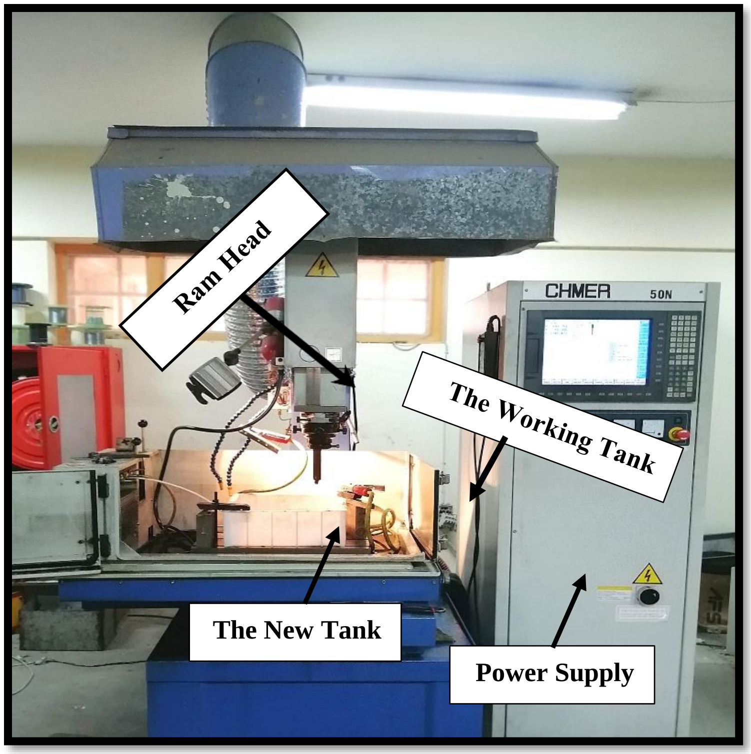


Figure (2): CHEMER EDM machine.

2.2 Workpiece material

high-speed steel (HSS) was used as the workpiece due to its high corrosion, In this work, M2 high strength and shock resistance, have a hardness of 62 HRC. The workpiece was made in square specimens with dimensions (25 x 25 x 3) mm as shown in Figure (3). The workpiece's chemical composition was tested at the central organization for standardization and quality control \ Ministry of Planning \ Iraq and according to ASTM E415 standard and the results are listed in Table (1).

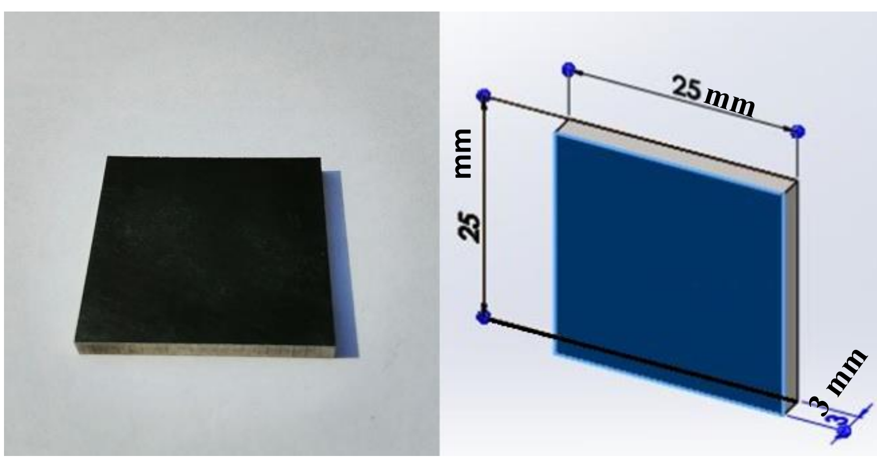


Figure (3): The workpiece before machining.

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.

2.3 Electrode material

The electrode material selected to carry out the experiments is copper with dimensional (75, 40 and 6) mm, as shown in Figure (4). Table (2) gives the chemical composition of the copper electrode which have been examined at the central organization for standardization and quality control \ Ministry of Planning \ Iraq.

