Journal of Engineering and Development
www.jead.org
Vol. 19, No. 05, September 2015
ISSN 1813-7822

PREDICTION OF SURFACE ROUGHNESS, MATERIAL REMOVAL RATE AND TOOL WEAR RATIO MODELS FOR SIC POWDER MIXING EDM

Ahmed Naif Ibrahim [1], Samir Ali Amin [2], Saad Mahmood Ali [3]

1) Assist. Prof., Mechanical Engineering Department, University of Technology, Baghdad, Iraq..
2) Assist. Prof., Mechanical Engineering Department, University of Technology, Baghdad, Iraq.
3) Assist. Lect., Mechanical Engineering Department, University of Karbala, Karbala, Iraq.

(Received:24/03/2015 ; Accepted:13/5/2015)

Abstract:

Powder mixed electric discharge machining (PMEDM) is one of the new innovations for the enhancement of capabilities of electric discharge machining process. This paper is an attempt to study the effect of SiC powder mixed in the kerosene dielectric fluid. The type of electrodes, the peak current and the pulse-on time are the main selected EDM input parameters. The workpiece and the electrodes materials are the AISI D2 die steel and copper and graphite materials, respectively. The output responses considered are the workpiece surface roughness (SR), the material removal rate (MMR) and the tool wear ratio (TWR). The experiments are planned using response surface methodology (RSM) design procedure. Empirical models are developed for SR, MRR and TWR using the analysis of variance (ANOVA) and regression models to study the effect of process parameters. The best results for the productivity of the process (MRR) obtained when using graphite electrodes at pulse current (22 A), pulse on duration (120 µs) and with silicon carbide (SiC) powder mixing in kerosene dielectrict at reaches (76.76 mm³/min). These results improved the material removal rate by (264%) with respect to the corresponding value obtained when using copper electrodes with kerosene dielectric alone. The best (TWR) results of the process obtained when using graphite electrodes at pulse current (8 A), pulse on duration (40 µs) and using the kerosene dielectric alone reduced to the level (0.1023 %). The use of graphite electrodes, the kerosene dielectric alone, the pulse current (8 A), and the pulse on duration (40 µs) yield the best (SR) with a value (2.87 µm) and improvement by (27%) with respect to the corresponding value obtained when using copper electrodes and the same parameters and machining conditions.

Keywords: *EDM, PMEDM, RSM, Surface Roughness, Material Removal Rate, Tool Wear Ratio, Die steel, Silicone Carbide powder .*

نماذج التنبؤ بالخشونة السطحية ومعدل إزالة المعدن ونسبة تآكل العدة لعمليات التشغيل بالشرارة الكهربائية ومسحوق كربيد السليكون الممزوج

الخلاصة:

يعتبر المسحوق الممزوج في عمليات التشغيل بالتفريغ الكهربائي احد الابتكارات الجديدة لتعزيز امكانيات عملية القطع بالتفريغ الكهربائي. وهذا البحث يهتم بدراسة تأثير مسحوق كربيد السليكون الممزوج في مائع الكيروسين العازل. ان نوع الأقطاب وتيار الذروة وزمن استمرارالنبضة هي معاملات الإدخال الرئيسية المختارة لعملية القطع بالتفريغ الكهربائي. ان مادتي المشغولة والأقطاب هي صلب القوالب ماركة D2 والنحاس والجرافيت على التوالي. اما معاملات الاستجابة للمخرجات فهي الخشونة السطحية ومعدل إزالة المعدن ونسبة تآكل العدة. تم تخطيطتصميم اسلوب اجراء التجارب باستخدام منهجية استجابة السطح. وتم تطوير النماذج التجريبية للخشونة السطحية ومعدل إزالة المعدن ونسبة تآكل العدة باستخدام تقنية تحليل التباين (ANOVA) ونماذج الانحدار لدراسة تأثير معاملات العملية. وأفضل النتائج المتحققة لإنتاجية العملية والتي تم الحصول عليها عند استخدام أقطاب الجرافيت عند استعمال تيار النبضة (٢٢ امبير) وزمن استمرارالنبضة (١٢٠ ميكرو ثانية) مع مسحوق كربيد السيليكون الممزوج في مائع الكيروسين العازل وبلغت (٧٦,٧٦ ملم^3 / دقيقة). هذه النتائج اظهرت تحسن في معدل إزالة المواد بنسبة (٢٦٤٪) نسبة للقيمة المطابقة التي تم الحصول عليها عند استخدام أقطاب النحاس مع مائع الكيروسين العازل لوحده. كما ان أفضل نتائج لنسبة تآكل العدة التي تم الحصول عليها عند استخدام أقطاب الجرافيت عند استعمال تيار النبضة (٨ امبير) وزمن استمرارالنبضة (٤٠ ميكرو ثانية) وباستخدام عازل الكيروسين لوحده حيث تم تقليل نسبة التآكل إلى المستوى (١٠٢٣و٠٪). كما ان استخدام أقطاب الجرافيت، وعازلة الكيروسين لوحده، تيار النبضة (٨ امبير) وزمن استمرارالنبضة (٤٠ ميكرو ثانية) اعطت أفضل النتائج للخشونة السطحية بلغت (٢,٨٧ ميكرون) وتحسن بنسبة (٢٧٪) نسبة إلى القيمة المطابقة التي تم الحصول عليها عند استخدام أقطاب النحاس ونفس المعاملات وشروط التشغيل.

كلمات البحث: *القطع بالتفريغ الكهربائي ، التشغيل بالشرارة الكهربائية ، مسحوق كربيد السليكون الممزوج ، منهجية استجابة السطح، الخشونة السطحية ، معدل إزالة المعدن ، نسبة تآكل العدة ، صلب القوالب، مسحوق كربيدالسيليكون .*

1. Introduction

New developments in the field of material science have led to new engineering metallic materials, composite materials, and high tech ceramics, having good mechanical properties and thermal characteristics as well as sufficient electrical conductivity, so that they can readily be machined by spark erosion [1−4]. The recent developments in the field of EDM have progressed due to the growing application of EDM process and the challenges being faced by the modern manufacturing industries, from the development of new materials that are hard and difficult-to-machine, such as tool steels, composites, ceramics, super alloys, hast alloy, nitralloy, waspalloy, nemonics, carbides, stainless steels, heat resistant steel, etc. being widely used in die and mold making industries, aerospace, aeronautics, and nuclear industries [5]. Since the EDM has been an indispensable operation in the manufacturing processes, the electrical discharge machining has been in the last few years the center of interest of several researchers [6−14].

In order to improve the machining efficiency, the addition of abrasives and metallic powders is done to dielectric fluid. This process is called powder mixed EDM (PMEDM). Till very few researches have been seen in grooving and slitting machining operation with addition of powder mixed EDM. In this process, the electrically conductive powder particles are mixed in the dielectric fluid, which reduces its insulating strength and increases the spark gap distance between the tool and workpiece to spread the electric discharge uniformly in all directions. As a result, the process becomes more stable, thereby improving material removal rate and surface finish [15−18]. The machining performance in EDM processes consists of the material removal rate (MRR), electrode wear (EW), surface roughness (SR) and surface quality. The effort made in literature conducted so far has been to increase the material removal rate, with the studies aimed to erode as much material as possible. Technologies still face some difficulties in the increase of the MRR value [19−22]. Studies to improve this proportion are going on [23−36]. From these researches, it can be seen that very few works have been reported yet relating to modeling of SR of D2 steel in EDM using RSM technique.

Therefore, this paper attempted to study the workpiece surface integrity, the process productivity and the electrodes wear rates producing by EDM and PMEDM parametric effects. This work is concerned also with the developing models for SR, MRR and TWR by using the RSM technique. Two groups of experiments are designed to study the performance of the EDM and PMEDM process on AISI D2 die steel. The first group was performed in pure kerosene dielectric, while the second was with addition of abrasives silicon carbide powders mixed with dielectric fluid in order to improve the process productivity efficiency and the workpiece surface quality.

2. EXPERIMENTATION

2.1. Used Material

Three samples from the selected raw material, the AISI D2 die steel are tested for chemical composition by using the AMETEXSPECTRO MAX material analyzer and the results are listed with the equivalent values given according to ASTM A 681-76 standard specification [37]for alloy and die steels in Table (1). This table indicates that the chemical composition of the used one is in conformity with that for the standard one.

2.2. Mechanical Tests

Four specimens are prepared for tensile tests by using the universal testing machine type UNITED on the bases on ASTM-77 steel standards for flat workpiece [38]. The same specimens are then tested for Rockwell hardness by using the hardness testing machine type INDENTEC. The tests results are given in Table (2). The workpieces are manufactured by using the wire electrical discharge machine (WEDM) type ACRA Brand/Taiwan and by a surface grinding machine and then polished mechanically and manually by abrasive silicon carbide paper up to grade ASTM 3000.

