Study the Effect of the Graphite Powder Mixing Electrical Discharge Machining on Creation of Surface Residual Stresses for AISI D2 Die Steel Using Design of Experiments

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ABSTRACT

This paper attempted to study the induced surface residual stresses due the effect of Electrical discharge machining (EDM) input parameters, (the pulse current, the pulse-on time and the type of electrode). The work included the use of two types of electrode, the copper and graphite as well as using or without using the graphite powder mixing with the kerosene dielectric (PMEDM) for machining AISI D2 dies steel. The response surface methodology (RSM) was used for design the experimental work matrices. The analysis of variance (ANOVA) was used, and models were built to predict the surface residual stresses. The obtained results showed that the minimum tensile surface residual stresses obtained when using the copper electrodes with pulse current (22 A) and pulse on duration (40 μs) when working with kerosene dielectric alone and (8 A) with (120 μs) when working with graphite powder mixing. The results concluded that the using of graphite electrodes and kerosene dielectric alone or with powder mixing induced minimum residual stresses with pulse current (22 A) and pulse on duration (120 μs). The copper electrodes with kerosene dielectric and graphite powder mixing improved the induced tensile residual stresses by about (80 %) lower than when using kerosene dielectric alone and about (50%) lower than with graphite electrodes and the kerosene dielectric alone or with graphite mixing powder.

Keywords: EDM, RSM, ANOVA, Surface residual stresses, Die steel, Graphite powder mixing PMEDM.

دراسة تأثير مسحوق الجرافيت المخلوط بعملية التشغيل بالتفريغ الكهربائي على إنشاء الاجهادات السطحية المتبقية لصلب القوالب نوع AISI D2 باستخدام تقنية تصميم التجارب

الخلاصة

هذا البحث حاول دراسة الاجهادات السطحية المتبقية الناجمة بسبب تأثير المدخلات لعملية التشغيل بالتفريغ الكهربائي (تيار النبضة ،زمن استمرار النبضة ونوع الالكترود). وتضمن العمل على استخدام نوعين من القطب (الالكترودات) وهما النحاس والجرافيت وكذلك باستخدام أو بدون استخدام مسحوق الجرافيت المخلوط (PMEDM) مع الكيروسين العازل لتشغيل صلب القوالب نوع AISI D2. وقد تم استخدام منهجية استجابة السطح (RSM) لتصميم مصفوفات العمل التجريبية. كما تم استخدام تحليل التباين ، وبنيت نماذج للتنبؤ بالاجهادات السطحية المتبقية. وأظهرت النتائج أن أدنى اجهادات سطحية شدية متبقية تم الحصول عليها عند استخدام أقطاب النحاس مع تيار نبضة مقداره (22 امبير) وزمن استمرار النبضة مقداره (40 ميكرو ثانية) عند العمل مع الكيروسين العازلة لوحده، و(8 امبير) مع (120 ميكرو ثانية) عند العمل مع مسحوق الجرافيت المخلوط. وخلصت النتائج إلى أن استخدام أقطاب الجرافيت والكيروسين العازل لوحده أو مع مسحوق الخلط فان اجهادات سطحية شدية متبقية ناجمة عند استعمال تيار نبضة مقداره (22 امبير) وزمن استمرار النبضة مقداره (120 ميكرو ثانية). ان استعمال أقطاب النحاس مع الكيروسين العازل ومسحوق الخلط الجرافيت عملت على تحسين الاجهادات السطحية الشدية المتبقية الناجمة بحوالي (80٪) أقل من حالة استخدام الكيروسين العازل لوحده، وحوالي (50٪) أقل من حالة استخدام أقطاب الجرافيت مع الكيروسين العازل لوحده أو مع مسحوق الخلط الجرافيتي

INTRODUCTION

Electrical discharge machining (EDM) is one of the important non-traditional machining processes. It is one of the most successful, practical and profitable non-conventional machining processes for machining newly developed high strength alloys with high degree of dimensional accuracy and economical cost of production. Machining of electrically conductive material irrespective of its hardness, by the application of thermal energy, is one of the prime advantages of electrical discharge machining process. These hard and brittle materials like high alloyed quenched steels, ceramic and tungsten carbide materials when fabricated by conventional machining operation cause excessive tool wear and expense Y.H. Guu,et al [1].