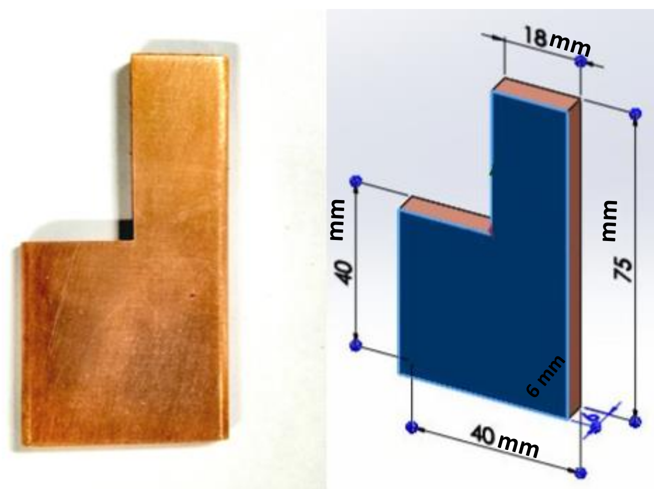


Figure (4): The copper electrode.

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.

2.4 Powder-mixed dielectric

Alumina (Al_2O_3) fine powder with a particle size of (0.9 ~ 1.2 µm) and transformer oil were mixed together to develop the powder suspended dielectric medium. Table (3) and Table (4) are shown the physical properties of dielectric fluid, that tested at production and metallurgy department laboratories, and the thermo-physical properties of alumina powder respectively.

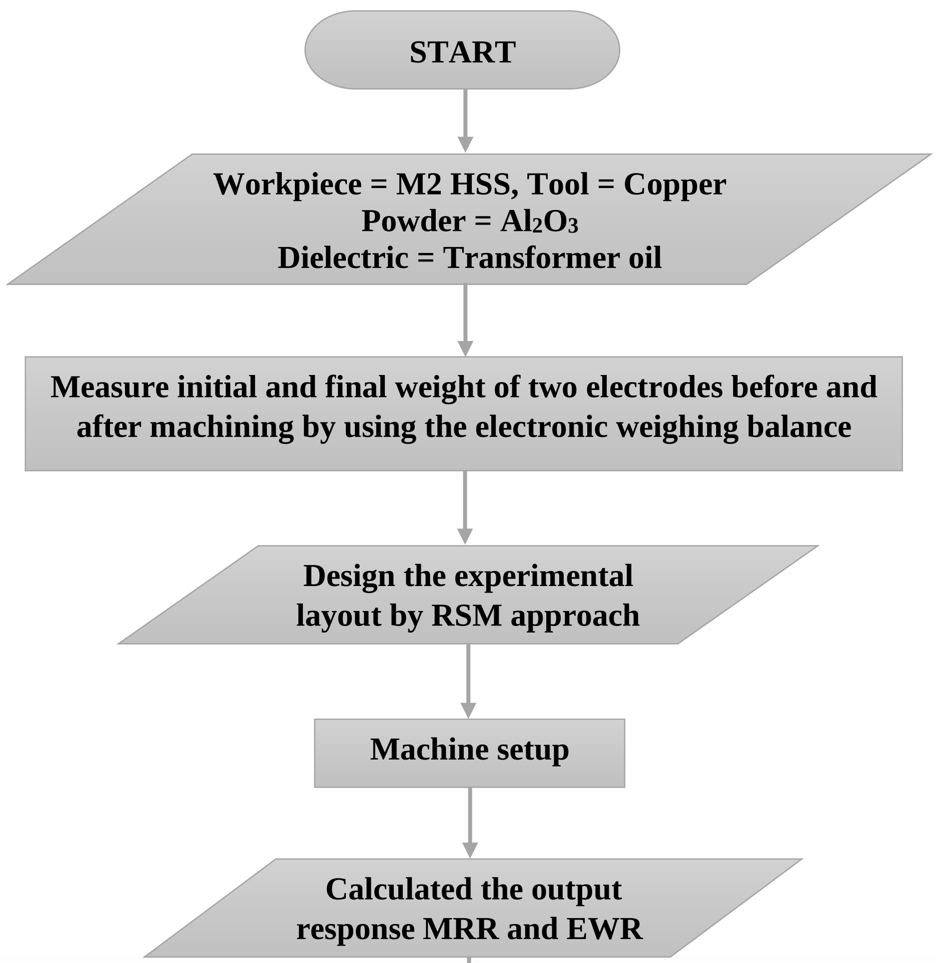
Table (3): Physical properties of transformer oil.

