Effect of Pulse on Time and Pulse off Time on Material Removal Rate and Electrode Wear Ratio of Stainless Steel AISI 316L in EDM

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ABSTRACT

The electrical discharge machining (EDM) is one of the non-traditional cutting processes, used in many important applications such as dies and auto industry. This thesis focuses on the study of machining responses such as material removal rate (MRR) and electrode wear ratio (EWR) under the effect of different machining conditions in EDM process. The process parameters are pulse on time (Ton), pulse off time (Toff) and electrical current (Ip). The main purpose of this work is to achieve best MRR and least EWR using copper electrode with fixed diameter (10 mm) for the machining of stainless steel AISI 316L with a constant thickness (0.8 mm). Different values for the Ton (25, 50 and 75) µs, Toff (9, 18 and 25) µs and Ip (16, 30 and 50) A were used. The results of experiments showed the main effects of machining conditions on MRR and EWR. Where, the MRR increased with increasing the Ton, MRR decreased with increasing the Toff and MRR increased with increasing Ip. While, the EWR decreased with increasing the Ton, EWR decreased with increasing Toff until access to a specific Toff then EWR increased with longer Toff and EWR increased with increasing Ip. The maximum MRR is (48.16 mm^3/min) at Ton (75 µs), Toff (9 µs) and Ip (50 A) and minimum EWR is (0.179 %) at Ton (75 µs), Toff (9 µs) and Ip (16 A). The results showed that the response surface methodology (RSM) that have been performed using Minitab 17 software. It can predict the machining responses with a good accuracy where it gave the coefficient of determination (R-sq) that determines the degree of fit between the experimental and predicted data. Higher value of R-sq shows a better fit. The values of R-sq are (97.46 %) for the MRR and (96.34 %) for EWR. Also, the SPSS 18 software was used to predict the machining responses with a good accuracy `

INTRODUCTION

Electrical discharge machining (EDM) is one of the most commonly used non-conventional machining processes which have been a great help to the manufacturing and processing engineers to produce complex forms on any conducting material or alloy [1]. It has unique feature that using thermal energy to machine electrically conductive materials [2]. Also, non-conductive materials can be machined successfully by using EDM technique [3]. The very hard and brittle materials can be easily machined and also to the required shape [4]. EDM differs from most traditional machining operations that it does not make physical contact between the tool and workpiece, eliminating mechanical stresses, vibration and chatter problems during machining [2, 5]. It is widely used in manufacture of mold and die, auto industry, aeronautics, medical equipment, sports and optical instruments and other applications [6].

Mohan and Chandan (2008) [7] studied effect of the different values of Ip, Ton and Toff on the MRR of machining tool steel AISI D2 by using copper electrode in EDM process. Also, RSM was used to develop model for MRR. **Harpreet and Amandeep (2012) [8]** studied the

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effect of Ton and Toff on machining die steel AISI D3 as workpiece using copper and brass electrode in EDM process. **Singh Jaspreet et al. (2013) [9]** studied the impact of three values of Ton, Toff and Ip on MRR in EDM for stainless steel AISI 202. The design of experiments was carried out using L27 orthogonal array. **Shishir and Sarathe (2014) [10]** studied the effect of Ip, Ton, Toff and electrode shape on the MRR, Ra and EW in EDM. **Bharat Raj Bundel (2015) [11]** investigated the effect of different values of Ton and Toff on EW in cylindrical copper electrode during EDM of die steel (HRC-58).

The aim of this work, it studies the effect of process parameters (pulse on time, pulse of time and current) on the MRR and EWR. Use intelligent software (Minitab 17 & SPSS 18) to predict the MRR and EWR to detect the best machining conditions for EDM process.

Table (1): list of symbols

Symbol	Description	Unit	Symbol	Description	Unit
CAD	Computer Aided Design	---	**S.I.E.R**	The State Company for Inspection and Engineering Rehabilitation	---
CNC	Computer Numerical Control		**SPSS**	Statistical Package for the Social Sciences	---
DC	Direct Current	A	**TAM**	weight of the electrode tool after machining	g
EDM	Electrical Discharge Machining	---	**TBM**	weight of the electrode tool before machining	g
EW	Electrode wear	---	**Ton**	Pulse on time	μs
EWR	Electrode Wear Ratio	%	**Toff**	Pulse off time	μs
Ip	Current	A	**t**	the machining time	min
MRR	Material Removal Rate	mm³/min	**WPBM**	weight of the work piece before machining	g
Ra	Surface roughness	μm	**WPAM**	weight of the work piece after machining	g
RSM	Response Surface Methodology	---	**Ø**	Diameter	mm
R-sq	The coefficient of determination	---	ρ	Density of material	g/mm^3