Table (1): The chemical compositions for the used material and the equivalent given by the standard for AISI D2 die steel

SAMPLE	*C %*	*Si %*	*Mn %*	*P %*	*S %*	*Cr %*	*Mo %*	*Ni %*	*Co %*	*Cu %*	*V %*	*Fe %*
Used material	1.51	0.174	0.264	0.014	0.003	12.71	0.555	0.158	0.0137	0.099	0.306	Bal.
Standard AISI D2 [37]	1.40 to 1.60	0.60 max.	0.60 max.	0.03 max.	0.03 max.	11.00 to 13.00	0.70 to 1.20	-	1.00 Max.	-	1.10 Max.	Bal.

Table (2): The mechanical properties for the selected materials

Ultimate Tensile stress N/mm²)	*Yield strength (N/mm²)*	*Elongation (%)*	*Hardness (HRB)*

704.25	415.25	18.125	90.25

2.3. Used Electrodes

Two types of electrodes materials, copper and graphite are selected. The electrodes are manufactured with a square cross-section of 24 mm and 30 mm length, with a quantity of 24 pieces for each type as shown in fig.(1). The prepared electrodes were polished as mentioned above.

2.4. EDM Parameters

The main designed EDM parameters are the gap voltage Vp (140 V), the pulse current Ip (8 and 22 A), the pulse on time duration period time Ton (40 and 120 μs), the pulse off time duration period Toff (14 and 40 μs), the SiC powder concentration (0 and 5g/l), the kerosene dielectric adjusted from both sides of the w/p with a flashing pressure =0.73 bar (10.3 psi) and the electrode polarity (+).

Figure (1): The copper and graphite electrodes and workpieces after PMEDM processes

The EDM experiments were conducted on ACRACNC-EB EDM machine with all the manufactured attachments shown in figure (4). A stainless steel container (of about 30 liters volume and overall dimensions 400 x 300 x 230 mm, thickness 3 mm) was manufactured. It contains a special kerosene dielectric pump, an electric motor (300 RPM) connected to a mixture containing a stainless steel impellers, a workpiece clamping fixture, valves and pipe accessories. For the power supply, an AC/DC converter for driving the special kerosene pump was attached in an electrical board. This board contains also a pressure gauge (one bar capacity), wiring, switches and piping accessories. The manufacturing of the stainless steel container was completed by using the TIG argon inert gas wielding process, as shown in figure (2). The silicon carbide powders substances are tested for chemical compositions by using the X-Ray diffraction apparatus, and then the powder was tested to measure its grains sizes using the laser diffraction particle size analyzer. The average grain size is (95,502 μm) for silicon carbide powder as given in the test certificates.

The surface roughness characteristics for each workpiece (43 specimens) and electrode (48 copper and graphite electrodes) before and after EDM and PMEDM machining are measured by using the portable surface roughness tester.

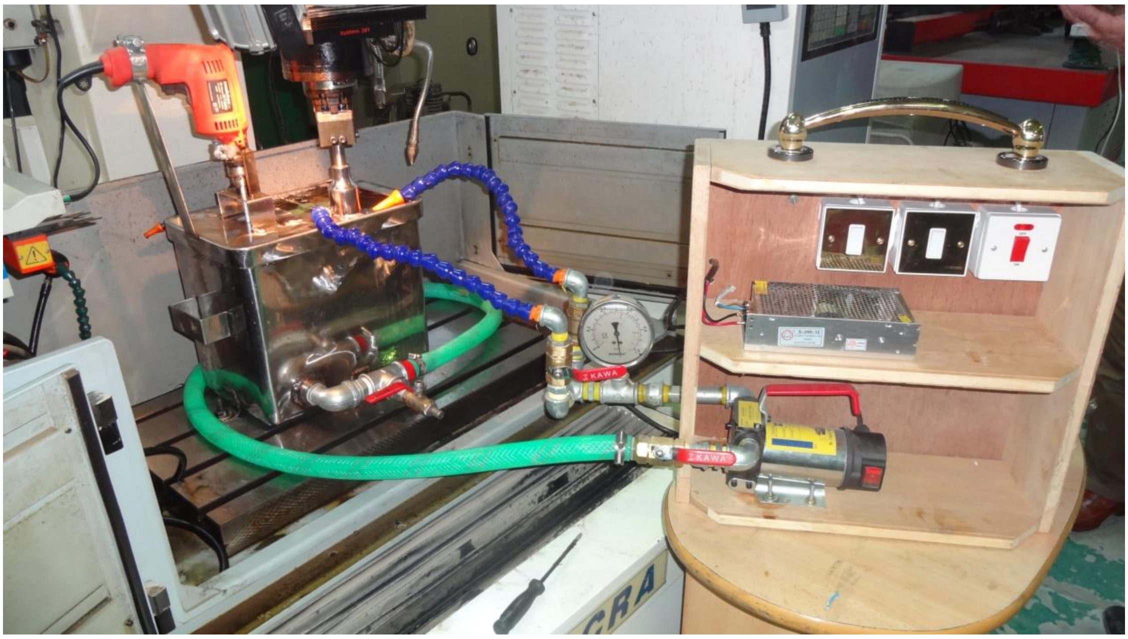

Figure (2): The (CNC) EDM machine with all the manufactured accessories designed for the implementation the PMEDM experiments

2.6. Material Removal Rate and Wear Rate Ratio Calculations

All the w/p specimens and electrodes are weighed before and after EDM machining by using the electronic weighting balance with accuracy of (0.0001g).

To calculate the material removal rate (MRR) for each experiment, the following equation was used:

$$\text{Material removal rate (MRR)} = (M1 - M2) / \rho w \cdot T \qquad (1)$$

Where:

M1&M2 =The mass of the workpiece before and after EDM machining (gm), respectively, ρw=The density of the workpiece material (gm/mm^3) and T= The machining time (min.).

The following equation is used to calculate the tool wear ratio (TWR):

$$\text{Tool wear ratio (TWR)} = (VE / VW) \cdot 100\% \qquad (2)$$

$$VE = ME / \rho E \quad \text{and} \qquad (3)$$

And:

$$Vw = Mw / \rho w \tag{4}$$

Where:

VE = Volume of material removal from the tool (electrode)

Vw = Volume of material removal from the workpiece

ME & Mw = The mass of the tool (electrode) and workpiece, respectively.

ρE & ρw = The density of the tool (electrode) and workpiece, respectively.

3. Results and discussions

3.1. Experimental Matrix Design

In this work, to study the performance characteristics of the process, two groups of experiments are designed using the kerosene dielectric alone or with SiC powder mixing, each contains (22) experiments for comparing the results producing by EDM and PMEDM machining. Each group was divided in two subgroups. The first subgroup used the copper electrodes, while the second subgroup used the graphite electrodes. A new set of w/p and electrode was used in each experiment.

The surface roughness (SR), the material removal rate (MRR) and the tool wear ratio (TWR), which are experimentally measured and calculated using equation (1-4) after EDM and PMEDM machining with the input parameters are modeled by using the response surface methodology (RSM) and the two level factorial (2^3) design for both experimental groups. The input EDM parameters and their levels are given in Table (3), while the output process responses are given in Table (4). The design EDM experimental matrix in a random manner with the selected actual factors and the experimental response results for the both groups using the kerosene dielectric or the kerosene dielectric with SiC powder mixing with copper and graphite electrodes are collected in one matrix, as given in Table (5).