Density at 15 ºC	Viscosity at 23 ºC	Specific heat	Boiling point temperature	Flash point temperature
0.850 (g/cm^3)	28.01 (Pa.s)	1.63 (KJ=kg.K)	280 (ºC)	140 (ºC)

Table (4): Thermo-Physical properties of alumina powder [21].

Density	Electrical resistivity	Thermal conductivity
3.98 (g/cm^3)	103 (μΩ-cm)	25.1 (W/m-K)

3. Experimental Procedures



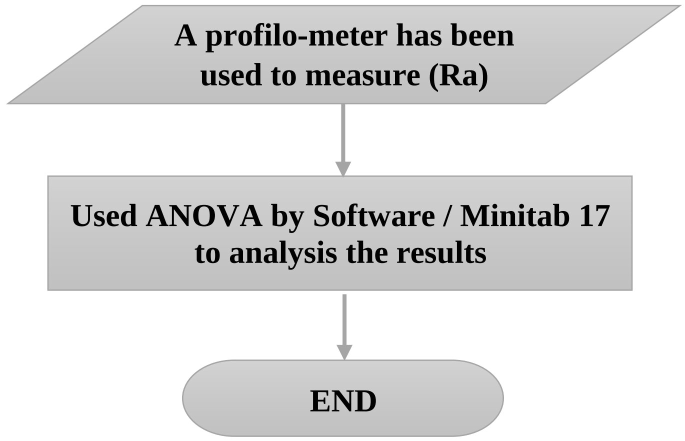


Figure (5) illustrate the flowchart of the experimental procedures.

The MRR and EWR was calculated by [16]:

(1) $$EWR = \frac{W_{ie} - W_{fe}}{T}$$ (2) $$MRR = \frac{W_{iw} - W_{fw}}{T}$$

Where:

MRR = Material Removal Rate (g/min)

W_{iw} = The initial weight of the workpiece (g).

W_{fw} = The final weight of the workpiece (g).

EWR = Electrode Wear Rate (g/min)

W_{ie} = The initial weight of the electrode (g).

W_{fe} = The final weight of the electrode (g).

T = Machining time (min).

4. Design of the Experiment

RSM is an effective statistical and mathematical technique that finding a quantitative formula of the relationship amongst the input and output parameters [22]. Three input parameters with three levels for each parameter were selected in this study as shown in Table (5). Whereas Table (6) illustrate the fixed input machining parameters. In order to conduct the experiments, face-centered central composite design (FCCD) matrices contained from RSM approach have been employed. The experimental layout and response result is giving in Table (7).

Table (5): Machining Parameters and Levels.

Parameters	Units	Levels		
		-1	0	1
Powder concentration (C_P)	g/l	0	10	20
Peak current (I_P)	Amp	10	14	24
Pulse on time (Ton)	μsec	50	75	100

Table (6): Fixed input parameters.

Machining Parameters	Fixed values
Workpiece polarity	Negative
Electrode polarity	Positive
Dielectric fluid	Transformer oil + Al_2O_3 powder
High voltage	140 V 1.2 A
S code	200
Servo feed	75 %
Working time	5.0 sec
Jumping distance	2.0 mm
Gap code	10
Gap distance	0.3125 mm
Depth of cut	1 mm

Table (7): Experimental layout and response result.