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 mould making industries, aerospace, aeronautics, and nuclear industries. EDM has also made its presence felt in the new fields such as sports, medical and surgical instruments, optical, dental and jewelry industries, including automotive R&D areas [2-6].

Considerable thermal residual stresses are created on the upper layer of workpiece surface due to rapid solidification of EDM processes, which will influence the component properties. The displaying of discharge in EDM is essentially a thermal erosion procedure [7]. There is very little information in literature on the residual stresses of after EDM.

EDM is a thermal process. Instantaneous temperature rise during the machining process changes the physical properties of the machining surface layer, resulting in the presence of residual stress which is one of the key factors affecting the machined surface quality and its functional performance [8-10].

Powder mixed electric discharge machining (PMEDM) is one of the new innovations for the enhancement of capabilities of electric discharge machining process. In this process, a suitable material in fine powder is properly mixed into the dielectric fluid. The added powder improves the breakdown characteristics of the dielectric fluid. Wang et al. [11] investigated the effect of mixing Al and Cr powder mixture in kerosene. The results indicated that Al and Cr mixture in kerosene fluid reduces the isolation and increases the spark gap. With this, the process gets stabilized, and the material removal rate (MRR) is enhanced considerably. The effect of various powder characteristics on machining of SKD-11(equivalent to AISI H13 die steel) material was reported by Tzeng and Lee [12].

Despite the promising results, powder mixed EDM process is applied in industry at very slow pace. One of the key reasons is that many fundamental issues of this new development, including the machining mechanism, are still not well understood [13]. Khundrakpam et al. [14], have been used Response Surface Method (RSM) to explore the influence of process parameter such as; peak current, powder concentration and tool diameter on the Material Removal Rate (MRR) on EN-8 steel. Reddy et al. [15], study the effect of fine metal powders such as aluminium(Al) and copper(Cu) which are mixed to the dielectric fluid, during Electric Discharge Machining (EDM) of AISI D3 Steel and EN-31 steel. Taguchi design of experiments is used to conduct experiments.

Many attempts had been made for modeling of EDM process and investigation of the process performance. Pradhan and Biswas [16] developed regression model and two artificial neural networks (ANNs) namely: Back propagation and radial basis function to predict surface roughness in electrical discharge machined surfaces.

This paper attempted to study the induced surface residual stress by the influence of the EDM parameters using two types of electrode, the copper and graphite and with using or without using the graphite powder mixing in kerosene dielectric (PMEDM) for AISI D2 die steel. The response surface methodology (RSM) was used to design the experimental work matrices for both electrodes materials. The analysis of variance (ANOVA) models are used to predict the surface residual stresses and to developing models for two groups of experiments. The first group was performed in pure kerosene dielectric, while the second with addition of abrasives graphite powders mixed in dielectric fluid (PMEDM) in order to improve the machining efficiency and the instability of arcing effects and to study the residual stresses induced by the process variations.

Experimental Procedure

The work piece materials used is the AISI D2 die steel [17], which is very widely used in moulds and dies. AISI D2 is a high-carbon, high-chromium tool steel alloyed with molybdenum and vanadium recommended for tools requiring very high wear resistance. The used material was tested for chemical composition by using the material analyzer tester. The results are given in table (1). These results indicate that the used material conforms to the equivalent standard AISI D2 die steel.

Four specimens were prepared for tensile tests by using the universal testing machine type UNITED on the bases on ASTM-77 steel standards for flat workpiece [18] as shown in figure (1 and 2). The same specimens are also tested by Rockwell ball hardness tests, as the workpiece material in as received state. The average HRB hardness value with the tensile tests results are given in table (2). The wire electrical discharge machine (WEDM) type ACRA Brand/Taiwan was used to manufacture the workpieces with a surface grinding machine. Finally, the specimens were polished mechanically and manually by abrasive silicon carbide paper up to grade ASTM 3000. The surface residual stresses were measured before and after EDM machining by using the X-RAY DIFRACTOMETER (XRD) testing equipment.

Two types of electrodes materials, Copper and Graphite are selected. The electrodes were manufactured with a square cross-section of 24 mm and 30 mm lengths, with a quantity of 24 pieces for each type shown in figure (3). The prepared electrodes were polished as mentioned above.