Table (3): The input EDM parameters and their levels for both groups

Factor	*Name*	*Units*	*Min.*	*Max.*	*Coded Values*		*Levels*
A	Pulse current (Ip)	(A)	8	22	-1	+1	2
B	Pulse on duration (Ton)	(s)	40	120	-1	+1	2
C	SiC powder mixed in kerosene dielectric	g/l	0	5	-1	+1	2

Table (4): The EDM process responses, MRR, TWR and SR

Response	*Name*	*Units*	*Obs*	*Analysis*	*Minimum*	*Maximum*	*Mean*	*Model*
R1	Material removal rate(MMR)	mm³/min	43	Factorial	6.1696	76.5684	25.7572	R3FI
R2	Tool wear ratio(EWR)	%	43	Factorial	0.1023	8.678	2.8964	R3FI
R3	Surface roughness (SR)	m	43	Factorial	2.81	6.26	4.94605	R2FI

Table (5): The design experimental matrix

		Input factors(Actual)				*Responses*		
BLOCK	*Run No.*	X1 A: type of electrode	X2 B: Pulse current (Ip) (A)	X3 C: Pulse on duration (Ton) (µs)	X4 D:SiC powder mixed in kerosene dielectric (g/l)	Material removal rate (MMR) (mm³/min)	Tool wear ratio (EWR) (%)	Surface roughness (SR) (µm)
1	1	Copper	8	120	0	9.3969	0.4168	3.91
1	2	Graphite	22	120	5	60.6946	2.2513	6.12
1	3	Graphite	8	120	0	7.2612	3.0141	4.75
1	4	Graphite	8	40	5	11.684	8.678	4.39
1	5	Copper	8	120	5	17.9747	0.1023	5.47
1	6	Copper	8	40	0	6.2369	3.1489	4.05
1	7	Graphite	8	40	0	8.5929	7.0756	2.87
1	8	Graphite	22	40	5	62.0854	3.0269	4.3
1	9	Graphite	22	120	0	35.6832	1.5401	6.22
1	10	Copper	22	40	5	25.3023	5.3694	5.37
1	11	Graphite	8	120	5	26.4031	1.8518	5.46
1	12	Copper	22	40	0	15.9392	6.0467	4.84
1	13	Copper	22	120	5	40.1884	1.9316	5.82
1	14	Copper	22	120	0	26.7538	1.898	5.65
1	15	Copper	8	40	5	15.2874	2.321	5.32
2	16	Copper	22	40	0	15.8625	5.9988	4.85
2	17	Copper	8	40	5	12.346	2.5663	5.36
2	18	Copper	8	120	0	8.4774	0.5054	3.94
2	19	Graphite	22	120	5	76.5684	1.7093	6.16
2	20	Copper	22	120	5	39.864	1.3765	5.8
2	21	Graphite	22	40	0	29.1021	3.1563	3.78
2	22	Graphite	8	120	0	6.8553	2.9883	4.73
2	23	Graphite	8	40	0	7.1359	6.5741	2.9
2	24	Copper	8	120	5	21.4767	0.1595	5.51
2	25	Graphite	22	120	0	37.4865	1.0934	6.26
2	26	Copper	8	40	0	6.8461	2.764	4.07
2	27	Copper	22	120	0	25.8697	1.9535	5.63
2	28	Graphite	8	120	5	26.3219	1.8518	5.5
2	29	Graphite	8	40	5	12.102	8.1893	4.43
3	30	Graphite	8	120	0	6.1696	1.5401	4.77
3	31	Copper	22	120	0	30.2452	1.9765	5.61

3	32	Graphite	22	40	0	29.1021	3.1563	3.78
3	33	Graphite	22	40	5	68.3515	3.034	4.31
3	34	Graphite	22	120	5	75.967	1.3316	6.14
3	35	Copper	8	120	0	9.2215	0.4273	3.94
3	36	Copper	22	120	5	42.1101	2.0436	5.84
3	37	Copper	8	120	5	19.4589	0.1785	5.49
3	38	Graphite	8	120	5	26.0014	1.8518	5.48
3	39	Copper	22	40	5	40.266	6.3014	5.38
3	40	Copper	8	40	0	7.4271	2.7986	4.09
3	41	Graphite	8	40	0	12.1531	5.7332	2.81
3	42	Graphite	22	120	0	36.3096	1.376	6.24
3	43	Copper	8	40	5	8.9781	3.2374	5.34

The two level factors (2^4) full factorial design (FFD) is used to set the necessary number of experiments to fit the model. The ANOVA technique is used to analyze the significance of EDM process parameters, where the F-test ratio is calculated for a 95% level of confidence.

3.2. Predicted Model of MRR

The ANOVA functions then run in order to assess the results for the material removal rate (MRR) response which are given in Table (6) using the three factor levels for backward transform model for lower the p-value. The Model F-value of 139.27implies the model is significant. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case, A, B, D, AB, BC, BD, CD, ABD, BCD are significant model terms.

The predicted final empirical equation is:

$$\mathbf{Sqrt(Material\ removal\ rate(MMR))=} - 2.29642 - 4.17191 *A+1.50749 * B-7.90277 * D + *A *B+5.07388E-003*B*C + 0.99365*B*D + 0.10759*C*D+0.22618*A*B*D \qquad (5)$$

Table (6): The (ANOVA) table for material removal rate (MRR) after the EDM

Source	*Sum of Squares*	*df*	*Mean Square*	*F Value*	*p-value Prob> F*	
Block	289.91	2	144.95			
Model	15161.94	9	1684.66	139.27	< 0.0001	significant
A-type of electrode	139.01	1	139.01	11.49	0.0019	
B-Pulse current (Ip)	2344.44	1	2344.44	193.81	< 0.0001	
D-SiC powder mixed in kerosene dielectric	92.94	1	92.94	7.68	0.0093	
AB	893.77	1	893.77	73.89	< 0.0001	
BC	441.78	1	441.78	36.52	< 0.0001	
BD	351.37	1	351.37	29.05	< 0.0001	
CD	146.47	1	146.47	12.11	0.0015	
ABD	564.59	1	564.59	46.67	< 0.0001	
BCD	102.34	1	102.34	8.46	0.0067	
Residual	374.99	31	12.10			
Cor Total	15826.83	42				

The three dimensional (3D) graphs given in figures (3 - 6) are used to interpret and evaluate the model for the experimental group. These figures show the influence of the EDM and PMEDM parameters on the material removal rate. Figure (3) indicates that when using the copper electrodes and kerosene dielectric alone, the MRR increasing with increasing the pulse current (up to 22 A) and the pulse on duration (up to120 µs) reaching the value (27.0836 mm³/min), and when using the SiC powder mixing in kerosene dielectric, it reaches the value (40.9274 mm³/min). This means that the process removal rate increased by (151%), as shown in figure (6). The same results obtained when working with graphite electrodes and kerosene dielectric alone, where the maximum productivity of the process obtained with higher level of pulse current (22 A) and with the pulse on duration (120 µs), reaches a value (37.6474 mm³/min) as shown in figure (4) and reaches a predicted value of (71.4401 mm³/min) with the same previous parameters and using the SiC powder mixing in kerosene dielectric, as shown in figure (6). This means the process improved by (264 %) when using the SiC powder and the graphite electrodes with respect to the use of copper and kerosene dielectric alone, and the observed improvement by experimental works is (253 %) as calculated from the date given in Table (5). This means that productivity increases with the pulse current and pulse on duration time, especially when using the graphite electrodes. The amount of thermal energy generated would be great and is working to increase the melting and abrasive processing to remove successive layers of workpiece surface.

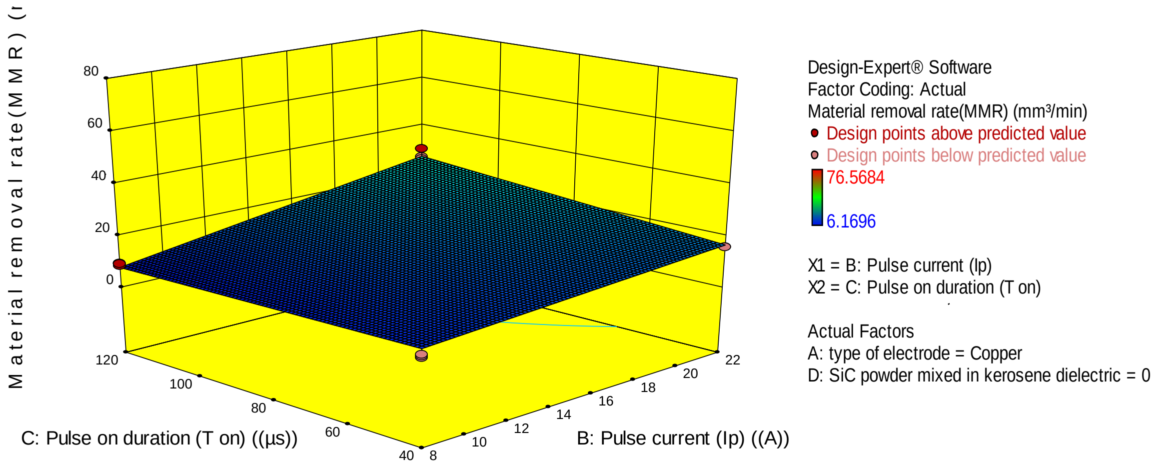

Figure (3): The 3D graph for MRR using kerosene dielectric alone and copper electrodes