Run order	C_P g/l	I_P Amp	Ton μsec	MRR g/min	EWR g/min	Ra μm
1	0	10	50	0.1829	0.00519	4.535
2	20	10	50	0.19378	0.00355	3.851
3	0	24	50	0.4258	0.095516	5.479
4	20	24	50	0.45353	0.068594	4.486
5	0	10	100	0.1918	0.001928	4.259
6	20	10	100	0.2307	0.000923	3.669
7	0	24	100	0.4173	0.04695	5.947
8	20	24	100	0.49966	0.035815	4.629

9	0	14	75	0.2647	0.011824	4.931
10	20	14	75	0.2872	0.007699	4.036
11	10	10	75	0.2074	0.002908	4.213
12	10	24	75	0.489	0.04472	4.921
13	10	14	50	0.26185	0.009479	4.573
14	10	14	100	0.31355	0.001824	4.395
15	10	14	75	0.2773	0.008246	4.558
16	10	14	75	0.26943	0.008635	4.463
17	10	14	75	0.2801	0.007959	4.547
18	10	14	75	0.27371	0.008796	4.491
19	10	14	75	0.27514	0.00962	4.417
20	10	14	75	0.26857	0.008593	4.538

5. Results and discussion

Based on the experimental outcomes obtained from Table (7), The influence of the input parameters (C_P), (I_P) and (Ton) on the three responses namely MRR, EWR and Ra were analyzed by analyses of variance (ANOVA) from RSM approach using MINITAB 17 software. (ANOVA) was conducted to test the significance of the model when the P-value is less than 0.05 (95 % of confidence interval), then the model terms are statistically significant. Tables (8), (9) and (10) demonstrate results of ANOVA for MRR, EWR and Ra respectively using backward elimination regression.

Table (8): Results of ANOVA backward elimination regression for MRR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0.184024	0.030671	223.00	0.000
Linear	3	0.180188	0.060063	436.71	0.000
Concentration	1	0.003549	0.003549	25.80	0.000
Current	1	0.174812	0.174812	1271.03	0.000
pulse on	1	0.001827	0.001827	13.28	0.003
Square	1	0.000476	0.000476	3.46	0.086
concentration*concentration	1	0.000476	0.000476	3.46	0.086
2-Way Interaction	2	0.001384	0.000692	5.03	0.024
concentration*current	1	0.000530	0.000530	3.85	0.071

concentration*pulse on	1	0.000854	0.000854	6.21	0.027
Error	13	0.001788	0.000138		
Total	19	0.185812			
Model Summary	S	R-sq	R-sq(adj)	R-sq(pred)	
	0.0117276	99.04%	98.59%	97.24%	

Table (9): Results of ANOVA backward elimination regression for EWR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	0.12308	0.001758	86.31	0.000
Linear	3	0.008969	0.002990	146.76	0.000
Concentration	1	0.000235	0.000235	11.54	0.005
Current	1	0.007678	0.007678	376.92	0.000
pulse on	1	0.001055	0.001055	51.81	0.000
Square	2	0.000588	0.000294	14.42	0.001
concentration*concentration	1	0.000086	0.000086	4.22	0.063
current*current	1	0.000164	0.000164	8.03	0.015
2-Way Interaction	2	0.000947	0.000474	23.24	0.000
concentration*current	1	0.000169	0.000169	8.32	0.014
current*pulse on	1	0.000778	0.000778	38.17	0.000
Error	12	0.000244	0.000020		
Total	19	0.12553			
Model Summary	S	R-sq	R-sq(adj)	R-sq(pred)	
	0.0045134	98.05%	96.92%	89.15%	