The main designed EDM parameters are the gap voltage V_p (140 V), the pulse current I_p (8 and 22 A), the pulse on time duration period time T_{on} (40 and 120 µs), the pulse off time duration period T_{off} (14 and 40 µs), i.e., the duty factor (33%), the graphite 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 (+). The EDM experiments were done on ACRA CNC-EB EDM machine with all the manufactured attachments shown in figure (4). A stainless steel container (of about 30 liters volume, and the overall dimensions (400x300x230 mm) were manufactured for the powder micro blasting (peening) of powder mixing with dielectric fluid (PMEDM). It contains a special kerosene dielectric pump, an electric motor (300 RPM) connected to a mixture contains 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 as shown in figure (5). The chemical composition tests of the graphite powders substances were conducted 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 (44,866 µm) for silicon carbide powder. Silicon carbide is an excellent abrasive and has been produced and made into grinding wheels and other abrasive products It is used in abrasives, refractories, ceramics, and numerous high-performance applications.

Design of experiments (DOE):

In this work, two groups of experiments are designed, each contains (22) experiments for studying the inducing surface residual stresses resulting from thermal stresses produced by EDM and PMEDM machining. Each group was divided in two subgroups for working with kerosene dielectric alone for the first subgroup and with kerosene dielectric mixing with graphite powder, with concentration (5 litter/gm.). In the first group, the copper electrodes were used, while the graphite electrodes were used in the second group. A new set of workpiece and electrode was using in each experiment. The surface residual stresses experimentally measured after EDM and PMEDM machining with the input parameters were modeled by using the response surface methodology (RSM) and the two level factorial designs for both experimental groups. The input EDM parameters and their levels are given in table (3). The designed EDM experimental matrix in a random manner with the selected factors (actual and coded) and the experimental results for residual stresses for both groups using the kerosene dielectric or the kerosene dielectric with graphite powder mixing with using copper and graphite electrodes are given in table (4) and (5), respectively, where (-1) and (+1) are the coded values represent the maximum and minimum values of each desired input parameter respectively.

The response results show that all the measured residual stresses after EDM and PMEDM machining are in tensile values for the both groups. In group (1) using copper electrodes, the minimum tensile residual stresses obtained is (175.485) MPa. In group (2) experiments using the graphite electrodes the minimum tensile residual stresses obtained is (245.239) MPa. The two level factors (2^3) full factorial design (FFD) is used to set the necessary number of experiments to fit the second-order model. The ANOVA technique is used to analyse the significance of EDM process parameters, where the F-test ratio is calculated for a 95% level of confidence. The inversion model obeys the least squares theory. The ANOVA function then runs in order to assess the results which are given in table (6) using the backward inverse two factor (2^3) levels transform model for lower the p-value. The Model F-value of 42.90 implies the model is significant. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, AC are significant model terms, where A is the pulse current (I_p), B is the pulse on duration (T_{on}) and C is the graphite powder mixed concentration in kerosene dielectric.
The predicted final empirical equation is:

1/(Residual stresses) = + 1.83189 E – 003 + 6.81252E – 005 *A + 9.59449 E - 006 * B + 7.327 E – 004 * C - 5.97498 E – 007 * A* B -3.06359E-005* A* C …..(1)

The ANOVA analysis for group (2) experiments using graphite electrodes with an inverse main factors transform two factor level (2^3) model is given in table (7). The Model F-value of 29.57 implies the model is significant. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C are significant model terms.
The final empirical equation for after EDM and PMEDM machining is:

1/(Residua lstresses)=+3.105E-003+1.354E-004*A+2.132E-004*B+4.617E-004*C .. (2)

The diagnostic Process for evaluate the model fit and transformation choice was shown in figure (6) for the normal probability plot to check for normality of residuals after EDM machining for copper and graphite electrodes. The plots show that the residual distributed normally on a straight line. The two dimensional (2D) contour model graphs given in figures (7 and 8) are used to interpret and evaluate the model for group (1).

