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Parametric Analysis of Surface Roughness and Metal Removal Rate during Electrical Discharge Machining of O1 Tool Steel

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ABSTRACT

This work studies the impact of input machining parameters of Electrical Discharge Machining (EDM) on the machining process performance. Tool steel O1 was selected as the workpiece material, copper as the electrode material, and kerosene as the dielectric medium. Experimental runs have been carried out with a Design of Experiment (DOE) technique. Twenty tests are accomplished with the current range of (18 to 24 Ampere), a pulse duration range of (150 to 200 μs), and a pulse-off time range of (25 to 75 μs). Based upon the experimental study's output results, the EDM parameter's effect (voltage of power supply, discharge current, pulse duration, and pulse pause interval) on the responses of the process represented by surface roughness value Ra and Metal Removal MR rate. The results obtained by the DOE approach are analyzed by STATISTICA software. It has been concluded that an increase in the current and pulse duration maximizes both metal removal rate and surface roughness. At the same time, they are minimized by maximizing the pulse pause interval.

Keywords: Electrical Discharge Machining, discharge current, pulse duration, surface roughness, metal removal rate.

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تحليل خشونة السطح ومعدل إزالة المعدن أثناء عملية التشغيل بالتفريغ الكهربائي لفولاذ العدد O1

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الخلاصة

يدرس هذا العمل تأثير متغيرات عملية التشـــغيل بالتفريغ الكهربائي (EDM) على أداء عملية المعالجة. تم اختيار أداة الفولاذ O1 كمواد لقطع العمل بينما تم اختيار النحاس كمواد قطب كهربائي والكيروسـين كوسـط عازل. تم إجراء عمليات التشـغيل التجريبية باستخدام تقنية تصـميم التجربة (DOE). تم إجراء عشرين اختبارًا مع النطاق الحالي من (18 إلى 24 أمبير) ، ونطاق مدة النبض (150 إلى 200 ميكرو ثانية) ، ونطاق زمني للنبض من (25 إلى 75 ميكرو ثانية). بناءً على نتائج الدراسـة التجريبية ، فإن تأثير متغيرات عملية EDM (جهد مصـدر الطاقة ، تيار التفريغ ، مدة النبضـة ، وفترة توقف النبض) على استجابات العملية التي تمثلها قيمة خشونة السطح Ra ومعدل إزالة المعادن بالرنين المغناطيسي. يتم تحليل النتائج التي تم الحصـول عليها من خلال نهج حساب الطاقة بواسـطة برنامج STATISTICA. اسـتنتج أن الزيادة في مدة التيار والنبض يزيد من معدل إزالة المعدن وخشـونة السـطح. في نفس الوقت ، يتم تصـغيرها عن طريق تعظيم الفاصل الزمني للنبض.

الكلمات الرئيسية: التشغيل بالتفريغ الكهربائي, تيار التفريغ, مدة النبضة، الخشونة السطحية, معدل إزالة المعدن.

1. INTRODUCTION

Electrical Discharge Machining (EDM) represents a precise manufacturing method for materials that are difficult to cut. EDM began in 1770 when English scientist Priestley discovered the electric charge's erosive impact upon the metal. Nonetheless, it wasn't until 1944 that the Russian scientists Lazarenko and Lazarenko succeeded in developing an approach to control the material's effect of erosion, permitting its adoption in the production processes. The EDM is a non-traditional treatment, like the hybrid-machining and electrochemical laser treatment **(Świercz et al., 2018)**. EDM represents one of the widely utilized unconventional processes of manufacturing, which use the spark's thermal energy for machining the electrically conductive and the non-conductive parts despite work material hardness. The EDM can cut the intricate contours or cavities in the pre-hardened metal or steel alloys (such as Inconel, Titanium, etc.) without heat treatment for softening and re-hardening materials. Throughout the process of the EDM, the tool makes no direct contact with the workpiece, which eliminates the mechanical stresses, vibration, and chatter issues. Hence, EDM became an indispensable option for machining in micro and meso manufacturing of complex-shaped molds and dies that are difficult to machine, such as those used in vital components of aerospace, medical automobile, and other industrial areas **(Mousa, 2018).**