The principle of EDM process

The EDM removes material from the work piece through the spark erosion principle [12]. The principle of EDM is based on erosion of materials by unloading the spark between the electrode and work piece [13]. The work piece and tool are linked to a power supply with pulsed direct current (DC) [14]. An EDM setup, as shown in Figure (1), the work piece and tool are separated by a small gap and immersed with dielectric liquid [15]. EDM process includes controlled erosion of conductive electrically materials by means the initiation of rapid and frequent electrical discharge between the work piece and tool [16], which generates a track for each discharge where the liquid becomes ionized in the gap. The zone which it occurs discharge is heated to very high temperatures where a small part of work piece surface is melted and removed. And, a small cavity is created in the tool surface that named tool wear. The dielectric flushes the small debris far away from the gap [15]. Unfired molten materials will solidify to be a recast layer [17]. An electrode penetrates the work piece then overcut occurs [15].
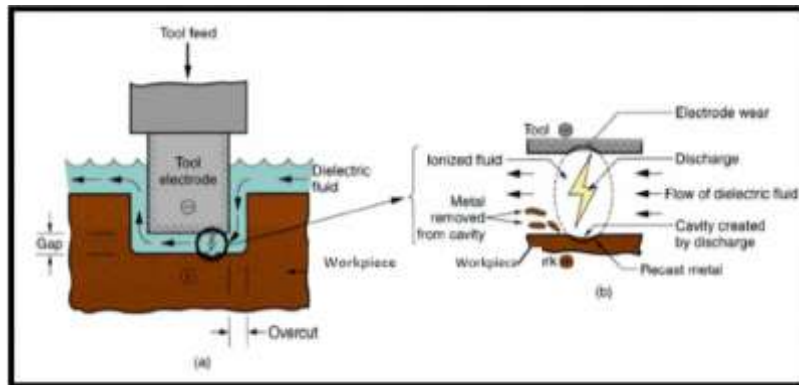
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**Figure (1): Electrical discharge machining (EDM) (a) overall setup and (b) close-up view
of gap, showing discharge and material removal [15].**

Experimental work:

The experimental work was conducted to investigate the effect of process parameters are Ton, Toff and Ip on machining responses such as MRR and EWR in EDM process. The experiments were performed on the CNC machine of EDM that called CHMER and its model (CM323C). This machine has been designed by advanced CAD system to ensure high accuracy machining and deformation free performance. A copper tool was used to machine a stainless steel AISI 316L work piece by using oil (Kerosene) as dielectric fluid in experiment. The calculations were performed of process responses like MRR and EWR by weighting the work piece and electrode before and after machining by digital balance for each experiment.

The electrode material

The copper material was used as a cutting tool with a shape of a shaft and constant diameter (Ø10 mm). The most important considerations when selecting EDM electrodes with its job and shape are corrosion resistance, high melting point and electrical conductivity because the electrical current is a tool which performs the cutting operation [18].

The work piece material

The work piece material used is stainless steel AISI (316L) and is a square plate with thickness (0.8) mm and dimensions (40x40) mm. The 316L stainless steel is austenitic alloy and has a 0.03 max carbon in addition to chromium, nickel, molybdenum and other, which makes it more corrosion resistant, improvement the tensile strength, resistance to the pitting and rupture resistance in the high temperature, and it has higher creep resistance, excellent formability and non-magnetic alloys [19]. The chemical composition and physical properties of the work piece material was obtained from the laboratories of the State Company for Inspection and Engineering Rehabilitation (S.I.E.R) are shown in tables (2) and (3).

Table (2) :The chemical composition of the work piece material (AISI 316L).

Metals	C%	Si%	Mn%	P%	S%	Cr%	Mo%
Result	0.034	0.339	1.62	0.033	<0.0005	18.72	2.09
Metals	Ni%	Al%	Co%	Cu%	V%	Fe%	
Result	9.64	<0.001	0.174	0.412	0.069	Balance	

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Table (3): physical properties of the work piece material (AISI 316L)

Grade	Elastic Modulus (GPa)	Density (g/cm³)	Machinability	Thermal Conductivity (W/m.°C)	Specific Electrical Resistivity (Ωmm²/m)	Specific thermal capacity (J/kg.°C)
316L	200	7.99	36%	١٥	0.75	500

Design of experiments

The design of experiments is very important to determine the number of experiments needed. A full factorial design was performed to calculate the MRR and EWR values. The levels of the three machining parameters were Ton, Toff and Ip, as shown in table (4). The design of experiments involves three parameters and three levels (3^3) which the number of experiments is 27 experiments, as shown in table (5).