These figures showed the influence the EDM and PMEDM parameters on the workpieces surface residual stresses for copper electrodes respectively. Both figures indicated a tensile residual stresses. For subgroup (1), without using the powder mixing the residual stresses decreases with increasing the pulse current up to (22A) and decreasing the pulse on duration value (to 40 µs), while for subgroup (2) with using the graphite powder mixing with decreasing the pulse current (to 8 A) and increasing the pulse on time duration (up to 120µs) as shown in figure (5 and 6) respectively. The minimum surface residual stresses reaches (316.8MPa) when working with kerosene dielectric alone, where the minimum residual stresses obtained when using the copper electrodes the kerosene dielectric with 5g/l graphite powder is (175.485) as shown in figures (7 and 8) respectively. This means that the using of copper electrodes with graphite powder mixing in kerosene dielectric improved the induced residual stresses by about (80%). Figures (7 and 8) show the (2D) surface graphs for the influence of the selected EDM parameters on surface residual stresses for graphite electrodes without and with graphite powder mixing in kerosene dielectric respectively. These figures show that the lower values of tensile residual stresses obtained when use the kerosene dielectric alone (figure 9) with maximum value of pulse current (22 A) and pulse on duration time (120 µs) and reaches (348.006 MPa). The lower values of tensile residual stresses obtained when use the kerosene dielectric with graphite powder mixing (figure 10) with maximum value of pulse current (22 A) and maximum value of pulse on duration time too (120 µs) and reaches (344.873 MPa). This means that the use of graphite mixed powder improve the residual stresses obtained by only about (1%) when comparing with the case of working with kerosene dielectric alone. Also the use of copper electrodes and kerosene dielectric alone gives residual stresses about (9%) lower than with graphite electrodes.

The best results for tensile minimum stresses obtained when using copper electrode and graphite powder mixing in kerosene dielectric and when using a lower levels of pulse currents and longer duration time, as a little amount of thermal energy generated and that will work on the formation of a recast hard workpiece surface with minimum thickness and with the presence of the hard graphite powder particles that will reduce the thickness of this layer. When the current increases, the amount of melting the surface layer will be increased due to the generation of large amount of thermal energy which leads to the formation of a solid and hard layer on the surface of the workpiece which is cooled quickly due to decrease the duration of the pulse current time and therefore lowering the effect of the powder mixed because it will impacted with a high molten surface layer. This will slightly increase the hardness of the recast layer as some carbides will be formation especially the iron and chromium carbides.

When using a graphite electrodes, the effect of the graphite powder mixture will be least with different current and time values, because the low electrical resistivity of graphite electrodes causing thermal energy not high enough to lead powder mixture molecules doing their role where they will impacting a hard and quenching surface in all the duration periods of the cutting process where the workpiece was submerging in the dielectric fluid as well as the high pressure dielectric flushing from both sides to the gab between the electrode and workpiece.

For development the predicted model with the best EDM and PMEDM parameters, a set of new goals for the response will be conducted to generate optimal combination conditions for these parameters. The new objective function named the desirability, will allow evaluating the goals by properly combining. The main goals are to minimize the values of response surface residual stresses with the same ranges of the selected EDM parameters and electrodes types as mentioned in table (8) for EDM experiments using the copper electrodes. The best solutions founded from the desirability process shows that the optimization predicted values of the surface residual stresses obtained when using the copper electrodes with pulse current (8A), pulse of duration (120μs) and with using the graphite mixed powder gives the best minimum tensile surface residual stress (186.099 MPa) with a maximum desirability ratio (0.944) . For graphite electrodes, the desirability process obtained with the parameters that similar with those when use the copper electrodes. The optimum predicted values of the tensile surface residual stresses obtained with pulse current (22A) and pulse of duration (120 μs) and with using of graphite powder mixing gives the minimum tensile surface residual stresses (256.577 MPa) with a maximum desirability ratio (0.929). The desirability process shows that the best predicting response values are approximately the same with the obtained values by experiments and this confirmation the results of the present work.

CONCLUSIONS:

The main conclusions obtained can be summarized in the following:

1- The results obtained indicated that when using the copper electrodes and kerosene dielectric alone, the tensile residual stresses decreases with increasing the pulse current up to (22A) and with decreasing the pulse on duration value (to 40 μs). The minimum tensile surface residual stresses reach (316.8 MPa).

2- When using the kerosene dielectric with 5g/l graphite powder the tensile residual stresses decreases with decreasing the pulse current to (8A) and increasing the pulse on duration value (up to 120 μs) and the minimum tensile surface residual stresses reaches (320.788 MPa) i.e. improved the induced residual stresses by about (80%) lower than when using kerosene dielectric alone.

3- When using the graphite electrodes, the use of graphite mixed powder will not improve to beneficial values the residual stresses obtained at high parameters rates (pulse current 22 A and pulse on duration time 120 μs) when comparing with the case of working with kerosene dielectric alone.