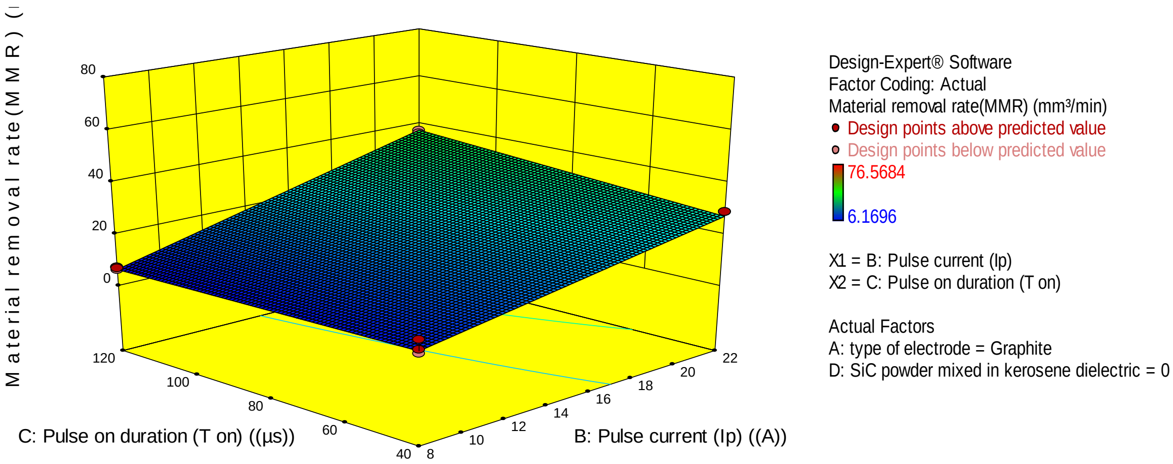

Figure (4): The 3D graph for MRR using kerosene dielectric alone and graphite electrodes

This energy will increase with increasing the pulse current period, especially when using the silicon carbide powder mixed in kerosene dielectric, which owns high level of hardness and abrasiveness and working to increase the removal property of the process. The high thermal conductivity of the graphite electrode material also works to increase the amount of thermal energy transformed to the workpiece surface, thereby improving removal and productivity efficiency.

3.2.1 Optimization of MRR

For optimization and development the predicted model with the best EDM and PMEDM parameters, a set of new goals for the MRR response will be conducted to generate optimal

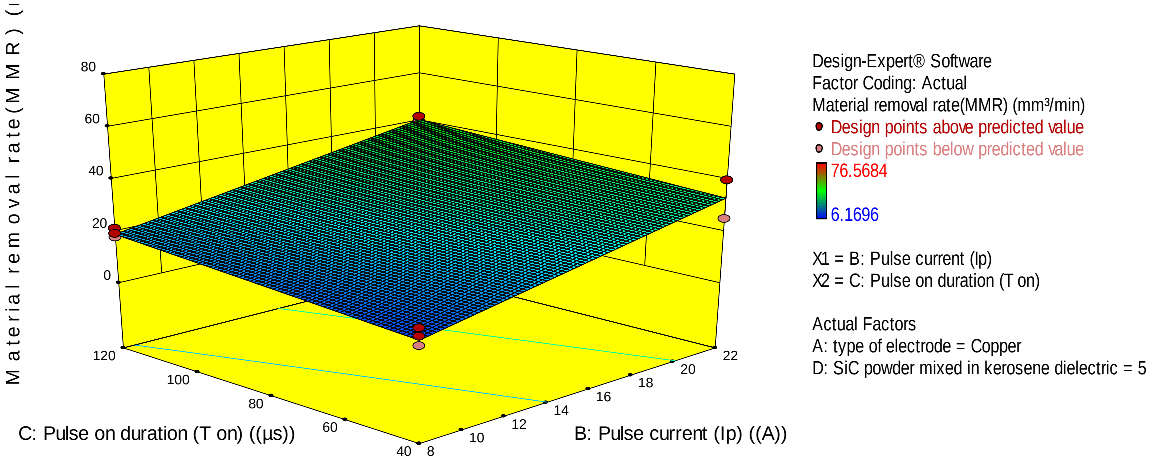

Figure (5): The 3D graph for MRR using kerosene dielectric with SiC powder mixing (PMEDM) and copper electrodes

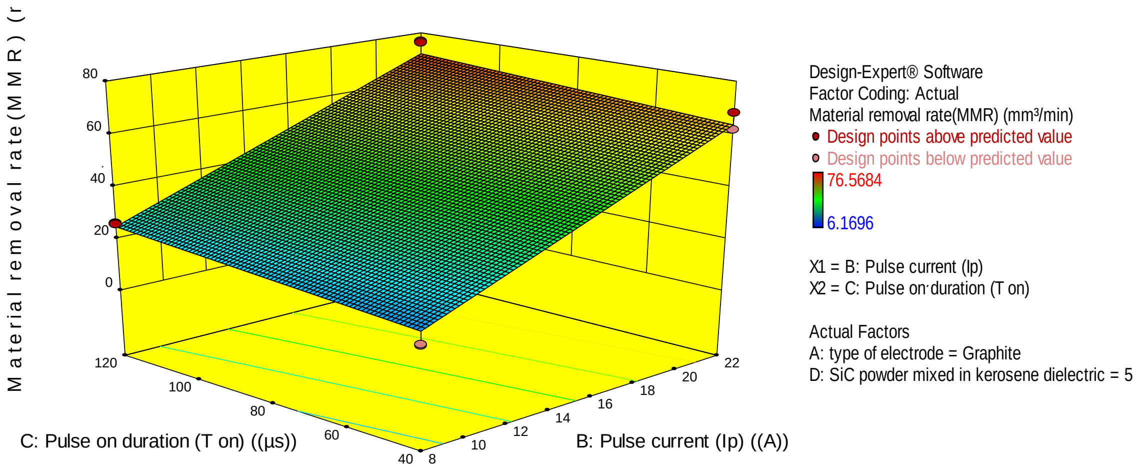

Figure (6): The 3D graphs for MRR using kerosene dielectric with SiC powder mixing (PMEDM) and the graphite electrodes

combination conditions for these parameters. The new objective function named the desirability will allow evaluating the goals by proper combining. The main goals are to maximize the values of response with the same ranges of the selected EDM parameters and electrodes types, as mentioned in Table (7). The best solution found from the desirability process shows that the optimum predicted values of the MRR obtained when using the graphite electrodes with pulse current about (22 A), pulse of duration about (120 µs) and using the Sic mixed powder gives the best maximum predicted MRR of (71.4401 mm³/min) with a maximum desirability ratio (0.927), as shown in table (8). The desirability process depicts that the best predicting response values are approximately the same with the obtained values by experiments, and this confirms the results of the present work.

Table (7): The new constraints goals for optimization theMRR of the process

Name	*Goal*	*Lower Limit*	*Upper Limit*	*Lower Weight*	*Upper Weight*	*Importance*
A:type of electrode	is in range	Copper	Graphite	1	1	3
B:Pulse current (Ip)	is in range	8	22	1	1	3
C:Pulse on duration (Ton)	is in range	40	120	1	1	3
D:SiC powder mixed in kerosene dielectric	is in range	0	5	1	1	3
Material removal rate(MMR)	maximize	6.1696	76.5684	1	1	3

Table (8): The desirability process for optimization of the predictedMRR

Number	*Type of electrode*	*Pulse current (Ip)*	*Pulse on duration (Ton)*	*SiC powder mixed in kerosene dielectric*	*Material removal rate (MMR)*	*Desirability*	
1	Graphite	22.000	120.000	5	71.440	0.927	Selected

3.3. Predicted Model of TWR

The ANOVA analysis for the tool wear ratio (TWR) response is given in table (9) using the three factor backward levels for transform model for lower the p-value. The Model F-value of 70.85implies the model is significant. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case, A, B, D, AB, AC, AD, BC, BD, CD, ABC, BCD are significant model terms. The predicted final empirical equation is:

Tool wear ratio (TWR)= + 7.65662 + 5.80684 * A - 0.079524 * B- 0.055686 * C+ 1.25665 * D

- 0.35579 * A * B-0.035305 * A * C + 0.44214 * A * D + 9.40164E-004 *B * C+9.40164E-004 * B * C-0.064853* B * D-0.013953 * C * D+ 2.31084E-003*A*B*C + 7.24107E-004*B*C*D (6)

Table (9): The (ANOVA) table for material removal rate (TWR) after the EDM

Source	*Sum of Squares*	*df*	*Mean Square*	*F Value*	*p-value Prob> F*	
Block	4.04	2	2.02			
Model	193.02	13	14.85	70.85	< 0.0001	significant
A-type of electrode	49.64	1	49.64	236.85	< 0.0001	
B-Pulse current (Ip)	2.30	1	2.30	10.99	0.0026	
C-Pulse on duration (T on)	39.14	1	39.14	186.75	< 0.0001	
D-SiC powder mixed in kerosene dielectric	2.31	1	2.31	11.04	0.0026	
AB	45.51	1	45.51	217.18	< 0.0001	
AC	15.67	1	15.67	74.78	< 0.0001	
AD	1.46	1	1.46	6.97	0.0136	
BC	2.86	1	2.86	13.66	0.0010	
BD	1.48	1	1.48	7.08	0.0130	
CD	2.44	1	2.44	11.64	0.0020	
ABC	17.16	1	17.16	81.87	< 0.0001	
ACD	0.79	1	0.79	3.76	0.0629	
BCD	1.66	1	1.66	7.94	0.0089	
Residual	5.66	27	0.21			
Block	4.04	2	2.02			