Table (10): Results of ANOVA backward elimination regression for Ra.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	4.78393	0.79732	99.08	0.000
Linear	3	4.52206	1.50735	187.32	0.000
Concentration	1	2.08578	2.08578	259.20	0.000
Current	1	2.43542	2.43542	302.65	0.000

pulse on	1	0.00086	0.00086	0.11	0.749
Square	1	0.05292	0.05292	6.58	0.024
current*current	1	0.05292	0.05292	6.58	0.024
2-Way Interaction	2	0.28732	0.14366	17.85	0.000
concentration*current	1	0.12977	0.12977	16.13	0.001
current*pulse on	1	0.15756	0.15756	19.58	0.001
Error	13	0.10461	0.00805		
Total	19	4.88854			

Model Summary	S	R-sq	R-sq(adj)	R-sq(pred)
	0.0897048	97.86%	96.87%	90.20%

Equations (3), (4) and (5) represented the mathematical relation amongst input parameters and MRR, EWR and Ra respectively which obtained from non-linear regression models by RSM method. These equations are used to calculate the predicted values of MRR, EWR, and Ra.

$$MRR = 0.0046 - 0.00117C_P + 0.017214I_P + 0.000127Ton - 0.000099C_P*C_P + 0.000114C_P*I_P + 0.000041C_P*Ton \quad (3)$$

$$EWR = -0.0372 - 0.000426C_P + 0.00250I_P + 0.000528Ton + 0.000052C_P*C_P + 0.000184I_P*I_P - 0.000065C_P*I_P - 0.000055I_P*Ton \quad (4)$$

$$Ra = 3.887 - 0.01549C_P + 0.1207I_P - 0.01302Ton - 0.00269I_P*I_P - 0.001787C_P*I_P + 0.000788I_P*Ton \quad (5)$$

The surface plots, shown in Figure (6), and the main effects plots, shown in Figure (7), for MRR bridge the gap observing that when the concentration of the alumina powder increased that help to between the two electrodes, hence the MRR tends to improve. Also, MRR rises with the increased of pulse on time, furthermore, this rises becomes more obvious when the peak current value increased, due to the production of strong spark that generates higher temperature leading to melting and vaporization of material and formation of craters on the workpiece. Consequently, this results in higher MRR. This tendency is exactly corresponding with the results of Kung et al. [16].

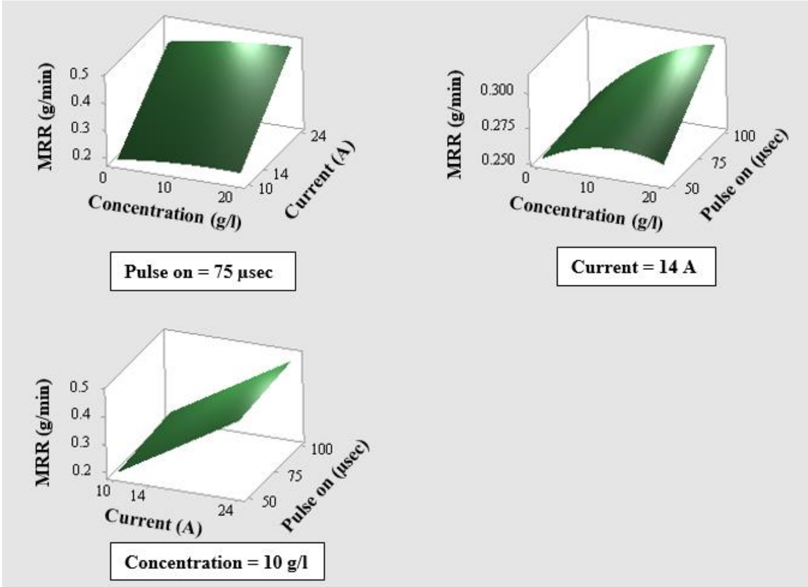


Figure (6): Surface plot of MRR versus the input parameter.