4- The use of copper electrodes and kerosene dielectric alone gives residual stresses about (9%) lower than with graphite electrodes.

5- The copper electrodes with kerosene dielectric and graphite powder mixing improved the induced residual stresses by about (50%) lower than with graphite electrodes and the kerosene dielectric alone or with graphite mixing powder.

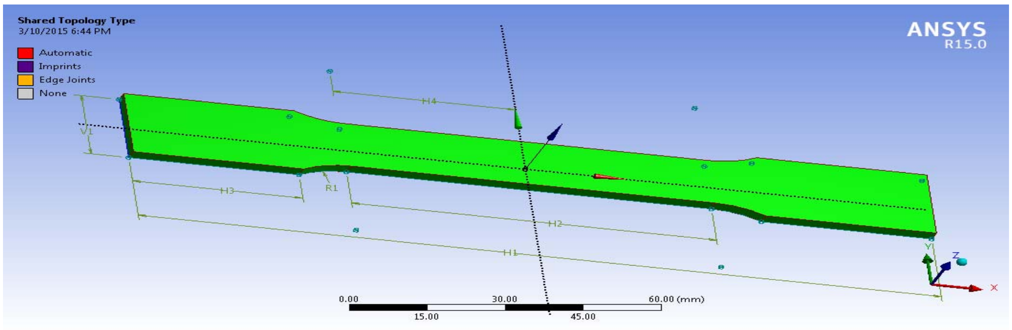


Figure (1): The tensile test dimensions according to ASTM A 681-77 (Total length=165 mm, Width=20 mm, Thickness 2.7 mm, Working length=50 mm)

Figure (2): The specimens prepared for tensile tests

Figure (3): The copper, graphite electrodes and workpieces after PMEDM processes

Figure(4): The (CNC) EDM machine with all the manufactured accessories designed for the implementation the PMEDM experiments

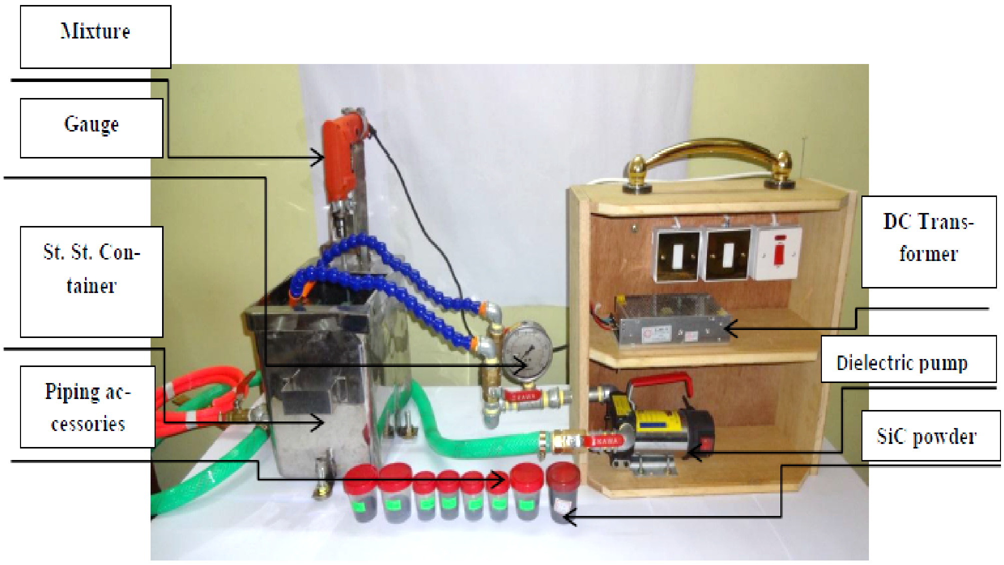
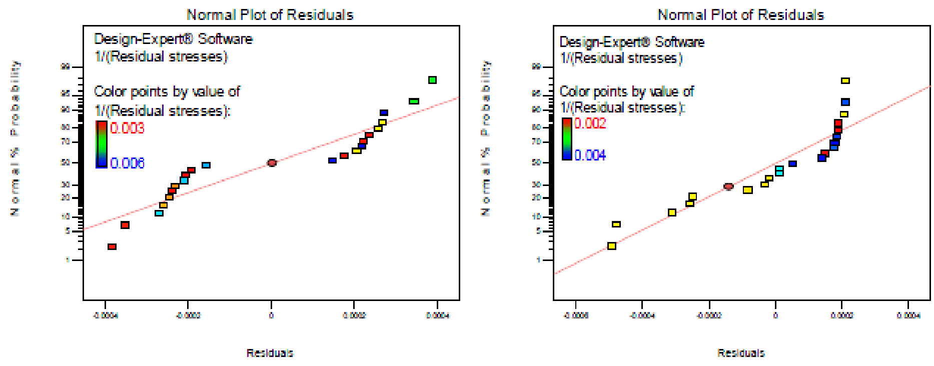
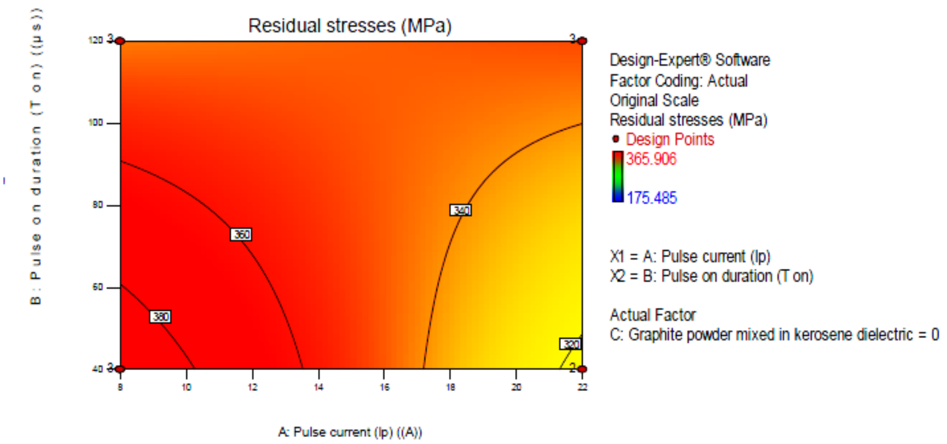