The three dimensional (3D) graphs given in figures (9 - 12) show the influence of the EDM and PMEDM parameters on the tool wear ratio. Figure (9) indicates that when using the pulse current (8 A) and pulse on duration (40 µs), the tool wear ratio decreased when using the copper electrodes and kerosene dielectric alone, reaching the values (2.70%) and (2.91%) when using the kerosene dielectric alone or with SiC, respectively. Figure (10) reveals the 3D graphs for TWR using the pulse current (22 A) and pulse on duration (40 µs), and the minimum tool wear ratio obtained when using the graphite electrodes SiC reaches the values (2.90%) and (3.32%) when using the kerosene dielectric alone or with powder mixing in kerosene, respectively. Figure (11) depicts the 3D graphs for TWR using the pulse current (8 A) and pulse on duration (120 µs), and the minimum tool wear ratio obtained when using the SiC powder mixing in kerosene dielectric and the copper and graphite electrodes reaches the values (0.03%) and (1.97%), respectively. Figure (12) manifests the 3D graphs for TWR using the pulse current (22 A) and pulse on duration (120 µs), and the minimum tool wear ratio obtained when using the graphite electrodes reaches the values (1.46%) and (1.65%) when using the kerosene dielectric or with SiC powder mixing in kerosene dielectric, respectively.

This means that the minimum value of TWR obtained when working with copper electrodes at pulse current (8 A), pulse on duration (120 µs) and kerosene dielectric with SiC powder mixing is (0.03%), experimentally (0.10%). This will allow for a greater amount of metal removal with the minimum electrode wear. It also allows access to the best accuracy for parts, especially when machining parts of large depths by using the same electrode without the need to be replaced, because the tool can maintain its original form for the longest period with these few percentage of wear ratios.

The increase in pulse on time duration from 40 to 120 µs for the same value of the used pulse current will reduce the wear ratio of the electrode, because the increase of time will fill the gap area between the electrode and workpiece with the removal molecules, and the flushing dielectric pressure will not be able to existing them outside the gap area with the required

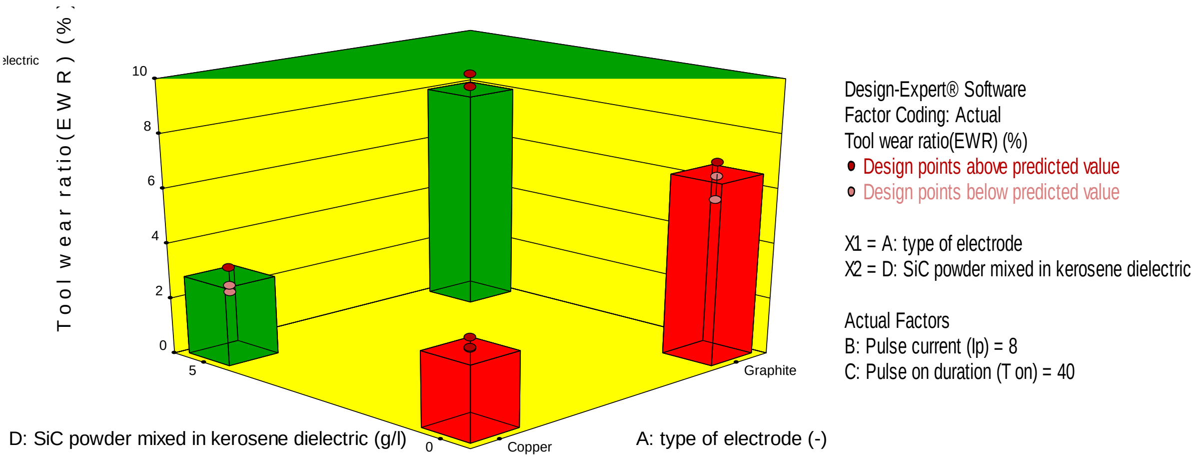

Figure (9): The 3D graphs for TWR using the pulse current (8A) and pulse on duration (40 µs)

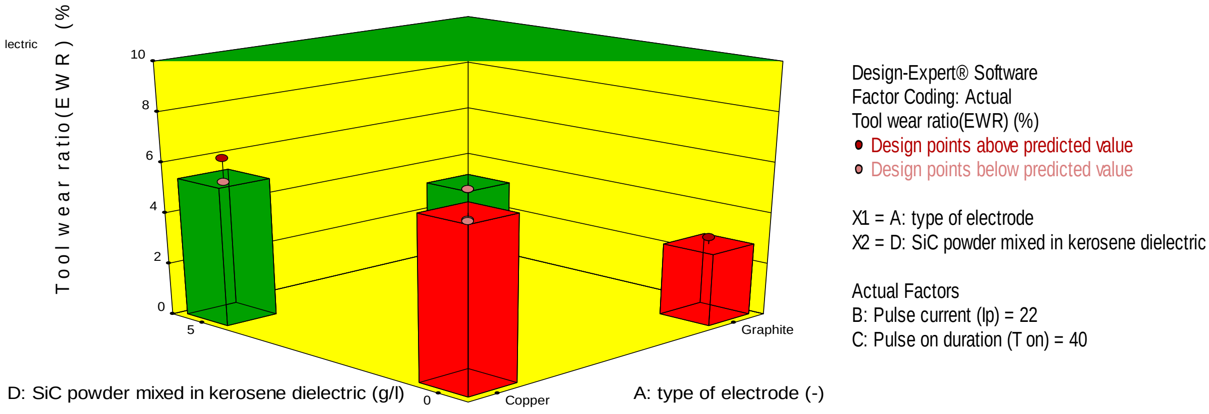

Figure (10): The 3D graphs for TWR using the pulse current (22 A) and pulse on duration (40 µs)

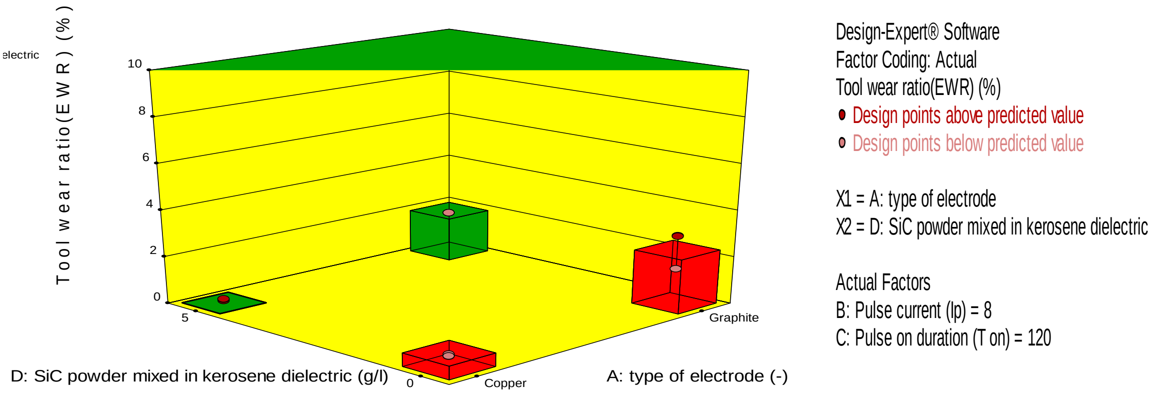

Figure (11): The 3D graphs for TWR using the pulse current (8 A) and pulse on duration (120 μs)

efficiency, which then reduces the rate of erosion of the workpiece surface layers. The use of copper electrode gives a wear ratio less than the graphite due to its high density as well as because the thermal conductivity of copper is less than graphite material which reduces the transition of thermal energy generated by the dielectric and thus to workpiece. This will reduce the ratio of carbon atoms interact with the electrode surface which is the main reason to its wear.

The use of silicon carbide powder increases the wear rate electrode when using a low pulse current value, because the removal process will work efficiently with the low levels of thermal energy generated. This wear ratio increases with increasing the duration of pulse current time at high values of the used pulse current because both of the melting, the abrasive and erosive processes will be involved in increasing the wear ratio of the electrode tool surface.

Preferably, the use of graphite electrodes when using high current for a short time because it transmits the generated heat away and cools quickly due to little amount of thermal energy generated, which maintains the surface of the electrode to minimum levels of erosion and wear. The gap area will be saturated with carbon atoms generated from the kerosene dielectric fluid, the powder mixed and electrode material, which reduces the wear ratio of the electrode materials.