Table (4): The machining parameters and its levels

No	Machining parameters	Symbol	unit	Levels		
				Level 1	Level 2	Level 3
1	Pulse on time	Ton	μs	75	50	25
2	Pulse off time	Toff	μs	9	18	25
3	Current	Ip	A	16	30	50

Table (5): Design of the experiments

No.	T_{on} (μs)	T_{off} (μs)	I_p (A)	No.	T_{on} (μs)	T_{off} (μs)	I_p (A)	No.	T_{on} (μs)	T_{off} (μs)	I_p (A)
1	75	9	16	10	50	9	16	19	25	9	16
2	75	9	30	11	50	9	30	20	25	9	30
3	75	9	50	12	50	9	50	21	25	9	50
4	75	18	16	13	50	18	16	22	25	18	16
5	75	18	30	14	50	18	30	23	25	18	30
6	75	18	50	15	50	18	50	24	25	18	50
7	75	25	16	16	50	25	16	25	25	25	16
8	75	25	30	17	50	25	30	26	25	25	30
9	75	25	50	18	50	25	50	27	25	25	50

Calculation the MRR and EWR

The material removal rate (MRR) is expressed as the ratio of the difference of weight of the work piece before and after machining to the machining time and density of the material. MRR was calculated by using the following equation:

$$MRR = \frac{WPBM - WPAM}{t \times \rho}$$ …... (1)

Where
MRR: material removal rate (mm³/min).
WPBM: weight of the work piece before machining (g).

WPAM: weight of the work piece after machining (g).
t: the machining time (min).
ρ : Density of stainless steel AISI 316L material, ρ =7.99 g/cm^3 = 7.99×10^{-3} g/mm^3.
The electrode wear ratio (EWR) expressed as a percentage ratio of the difference of weight of the electrode before and after machining to the weight of the electrode before machining. EWR was calculated by using the following equation:

$$EWR = \frac{TBM - TAM}{TBM} \times 100\% \qquad \text{…… (2)}$$

Where
EWR: electrode wear ratio (%).
TBM: weight of the electrode tool before machining (g).
TAM: weight of the electrode tool after machining (g).

SOFTWARE:
Response surface methodology (RSM)
   Response surface methodology (RSM) is a set of statistical and mathematical techniques that are useful for analyzing and modeling of data in which the response influenced by many variables and the target is to find the relationship between the response and the variables. RSM is applied using Minitab 17 software that is one of the most important computer programs used in the statistical analysis [7]. These models are only an approximation, but used because such a model is easy to estimate and apply, even when little is known about the process. The process of RSM includes designing of a series of experiments for sufficient and reliable measurement of the response and developing a mathematical model of second order to predict the response surface of EDM process with the best fittings [20]. The mathematical model is developed to predict the responses, where it clarifies the correlation between the process parameters (pulse on time, pulse off time and current) and responses (MRR and EWR). The system behavior is explained using the second-order polynomial equation as following [7]:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{i=2}^{k} \beta_{ij} X_i X_j \qquad \text{…… (3)}$$

Y : The process response (Dependent).
β_0 : Constant.
β_i , β_{ii} , β_{ij} : Coefficients.
X_i : The linear process parameters (Independent).
X_i^2 : The square process parameters (Independent).
$X_i X_j$: The interaction process parameters (Independent).

Statistical Package for the Social Sciences (SPSS 18) software
   The SPSS18 computer software was used in the statistical analysis where it used to predict the process responses of EDM. The program features are a simpler and more flexible graphical interface so that contain many tools to help you accomplish tasks accurately, statistical analysis program allow to the possibility of graphic illustrations and shapes that are deduced from analyzing the process.