Figure (5): The manufactured stainless steel container with accessories

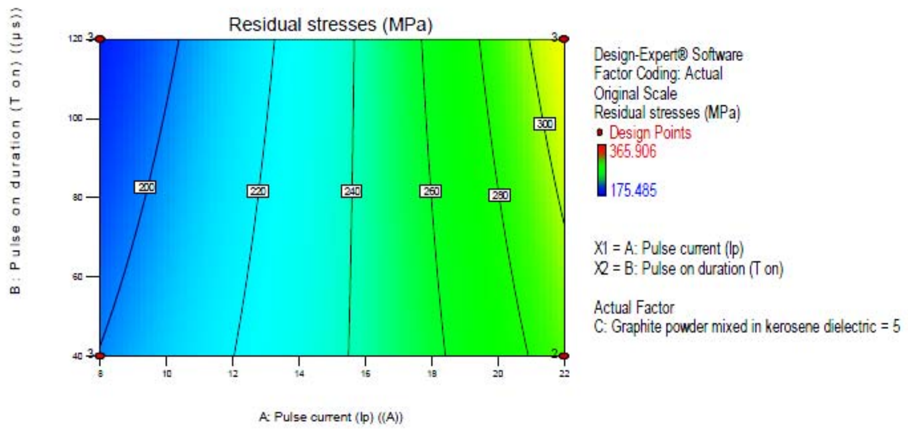


(a) **(b)**

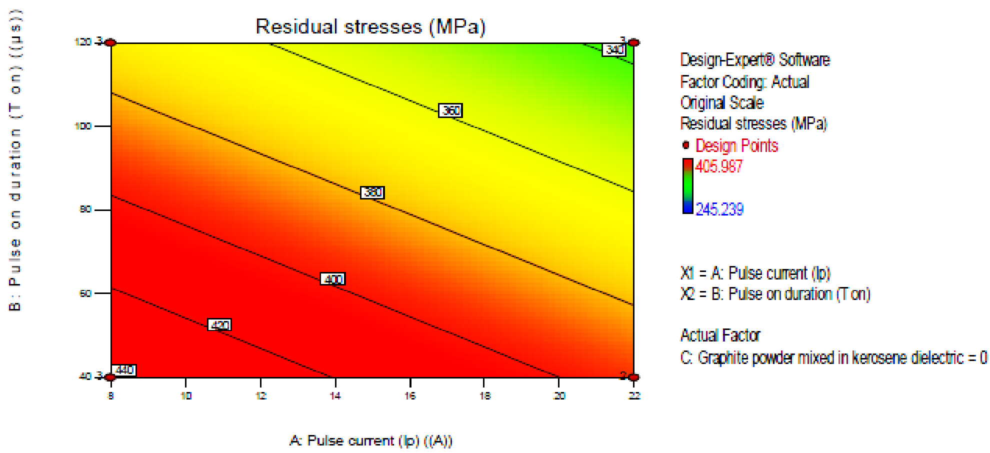
Figure (6): The normal probability – residuals plot, (a) copper electrodes and (b) graphite