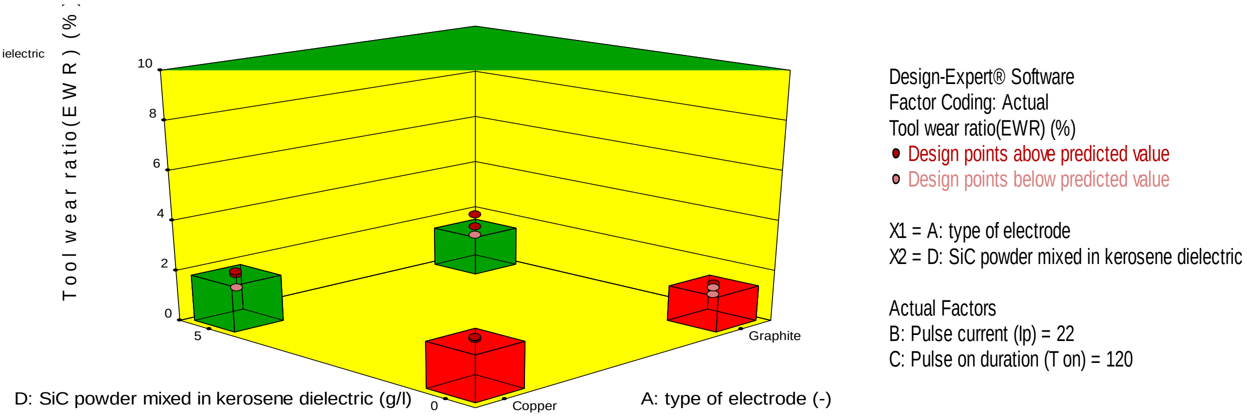

Figure (12): The 3D graphs for TWR using the pulse current (22 A) and pulse on duration (120 μs)

3.3.1 Optimization of TWR

For optimization the predicted model with the best EDM and PMEDM parameters, the desirability is to minimize the values of response with the same ranges of the selected EDM parameters and electrodes types, as mentioned in table (10). The best solutions found from the desirability process shows that the optimum predicted values of the TWR when using the copper electrodes with pulse current about (8.113 A), pulse of duration about (119.637 µs), and using the Sic mixed powder gives the best minimum predicted TWR of (0.057%) with a maximum desirability ratio (1.000), as shown in table (10). The desirability process reveals that the best predicting response values are approximately the same with the obtained values by experiments, and this confirms the results obtained experimentally.

Table (10): The desirability process for optimization of the predicted TWR

Number	*Type of electrode*	*Pulse current (Ip)*	*Pulse on duration (Ton)*	*SiC powder mixed in kerosene dielectric*	*Tool wear ratio(TWR)*	*Desirability*	
1	Copper	8.113	119.637	5	0.057	1.000	Selected

3.4. Predicted Model of SR

The ANOVA analysis for the surface roughness (SR) response is given in table (11) using the three factor backward levels for transform model for lower the p-value. The Model F-value of 86.78 implies the model is significant. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case,A, B, C, D, AC, BD, CD are significant model terms. The predicted final empirical equation is:

$$\mathbf{1/(Surfaceroughness(SR))} = + 0.30125 + 0.053812*A - 2.57236E\text{-}003 * B - 6.24073E - 004 *C - 0.065707*D - 5.21257E\text{-}004*A*C + 1.91312E\text{-}003*B*D + 2.00568E\text{-}004*C*D \quad (7)$$

Table (11): The (ANOVA) table for material removal rate (SR) after the EDM

Source	*Sum of Squares*	*df*	*Mean Square*	*F Value*	*p-value Prob> F*	
Block	8.101E-005	2	4.051E-005			
Model	0.099	7	0.014	86.78	< 0.0001	significant
A-type of electrode	0.022	1	0.022	136.31	< 0.0001	
B-Pulse current (Ip)	0.014	1	0.014	83.90	< 0.0001	
C-Pulse on duration (T on)	0.026	1	0.026	159.97	< 0.0001	
D-SiC powder mixed in kerosene dielectric	0.020	1	0.020	121.99	< 0.0001	
AC	0.018	1	0.018	112.23	< 0.0001	

BD	7.473E-003	1	7.473E-003	45.73	< 0.0001
CD	2.673E-003	1	2.673E-003	16.36	0.0003
Residual	5.393E-003	33	1.634E-004		
Cor Total	0.10	42			

The three dimensional (3D) graphs given in figures (13 - 16) show the influence the EDM and PMEDM parameters on the surface roughness. Figure (13) indicates that when using the pulse current (8 A) and pulse on duration (40 µs), the minimum SR obtained when using the graphite electrodes and kerosene dielectric alone reduced to (3.0252 µm). When using the SiC powder mixing, the minimum surface roughness reduced to values (4.0712 µm) with using the graphite electrodes. Figure (14) illustrates the 3D graphs for SR using the pulse current (22 A) and pulse on duration (40 µs), and the minimum surface roughness obtained when using the graphite electrodes reaches the values (3.7363 µm) and (4.2306 µm) when using the kerosene dielectric alone and the SiC powder mixing, respectively. Figure (15) clarifies the 3D graphs for SR using the pulse current (22 A) and pulse on duration (40 µs), and the minimum surface roughness obtained when using the kerosene dielectric alone reaches the values (4.1636 µm) and (4.4914 µm) when using the copper and graphite electrodes, respectively. Figure (16) depicts the 3D graphs for SR using the pulse current (22 A) and pulse on duration (120 µs), and the minimum surface roughness obtained when using the copper electrodes reaches the values (5.6541 µm) and (5.6165 µm) when using the kerosene dielectric alone or with SiC powder

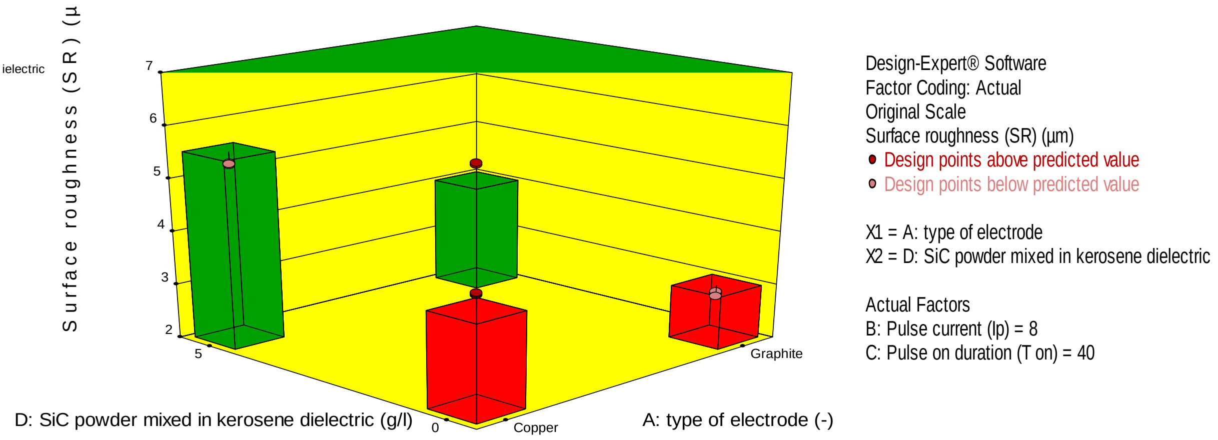

Figure (13): The 3D graphs for SR using the pulse current (8 A) and pulse on duration (40 µs)

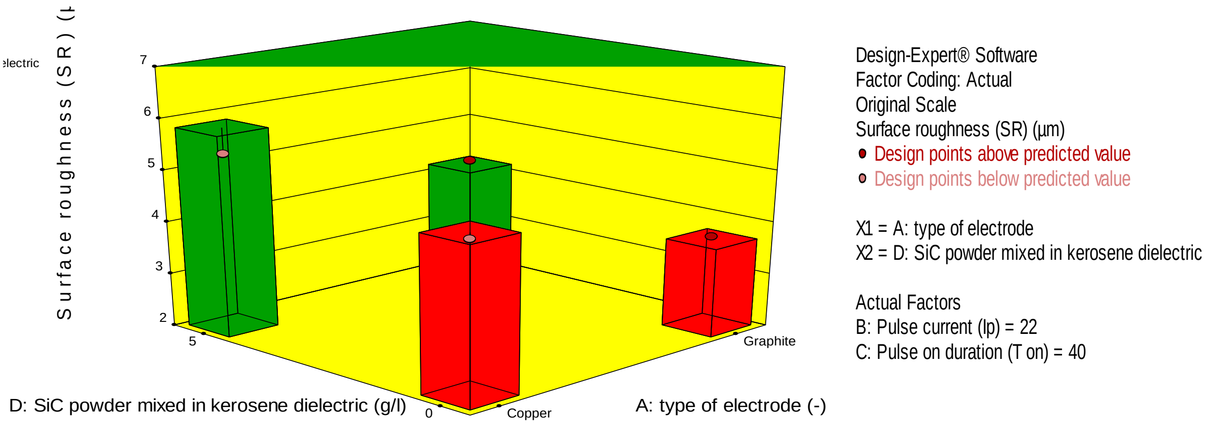

Figure (14): The 3D graphs for SR using the pulse current (22 A) and pulse on duration (40 µs) mixing respectively This means that the overall predicted minimum SR for all experiments runs obtained when working with graphite electrodes, the pulse current (8 A), the pulse on duration (40.µs) and kerosene dielectric alone with(3.0252 µm) value, experimentally (2.87 µm).