Results and Discussion:
The effect of machining parameters on MRR
   The effect of pulse on time (Ton) on material removal rate (MRR) is shown in Figure (2). It is seen that MRR increases with increasing Ton. The reason is increasing discharge energy of plasma channel and the period longer of the transformation of this energy into the electrodes which leads to creation a high spark with high temperature to melt and vaporize the material and formation the bigger craters on the work piece. The maximum MRR value is (48.16 mm^3/min) at highest Ton (75 μs) and highest Ip (50 A).
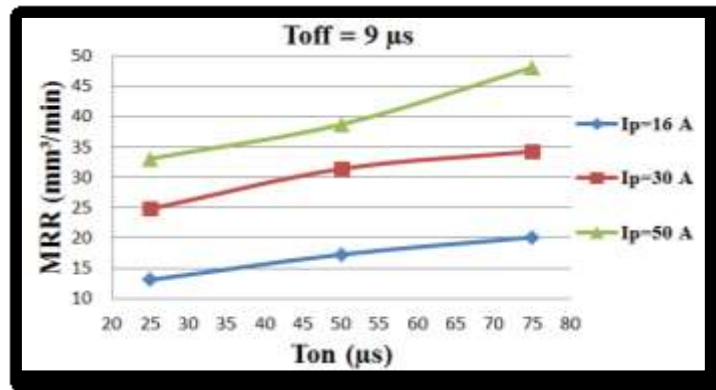
Figure (2): The effect of pulse on time on MRR.

The effect of pulse off time (Toff) on material removal rate (MRR) is shown in Figure (3). It Is seen that MRR decreases with increasing Toff until reach to half way (Toff=18 µs) in the beginning then the MRR starts increasing with longer Toff. The reason is when short Toff until (18 µs) MRR is less due to the likelihood of arcing is great, that's because the dielectric fluid in discharge gap can't flush far away correctly and the debris still in the cutting gap and this leads to the arcing where leads to the decreasing of MRR. When Toff increases after (18 µs), better flushing of debris happen in the gap between the electrode and work piece where it prevents creating the arcing where the MRR increases with increasing the Toff. A higher value of MRR is reached at lower Toff, but some values lie out of its expected location because of some reasons like electricity shutdown, machine vibration and dielectric liquid pollution. The maximum MRR is (48.16 mm^3/min) at lower Toff (9 µs) and highest Ip (50 A).
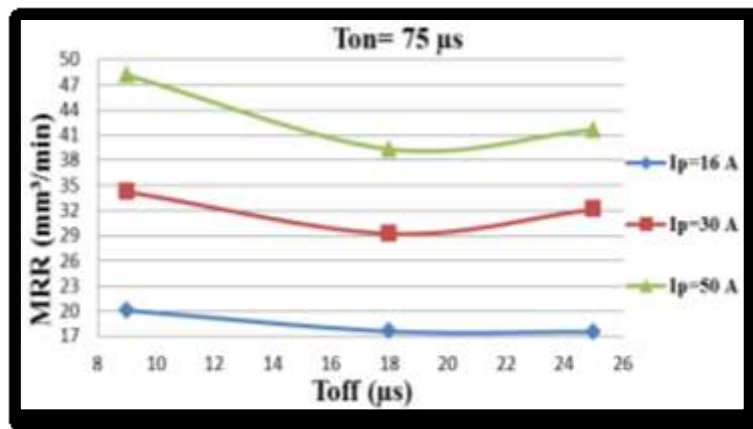

Figure (3): The effect of pulse off time on MRR.

The effect of current (Ip) on material removal rate (MRR) is shown in Figure (4). The MRR increases with increasing Ip. That attributed to controlling the input discharge energy where the increase in pulse current produces strong spark that creates the higher temperature lead to melting and vaporization the material and formation the craters on the work piece. Highest value of MRR can be reached at highest Ip. The maximum MRR value is (48.16 mm3/min) at higher Ip (50 µs), higher Ton (75 µs) and lower Toff (9 µs).
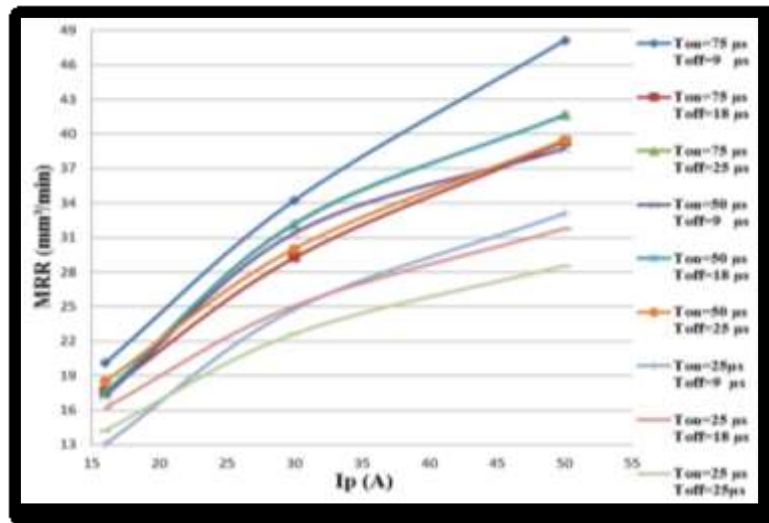
Figure (4): The effect of current on MRR.