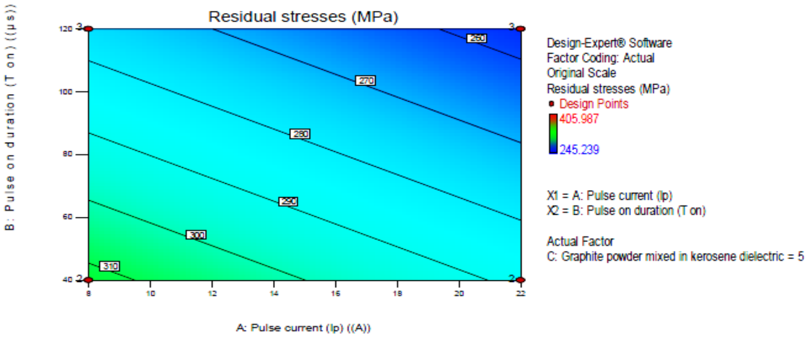
Figures (7): The contour model graphs for EDM processes using copper electrodes and the kerosene dielectric alone, group (1)



Figures (8): The contour model graphs for EDM and PMEDM using copper electrodes and the kerosene dielectric with 5g/l SiC powder, group (1)



Figures (9): The contour model graphs for EDM processes using graphite electrodes and the kerosene dielectric alone, group (2)



Figures (10): The contour model graphs for EDM and PMEDM using graphite electrodes and the kerosene dielectric with 5g/l SiC powder, group (2)

Table (1): The chemical composition for the selected workpiece 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 %
Tested plates	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 ASTM A681-76 [17]	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 stressN/mm²	Yield strengthN/mm²	Elongation%	HRB hardness
Average	704.25	415.25	18.125	90.25

Table (3): The input EDM parameters and their levels for both groups (I_p), (T_{on})

Fac.	Name	Units	Type	Subtype	Min.	Max.	Coded Values		Levels
A	Pulse current (I_p)	(A)	Numeric	Continuous	8	22	-1	+1	2
B	Pulse on duration (T_{on})	(µs)	Numeric	Continuous	40	120	-1	+1	2
C	Graphite powder mixed in kerosene dielectric	g/l	Numeric	Continuous	0	5	-1	+1	2

Table (4): The designed experimental matrix for Group (1) using copper elect- rodes

Std	BLOCK	Run No.	Input factors(Actual)			Input factors (Coded)			Response
			X1	X2	X3				
			A: Pulse current I_p (A)	B: Pulse on duration T_{on}(µ tion T_{on}(µs)	C:Graphite powder mixed in kerosene dielectric(g/l)	X1	X2	X3	Residual stresses (MPa)
12	1	1	8	40	5	-1	-1	+1	208.625
4	1	2	22	40	0	+1	-1	-1	356.99
1	1	3	8	40	0	-1	-1	-1	358.885
20	1	4	22	120	5	+1	+1	+1	338.929
6	1	5	8	120	0	-1	+1	-1	364.505
15	1	6	22	40	5	+1	-1	1	261.682
9	1	7	22	120	0	+1	+1	-1	316.8
17	1	8	8	120	5	-1	+1	+1	178.332
21	2	9	22	120	5	+1	+1	+1	340.529
2	2	10	8	40	0	-1	-1	-1	360.197
13	2	11	8	40	5	-1	-1	+1	212.488
5	2	12	22	40	0	+1	-1	-1	356.05
18	2	13	8	120	5	-1	+1	+1	181.537
16	2	14	22	40	5	+1	-1	+1	260.458
10	2	15	22	120	0	+1	+1	-1	318.167
7	2	16	8	120	0	-1	+1	-1	365.906
14	3	17	8	40	5	-1	-1	+1	204.637
11	3	18	22	120	0	+1	+1	-1	317.849
19	3	19	8	120	5	-1	+1	+1	175.485
8	3	20	8	120	0	-1	+1	-1	363.499
22	3	21	22	120	5	+1	+1	+1	336.095
3	3	22	8	40	0	-1	-1	-1	359.429