In general, the use of silicon carbide powder increases the surface roughness because it is an abrasive and erosive material and operates when increasing the gab temperature and with the pressurized dielectric to remove new layers from the surface of the workpiece and deliver them to the outside of the gab area by the combining operation of evaporation and melting, shearing and shocked molecules erosion of carbon and carbides, and all of this leads to increase the workpiece surface roughness.

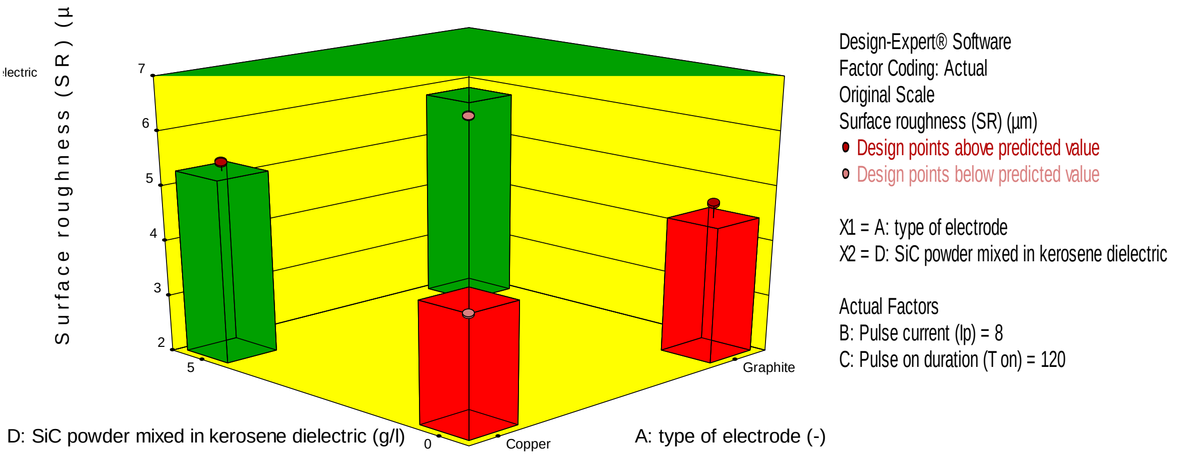

Figure (15): The 3D graphs for SR using the pulse current (8 A) and pulse on duration (120 µs)

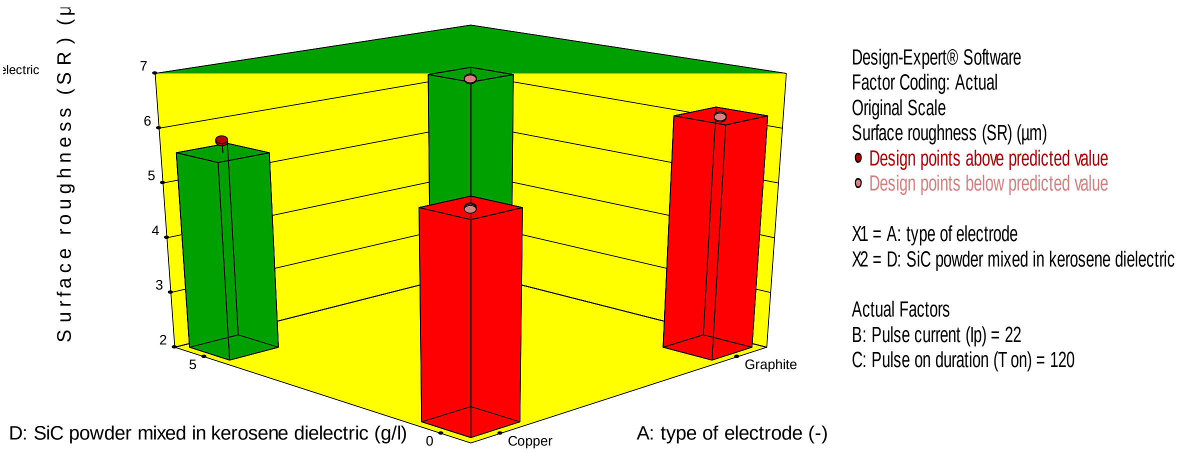

Figure (16): The 3D graphs for SR using the pulse current (22 A) and pulse on duration (120 µs).

The influence of the powder increases when using the low pulse current levels for a small period of time, because all the granules stripped from the surface of the workpiece will be removed, especially in the period of discharge off time and thus new layers composed suited to erosion and removal in largely manner.

The use of graphite electrodes gives better surface roughness when using low pulse current levels for a small period of time, because the abrasion process cannot accomplish its work completely due to the little amount of thermal energy necessary for melting the surface layer of workpiece and the short duration time of their generation, and thus the less melting and softening abilities of the surface layers are required to be removed as well as the lack of interactions is required for the generation of new carbides due to low level of energy generated.

The copper electrode gives better workpiece surface roughness when using high pulse current level with a short duration time because it generates a higher thermal energy and thus increases the melting of the surface layers of the workpiece, leading to the formation of a molten layer that freezes on the surface which is of better roughess than the erosive surfaces.

It is better to use the copper electrodes when using high pulse current level with a long duration time for the above mentioned reason and at the same time, the effect of using silicon carbide powder on the value of the obtained surface roughness is reducing, because the melting overcomes on the abrasive phenomenon, especially when using long periods of discharge times, where the amount of thermal energy generated are increasing.

3.4.1 Optimization of SR

For optimization the predicted model with the best EDM and PMEDM parameters, the desirability for minimize the values of response with the same ranges of the selected EDM parameters and electrodes types, as mentioned in table (12). The best tesolution found from the desirability process reveals that the optimum predicted values of the SR when using the graphite electrodes with pulse current about (8 A), pulse of duration about (40 µs) and using the kerosene dielectric alone gives the best minimum predicted SR of (3.025 µm) with a maximum desirability ratio (0.938), as shown in table (12). The desirability process exhibits that the best predicting response values are approximately the same with the obtained values by experiments (2.87 µm), with a difference less than (0.16 µm), and this confirms the results obtained experimentally.

Table (12): The desirability process for optimization of the predicted SR

Number	*Type of electrode*	*Pulse current (Ip)*	*Pulse on duration (Ton)*	*SiC powder mixed in kerosene dielectric*	*Surface roughness (SR)*	*Desirability*	
1	Graphite	8.000	40.000	0	3.025	0.938	Selected

4. Conclusions

The main conclusions obtained can be summarized in the following:

The best results for the productivity of the process (MRR) obtained when using the graphite electrodes, the pulse current (22 A), the pulse on duration (120 µs) and using the SiC powder mixing in kerosene dielectric reaches (76.76 mm³/min). This result gives an improvement in material removal rate by (264%) with respect to the corresponding value obtained when using copper electrodes with kerosene dielectric alone.

The best results for the tool wear ratio (TWR) of the process obtained when using the graphite electrodes, the pulse current (8 A), the pulse on duration (40 µs) and using the kerosene dielectric alone reaches (0.1023 %)

The use of graphite electrodes, the kerosene dielectric alone, the pulse current (8 A), and the pulse on duration (40 µs) gives the best surface roughness (SR) of a value (2.87 µm). This result yields an improvement in SR by (27%) with respect to the corresponding value obtained when using copper electrodes with the same parameters and machining conditions.

The desirability process shows that the best predicting response values are approximately the same as to those obtained by experiments as mentioned in the three above items, and this confirms the results of the present work.