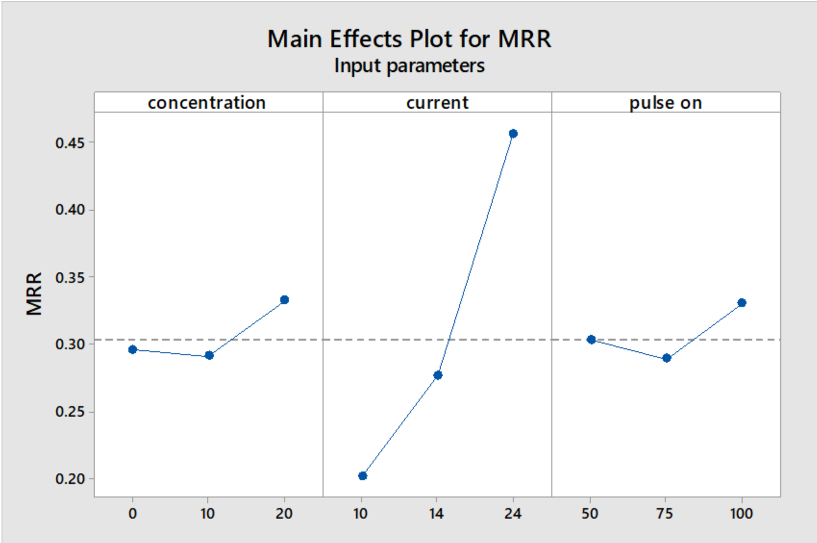


Figure (7): Main effects plots for MRR.

From Figures (8) and (9) It was concluded that the EWR increases with the increase in powder concentration, yet it is still better than conventional EDM i.e. when the powder concentration is 0 g/l. This can be explained by the fact that when increased the concentration in dielectric media, the gap voltage and insulating strength of the media reduced. This causes the early explosion by a short circuit in the gap causing high EWR.

Furthermore, EWR seems to be decreased with increasing the pulse on. That's because, at the beginning of spark, the motion of the electrons overcomes the motion of the ions under the workpiece where the amount of material removal from the workpiece is more than the electrode that leads to the decrease of EWR.

Conversely, EWR increases significantly with the increase in peak current. This obtains because similar trend is detected by of high current produced a high spark that removing the electrode material Rathi and Mane [18].

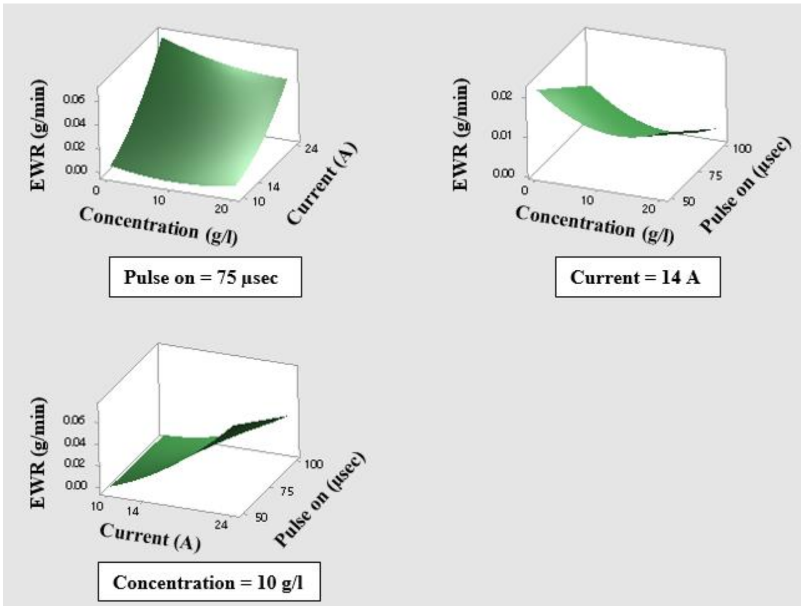


Figure (8): Surface plot of EWR versus the input parameter.