On the other hand, this process has a set of limitations, like long lead times, high specific energy consumptions, and a lower degree of productivity, that limit its applications. Therefore, researchers worldwide focus on EDM optimization and process modeling to improve the procedure's productivity and finishing ability **(Abu Qudeiri et al., 2020).** The workpiece and electrode are immersed in a dielectric fluid. In the EDM, the dielectric fluid plays the role of coolant and maintains a constant gap between the electrode and the workpiece. There won't be any contact between the electrode and the workpiece throughout the machining process, so materials of different hardness values may be cut. With the condition that they conduct electric current, the physical pressure that is imparted on the workpiece is low. The clamping pressure amount needed for holding the workpiece is also minimized. The process of EDM has a broad range of applications in the aerospace, automotive, and nuclear industries for machining complex, accurate, and irregular shapes.

Wire EDM process parameters are Peak current, Pulse off time (POFF), gap voltage, Pulse on time (PON), servo voltage, dielectric flow rate, servo feed rate, wire feed or wire speed, and wire tension, and so on. The electric discharge machining has to occur (ON time) and stop (OFF time) alternately throughout the machining. Throughout the ON time, voltage is applied to the gap between the electrode (i.e., wire) and the workpiece, whereas no voltage is applied throughout the OFF time. Subsequently, the electric discharge only takes place for ON time duration. The peak current represents the power amount utilized in the WEDM and is measured in the units of amperes. Throughout every pulse ON time, the current is increased to the pre-set level and is directed by the cut's surface area. High current values will be utilized for the rough operations and the cavities with large surface areas. The gap voltage denotes the voltage to be placed in the gap between the electrode and the workpiece. Servo voltage (SV) has been utilized to control the wire retracts and advances. The servo feed rate denotes the table's feed rate throughout machining, which may be set manually in the WEDM. Generally, the electric discharge may be carried out in the air. However, it isn't stable and can't be utilized for rough machining. To obtain a stable electric discharge, dielectric fluid is needed. The EDM may be stabilized in dielectric fluid through sufficient cooling and chip removal. De-ionized water is usually deployed as dielectric in the wire EDM **(Rao and Kambagowni, 2016).**

(Guleryuza et al., 2012) investigated the effects of parameters of EDM upon surface roughness as a substitute approach for the Al/SiCp metal matrix composite machining produced with powder metallurgy. Current, pulse-on-time, type of electrode, particle reinforcement weight ratio, and voltage have been utilized as parameters of the process. An experimental plan (L-18) has been established using Taguchi orthogonal design. The experimental results have shown that the current (31.26%) and pulse-on-time (34%) are the most influencing parameters. In addition to that, particle reinforcement percentage contribution upon surface roughness has been equal to 6.71%. **(Al-Khazraji et al., 2016)** studied the influence of EDM and shot blast peening factors on the lives of workpiece fatigue utilizing graphite and copper electrodes. The results show that fatigue's safety factors were minimized by (11 %) after EDM utilizing copper electrodes compared with as-received material, and this amount is more by (3.35 %) with graphite electrode utilization. **(Castillo et al., 2018)** examined the effects of pulse on time, pulse current, and

pulse off time on surface roughness of the AISI304 stainless steel work-pieces produced by the EDM with the use of the grade GSP70 graphite electrodes. The factorial design has been carried out, considering 2 levels for every one of the 3 parameters that have been established. From statistical analyses, it has been concluded that pulse on time and pulse current represents the most important parameters of machining on obtained values of surface roughness of stainless steel AISI304 work-pieces that the EDM has machined. However, the 2^{nd} order model regression analysis is carried out to estimate average roughness (Ra) in terms of pulse on time, pulse current, and pulse off time. The mean absolute percentage error (MAPE) of roughness values estimated by the 2nd-order regression model and experimentally obtained roughness has also been presented.
(Tomadi et al., 2009) considered the impacts of tungsten carbide's operating parameters upon machining properties, like the rate of material removal, electrode wear, and surface quality. It is followed by optimizing machining conditions for the confirmation tests. A confirmation test is conducted to evaluate the error margin between the results predicted by the software and the experimentation concerning the machining characteristics. EDM process effectiveness with the tungsten carbide, WC-Co had been assessed based upon the material removal rate, the relative ratio of the wear, and the quality of surface finish of the produced workpiece. It has been noticed that copper tungsten is most appropriate to be used as a tool electrode in the WC-Co's EDM. Sufficient performance of machining results with an electrode as a cathode and a workpiece as an anode. **(Aghdeab et al., 2023)** discussed the ideal EDM factors that influence the metal removal rate utilizing two types of electrodes as a machining tool, and the workpiece was AISI M2. As a result of this study, the maximum MRR with copper & brass tools with200 μs pulse on time, 12 μs pulse off-time, and 42 A current, at (0.31284 g/min and 0.18769), respectively.
The main goal of this work is to conduct a parametric analysis of the effect of the input parameters, namely: the voltage of power supply, peak current, and pulse on/off time on the responses of the process that is represented by surface roughness (Ra), and Metal Removal (MR). The experimental results obtained by the Design of Experiments DOE approach are collected and analyzed using STATISTICA software.