5. References

1. E. C. Jameson,(2001),"Electrical Discharge Machining", Dearborn, Michigan, *SME*,.
2. O. H. Erzurumlu,(2007),"Comparison of response surface model with neural network in determining the surface quality of moulded parts," *Materials and Design*, Vol. 28, no. 2, pp. 459–465,.
3. Puertas I. and Luis, C. J.,(2004),"A study on the machining parameters optimisation of electrical discharge machining", *J. Mater. Process. Technol.* , 143/144, pp. 521–526,.
4. Tsai H. C., Yan B. H. and Huang F. Y.,(2003),"EDM performance of Cr/Cu-based composite electrodes", *Int. J. Mach. Tool Manuf.*, Vol. 43, pp. 245–252,.
5. S. Plaza, J. A. Sanchez, and E. Perez, el al.,(2014), "Experimental study on micro EDM-drilling of Ti6Al4V using helical electrode," Precision Engineering, Vol. 38, issue 4, pp. 821-827.
6. T. Wang and M. Kunieda,(2004), "Dry EDM for finish cut", *Key Engineering Materials*, Vol. 25, pp. 562–566,.
7. G. P. Petropoulos,(2007),"Multi-parameter analysis and modeling of engineering surface texture", *Journal of Achievements in Materials and Manufacturing Engineering,* Vol. 24/1, pp. 91-100,.
8. M. J. Jackson and G. M. Robinson,(2007),"Micromachining electrical grade steel using pulsed Nd-YAG lasers", *Journal of Achievements in Materials and Manufacturing Engineering,* Vol. 20,pp. 451-454,.
9. M. Kunieda, Y. Miyoshi, T. Takaya , N. Nakajima, Z.-B. Yu and M. Yoshida,(2003),"High speed 3D milling by dry EDM", *Annals of the CIRP*, Vol. 52/1, pp.147–150.
10. B. Kosec, G. Kosec and M. Sokoviæ,(2007), "Temperature field and failure analysis of die-casting die", *Archives of Materials Science and Engineering*, Vol. 28/3,pp. 182-187.
11. C. C. Kao, J. Tao and A. J. Shih,(2007)"Near dry electrical discharge machining", *International Journal of Machine Tools and Manufacture*, Vol. 47,pp. 2273–2281,.
12. G. F. Batalha, S. Delijaicov, J. B. Aguiar, E. C. Bordinassi and M. S.Filho,(2007),"Residual stresses modeling in hard turning and its correlation with the cutting forces", *Journal of Achievements in Materials and Manufacturing Engineering* , Vol. 24/ 1,pp. 350-356,.

13. J. C. Ferreira,(2006) “A study of die helical thread cavity surface finish made by Cu-W electrodes with planetary EDM”, *International Journal of Advanced Manufacturing Technology*, Vol. 30, pp. 1-13,.

14. M. Kiyak and O. Cakır,(2007)“ Examination of machining parameters on surface roughness in EDM of tool steel”, *Journal of Materials Processing Technology*, Vol.191, pp. 141-144,.

15. S. Prabhu and B. K. Vinayagam,(2010) “Analysis of surface characteristics of AISI D2 tool steel material using Electric Discharge Machining process with Single wall carbon nano tubes”, *International Journal of Engineering and Technology*, Vol. 2, pp. 35-41,.

16. A. Muttamara,(2015)” Comparison Performances of EDM on Ti6Al4V with Two Graphite Grades”, *International Journal of Chemical Engineering and Applications*, Vol. 6, No.4, August.

17. N. S. Khundrakpam, H. Singh, S. Kumar and G. S. Brar,(2014) ”Investigation and Modeling of Silicon Powder Mixed EDM using Response Surface Method”, *International Journal of Current Engineering and Technology*, Vol.4, No.2, April.

18. B. Reddy, G . N. Kumar and K. Chandrashekar, (2014)“Experimental Investigation on Process Performance of Powder Mixed Electric Discharge Machining of AISI D3 steel and EN-31 steel”, *International Journal of Current Engineering and Technology*,Vol. 4, No.3, June.

19. G. kocher, K. Chopra, S. Kumar,(2012), “Investigation of Surface integrity of AISI D3 tool steel After EDM”, *International Journal of Emerging Technology and Advanced Engineering*, ISSN 2250-2459, Vol. 2, Issue 4, April.

20. R. Atefi, N. Javam, A. Razmavar and F. Teimoori,(2012)," The Influence of EDM Parameters in Finishing Stage on Surface Quality, MRR and EWR”, *Research Journal of Applied Sciences, Engineering and Technology*, 4(10), pp.1287-1294,.

21. B. B. PATEL and K. B. RATHOD, (2012),“Multi-Parameter Analysis and Modeling of Surface Roughness in Electro Discharge Machining of AISI D2 Steel”, *International Journal of Scientific & Engineering Research*, Vol. 3, Issue 6, pp. 1-6, June,.

22. O. Belgassim and A. Abusada,(2012),” Optimization of the EDM Parameters on the Surface Roughness of AISI D3 Tool Steel”, *Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management*, Istanbul, Turkey, July, .

23. Fuling Z., Zhozhu L. and Baorang, Z.,(2004), “Study on the technological characteristics of powder-mixed electrical discharge machining”, *In: Proceedings of the Third International Conference and Exhibition on Design and Production of Dies and Mold*s, Bursa, Turkey, pp. 240–244, .

24. Lin J. L., Wang K. S., Yan B. H. and Tarng Y.S.,(2000),“Optimization of the electrical discharge machining process based on the Taguchi method with Fuzzy logics”, *J. Mater. Process. Technol.* , Vol. 102 (1–3), pp. 48–55,.

25. S. Kumar, R. Singh, T. P. Singh, and B.L. Sethi,(2009),“Surface modification by electrical discharge machining: A review”, *Journal of Materials Processing Technology*, Vol. 209, pp. 3675–3687, .

26. Ho K.H., Newman S. T.,(2003),“State of the art electrical discharge machining (EDM)”, *International Journal of Machine Tools & Manufacture*, Vol. 43, pp. 1287–1300.

27. Y. C. Lina, Y. F. Chena, D. A. Wanga and H. S. Leeb,(2009), “Optimization of machining parameters in magnetic force assisted EDM based on Taguchi method”, *Journal of Materials Processing Technology*, Vol. 209, pp. 3374–3383.

28. iyak M. and Akır O. C.,(2007), “Examination of machining parameters on surface roughness in EDM of tool steel”, *Journal of Materials Processing Technology,*Vol.191, pp. 141–144.

29. S. Ben Salem, W. Tebni and E. Bayraktar,(2011),”Prediction of surface roughness by experimental design methodology in Electrical Discharge Machining (EDM)”, Journal of Achievements in *Materials and Manufacturing Engineering*, Vol. 49, Issue 2, December .

30. S. R. Nipanikar,(2012), "Paraneter Optimization of Eectrodischarge machining of AISI D3 steel Material by Using Taguchi Method”, *Journal of Engineering Research and Studies, JERS*, Vol. III, Issue III,.

31. T. C Bhagat, B. L. Seth and H. S. Payal,(2013), “Optimization of EDM process parameters for surface roughness machining of die steel using copper tungsten electrode by adopting Taguchi array design ”, International Journal of Innovative Technology and Exploring Engineering (IJITEE),ISSN: 2278-3075, Vol. 3, Issue-3, August.

32. P. Janmanee,(2011),“Optimization of EDM of composite 90WC- 10Co based on Taguchi approach”, *European Journal of Scientific Research,*Vol. 64 No.3, ISSN 1450-216X.

33. Rama R and S. Padmanabhan,(2012), “Application of Taguchi method for metal removal rate in electro chemical machining of AISI composites”, *International Journal of Engineering Research and Application*, Vol. 2, Issue 3 ISSN 2248-9622, .

34. H. P. Beant,(2008),“Analysis of electro discharge machining EN 31 steel tool”, *Journal of Industrial and Scientific Research*, Vol. 67, pp 1072-1077, .

35. A. Bergaley and N. Sharma,(2013), “Optimization of Electrical and Non Electrical Factors in EDM for Machining Die Steel Using Copper Electrode by Adopting Taguchi Technique”, *International Journal of Innovative Technology and Exploring Engineering (IJITEE)*, ISSN: 2278-3075, Vol.-3, Issue-3,.

36. P. R. Kubade and V. S. Jadhav,(2012), “An Experimental Investigation of Electrode Wear Rate (EWR), Material Removal Rate (MRR) and Radial Overcut (ROC) in EDM of High Carbon-High Chromium Steel (AISI D3)”, *International Journal of Engineering and Advanced* Technology (IJEAT), ISSN, pp. 2249 – 8958, Vol. 1, Issue-5, .

37. ASTM A681,(1977),“Standard Specification for Tool Steels Alloy”, *American Society for Testing and Materials*, Washington, D.C., 1976.

38. ASTM A370, “Standard Test Method and Definitions for Mechanical Testing of Steel Products”, *American Society for Testing and Materials*, Washington, D.C., .