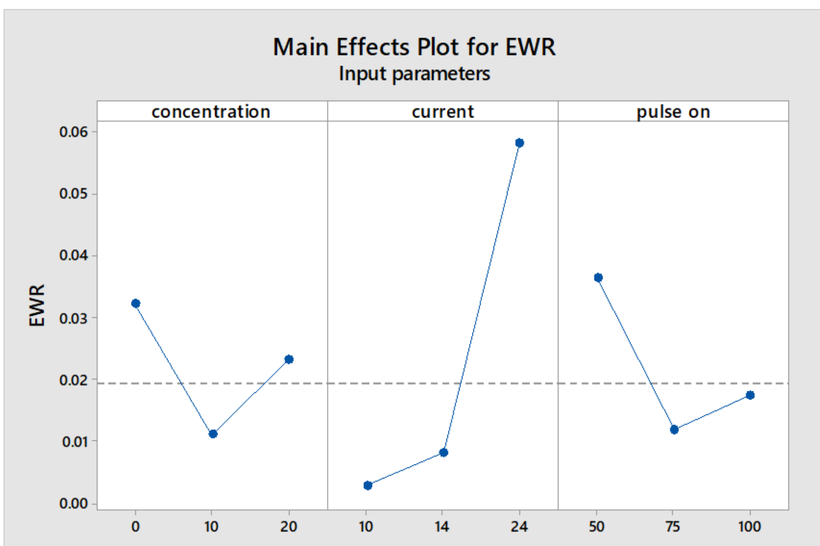


Figure (9): Main effects plots for EWR.

The effect of process parameters on Ra is given in Figures (10) and (11). It shows that even with high peak current, the value of Ra keeps on reducing when powder concentration increased compared with conventional EDM (0 g/l concentration). That's due to the suspended powder particles lead to the uniform dispersion of discharge energy in all directions, which results in shallow and small craters on the machining surfaces resulting in less Ra.

On the other hand, the Ra increased with increasing the peak current. High current means rise in temperature and more material melting and vaporize this leads to increase MRR and creates a rough surface, same results observed at [8]. While no obvious effects on Ra shown when used different pulse on.

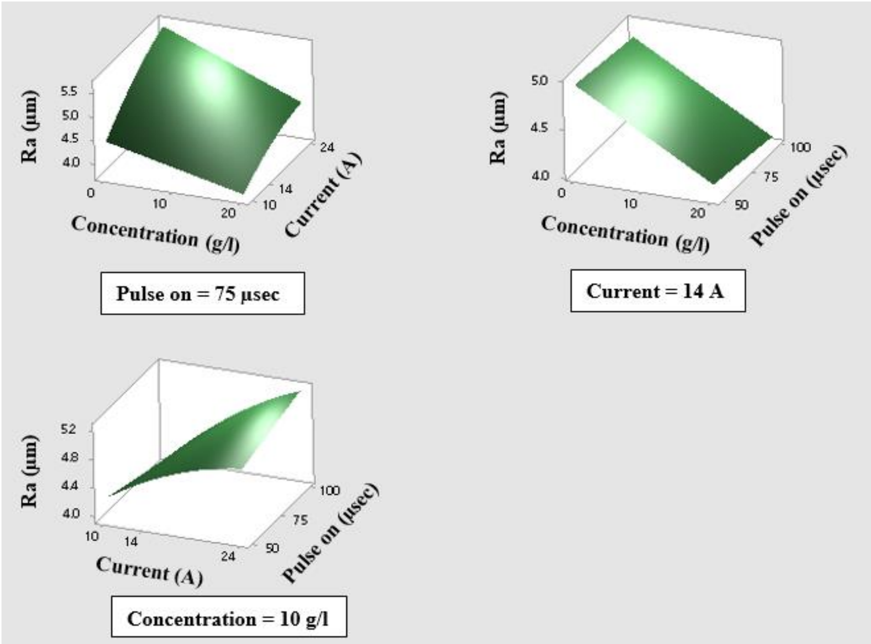


Figure (10): Surface plot of Ra versus the input parameter.