The effect of machining parameters on EWR

The effect of pulse on time (Ton) on electrode wear ratio (EWR) is shown in Figure (5). It is seen that EWR significantly decreases with increasing Ton. The reason that in the beginning of spark, the electrons motion overcomes the ions motion under the wok piece where the amount of material removal from the work piece is more than the tool. As time passes, the plasma channel's efficiency decreases in the material removal at the end of each pulse where the current density decreases with increasing discharge Ton and longer time for heat transfer from the molten crater in workpiece to the body of tool, which results in less material removal from the crater. Another factor in the reduction of EWR is the pollution increasing of dielectric liquid with increasing Ton where the number of sparks drops that leads to the reduction of EWR. The minimum EWR value is (0.179 %) at higher Ton (75 μs) and lower Ip (16 A).
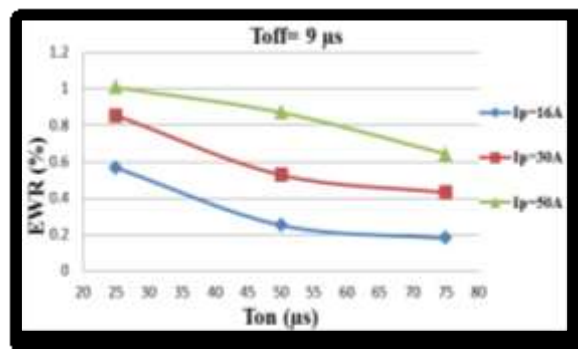

Figure (5): The effect of pulse on time on EWR.

The effect of pulse off time (Toff) on electrode wear ratio (EWR) is shown in Figure (6). EWR decreases until access to half way (18 μs) then after it the EWR start increasing with increase Toff. The reason is due to the EWR is less at short Toff due to that with short Toff there is a very high probability to creating the arcing, because of that in beginning the spark, more material removed that produces high pollution where the dielectric liquid is not able to flushing far away correctly and the debris remains in machining gap between the electrode and the work piece and arcing that leads to the decreasing the EWR until (18 μs) then after it, with increasing Toff happens best flushing of debris particles from the gap, where does not happen arcing, which leads to increasing in the EWR with longer Toff. The minimum EWR value is (0.476 %) at Toff (18 μs) and lower Ip (16 A).
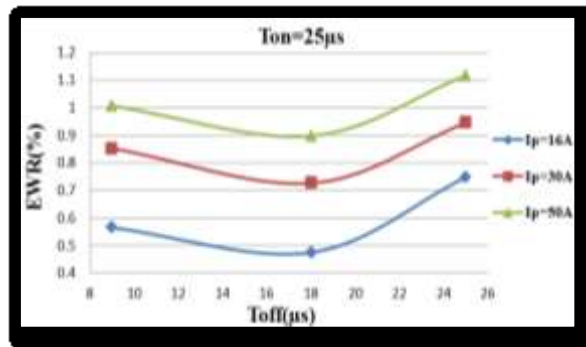
Figure (6): The effect of pulse off time on EWR