Table (5): The designed experimental matrix for Group (2) using graphite electrodes

Std	BLOCK	Run No.	Input factors(Actual)			Input factors(Coded)			Response
			X1	X2	X3				Residual stresses (MPa)
			A: Pulse current I_p (A)	B: Pulse on duration T_{on} (µs)	C:Graphite powder mixed in kerosene dielectric (g/l)	X1	X2	X3	
1	1	1	8	40	0	-1	-1	-1	467.98
16	1	2	8	120	5	-1	+1	+1	372.719
9	1	3	22	120	0	+1	+1	-1	367.231
4	1	4	22	40	0	+1	-1	-1	358.916
14	1	5	22	40	5	+1	-1	+1	405.987
6	1	6	8	120	0	-1	+1	-1	346.369
12	1	7	8	40	5	-1	-1	+1	358.426
19	1	8	22	120	5	+1	+1	+1	363.136
13	2	9	8	40	5	-1	-1	+1	356.675
20	2	10	22	120	5	+1	+1	+1	362.194
17	2	11	8	120	5	-1	+1	+1	344.873
10	2	12	22	120	0	+1	+1	-1	405.336
2	2	13	8	40	0	-1	-1	-1	469.062
15	2	14	22	40	5	+1	-1	+1	359.265
5	2	15	22	40	0	+1	-1	-1	373.753
7	2	16	8	120	0	-1	+1	-1	368.014
21	3	17	22	120	5	+1	+1	+1	465.73
18	3	18	8	120	5	-1	+1	+1	403.279
11	3	19	22	120	0	1	+1	-1	348.006
3	3	20	8	40	0	-1	-1	-1	367.692
8	3	21	8	120	0	-1	+1	-1	373.876

Table (6): The (ANOVA) analysis for the EDM group (1) experiments using copper electrodes

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Block	8.483E-008	2	4.241E-008			
Model	2.229E-005	5	4.458E-006	42.90	< 0.0001	significant
A-Pulse current (I_p)	7.181E-007	1	7.181E-007	6.91	0.0198	
B-Pulse on duration (T_{on})	6.085E-007	1	6.085E-007	5.86	0.0297	
C-Graphite powder mixed in kerosene dielectric	1.407E-005	1	1.407E-005	135.44	< 0.0001	
AB	5.758E-007	1	5.758E-007	5.54	0.0337	
AC	6.271E-006	1	6.271E-006	60.36	< 0.0001	
Residual	1.455E-006	14	1.039E-007			
Cor Total	2.383E-005	21				

Table (7): The (ANOVA) analysis for the EDM group (1) experiments using graphite electrodes

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Block	1.482E-008	2	7.411E-009			
Model	6.195E-006	3	2.065E-006	29.57	< 0.0001	**significant**
A-Pulse current (I_p)	3.783E-007	1	3.783E-007	5.42	0.0343	
B-Pulse on duration (T_{on})	8.623E-007	1	8.623E-007	12.35	0.0031	
C-Graphite powder mixed in kerosene dielectric	4.400E-006	1	4.400E-006	63.01	< 0.0001	
Residual	1.047E-006	15	6.983E-008			
Cor Total	7.257E-006	20				

Table (8): The new constraints goals for numerical optimization for copper electrodes

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Pulse current (I_p)	is in range	8	22	1	1	3
B:Pulse on duration (T_{on})	is in range	40	120	1	1	3
C:Graphite powder mixed in kerosene dielectric	is in range	0	5	1	1	3
Residual stresses	minimize	175.485	365.906	1	1	3

Table (9): The desirability process for optimization of the predicted surface residual stresses for copper and graphite electrodes

Number	Type of electrode	Pulse current (I_p)	Pulse on duration (T_{on})	Graphite powder mixed in kerosene dielectric	Residual stresses	Desirability	
1	Copper	8.000	120.000	5.000	186.099	0.944	Selected
1	Graphite	22.000	120.000	5.000	256.577	0.929	Selected

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