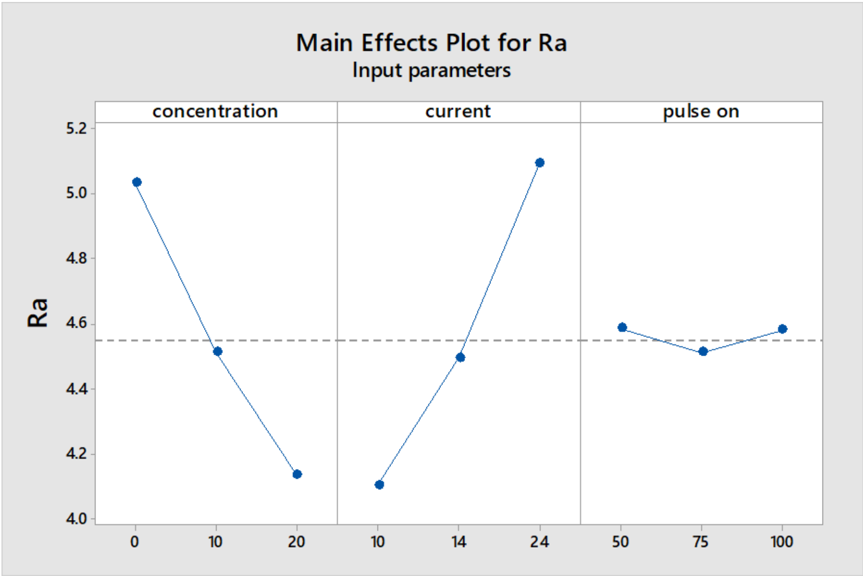


Figure (11): Main effects plots for Ra.

6. Conclusions

The conclusions drawn from this study are:

i. PMEDM enhances the MRR, EWR, and Ra in comparison with conventional EDM.

ii. For the best sitting of MRR powder concentration of (20 g/l), peak current of (24 A), and pulse-on time of (100 µs) must be considered that yields the best value of MRR of (0.49966 g/min).

iii. The best sitting for Minimum EWR and Ra was (0.00092 g/min) and (3.669 µm) respectively and obtained at concentration of (20 g/l), peak current (10 A) and pulse on (100 µs).

iv. Powder concentration (C_P), peak current (I_P), pulse on time (Ton), and the interaction effect of powder concentration and pulse on time ($C_P \times Ton$) were the significant effected terms on MRR.

v. The most influential terms on EWR were found are the linear terms of (C_P), (I_P) and (Ton), the quadratic term of (I_P^2) as well as the interaction effect of ($C_P \times I_P$) and ($I_P \times Ton$).

vi. The affecting parameters on Ra were found to be the (C_P), (I_P), the second-order term of (I_P^2) and the 2-way interaction of ($C_P \times I_P$) and ($I_P \times Ton$).

For this study powder concentration, peak current, and pulse-on time at different levels have been investigated to evaluate the MRR, EWR, and Ra of Al_2O_3 powder mixed dielectric in EDM. For future recommendations, the researchers may study the influence of different powders in Nanoscale, choosing an alternative range of the process parameters, and using other types of dielectric fluid like tap water, distilled water, vegetable oil, etc.

List of Abbreviations:

EDM	Electrical Discharge Machining
PMEDM	Powder Mixed Electrical Discharge Machining
HSS	High Speed Steel
MRR	Material Removal Rate
EWR	Electrode Wear Rate
TWR	Tool Wear Rate
Ra	Surface Roughness
RSM	Response Surface Methodology
HRC	Rockwell Hardness
ANOVA	Analysis Of Variance
I_P	Peak Current
C_P	Powder Concentration
Pon	Pulse On Time
DF	Degree of Freedom
Adj SS	Adjusted Sums of Squares
Adj MS	Adjusted Mean Squares
S	Standard deviation
R-sq	The determination coefficient
R-sq(adj)	Adjusted determination coefficient
R-sq(pred)	Predicted determination coefficient

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