The effect of current (Ip) on electrode wear ratio (EWR), is shown in Figure (7). It is seen that EWR increases with increase Ip due to that a higher current produce a stronger spark where would cause more material to be removed from the electrode. The minimum EWR value is (0.179 %) at lower value of Ip (16 A), higher Ton (75 µs) and lower Toff (9 µs).
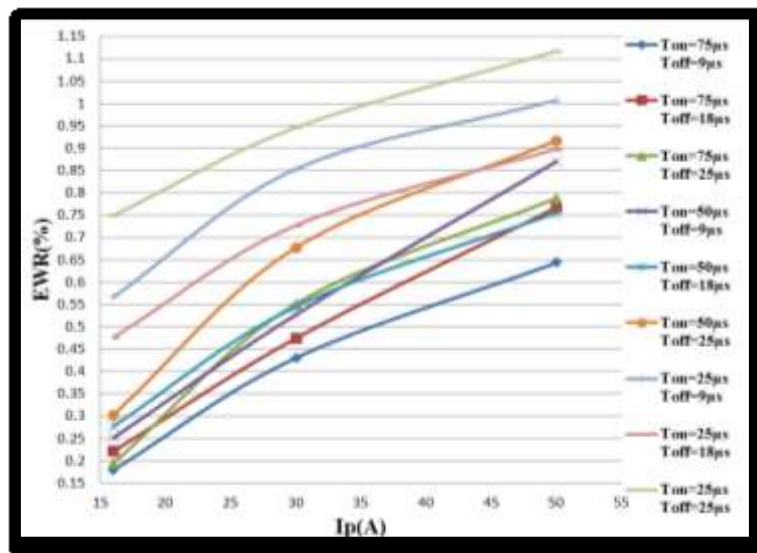

Figure (7): The effect of current on EWR.

Prediction of MRR and EWR using response surface methodology (RSM)

A response surface methodology was applied to develop a second-order polynomial mathematical models to predict of the MRR and EWR using the experimental results.
The regression Equation for MRR as following:-

$$\text{MRR} = -15.04 + 0.449\,\text{Ton} + 0.159\,\text{Toff} + 1.319\,\text{Ip} - 0.00391\,\text{Ton}^2 + 0.0022\,\text{Toff}^2$$

$$- 0.01245\,\text{Ip}^2 - 0.0028\,\text{Ton}*\text{Toff} + 0.00467\,\text{Ton}*\text{Ip} - 0.00625\,\text{Toff}*\text{Ip} \qquad \text{...... (4)}$$

And the regression Equation for EWR as following:-

$$\text{EWR} = 0.813 - 0.0207\,\text{Ton} - 0.0353\,\text{Toff} + 0.02763\,\text{Ip} + 0.000119\,\text{Ton}^2 + 0.0012\,\text{Toff}^2$$

$$- 0.00025\,\text{Ip}^2 - 0.000022\,\text{Ton}*\text{Toff} + 0.000074\,\text{Ton}*\text{Ip} + 0.000021\,\text{Toff}*\text{Ip} \qquad \text{...... (5)}$$

The coefficient of determination (R-sq) determines a degree the fit between the experimental and predicted data where higher value of R-sq shows the better fit. The values of R-sq and R-sq (adj) for MRR model are (97.46%, 96.11%) respectively and the values of R-sq and R-sq (adj) for EWR model are (96.34%, 94.41%) respectively those show the observed variability in the

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independent variables. This means that the regression models provide an excellent clarification for relationship between the observed values and prediction for the dependent variables (MRR and EWR).

Prediction of MRR and EWR by SPSS 18 software

The SPSS 18 software has been applied to analysis the results that obtained from experiments and developing the mathematical model to predict the machining responses with a good accuracy (R-sq = 97.4 %) for MRR and (R-sq = 96.3 %) for EWR with the percentages of error are (2.6 %) for MRR and (3.7%) for EWR.

CONCLUSIONS

From this work, were extracted the following conclusions:
1. The experimental results show the main impact of process parameters on MRR. MRR increases with increasing the pulse on time and current, MRR decreases with increasing the pulse off time.
2. The maximum MRR was (48.16 mm³/min) at Ton (75 μs), Toff (9 μs) and Ip (50 A). The minimum MRR was (13.072 mm³/min) at Ton (25 μs), Toff (9 μs) and Ip (16 A).
3. The experiments results show the main effect of process parameters on EWR. Where the EWR decreases with the increasing in pulse on time, EWR decreases with increasing pulse off time from 9 to 18 μs then the EWR increasing with a further increasing of a pulse off time from 18 to 25 μs and the EWR increases with increase in the current.
4. The maximum EWR was (1.117 %) at Ton (25 μs), Toff (25 μs) and Ip (50 A). The minimum EWR was (0.179 %) at Ton (75 μs), Toff (9 μs) and Ip (16 A).
5. The results revealed that the response surface methodology (RSM) model can predict the machining responses with a good accuracy of (97.46%) for MRR and (96.43%) for EWR.
6. Also, the SPSS 18 software was used to develop a mathematical model to predict the MRR and EWR with a good accuracy of (97.4%) for MRR and (96.3) for EWR and these results are a very significantly identical for results of Minitab17 software.

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