2. EXPERIMENTAL PROCEDURE

The response surface methodology is reliable, giving a simple and systematic qualitative optimal design for minimizing cost. This offline (Engineering) quality control technique involves all stages of process development. So that the best way to evaluate the best quality at minimum cost is Design of Experiments (DOE) **(Świercz et al., 2018)**. In the present work, Response Surface Methodology, RSM L_{20} orthogonal array given in **Table 1.** is used to reveal the role of process conditions viz, pulse duration time, current, pulse pause time on the surface roughness and rate of the metal removal of the work material. In contrast, the other machining parameters are kept constant throughout the process.

3. WORKPIECE MATERIAL

Tool steel O1 was considered in this study as a workpiece with dimensions 42x42 mm, as shown in **Fig. 1**. All experiments have been carried out on the ELEKTRA with the pulse generator ELPULS50 f EDM as shown in **Fig. 2** machine as per response surface methodology L_{20} Orthogonal Array. The copper electrode of 10 mm diameter and kerosene has been utilized as an electrode and dielectric fluid, respectively. The chemical composition of O1 is given in **Table 2**.

Table 1. Response Surface Methodology RSM for the experiments

Run Order	Blocks	Current (A)	Pulse Durations (μs)	Pulse-off time (μs)
1	1	18	150	50
2	1	24	200	25
3	1	18	100	50
4	1	12	100	25
5	1	24	100	75
6	1	18	150	50
7	1	12	200	25
8	1	12	100	75
9	1	18	150	25
10	1	18	200	50
11	1	18	150	50
12	1	18	150	50
13	1	12	150	50
14	1	24	150	50
15	1	24	100	25
16	1	24	200	75
17	1	18	150	50
18	1	12	200	75
19	1	18	150	75
20	1	18	150	50

Table 2. Chemical composition of O1 tool steel

Elements	C	Si	Ni	V	P	Mn	Cr	W	Cu	S
Content (%)	0.85-1	0.5	0.3	0.3	0.03	1-1.4	0.4-0.6	0.4-0.6	0.25	0.03

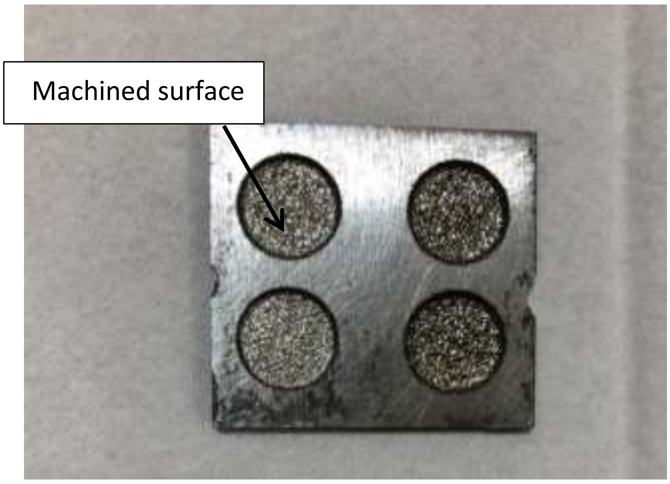

Figure 1. Machined Samples of Tool Steel Using EDM.

Figure 2. EDM Machine.

4. SELECTION OF MACHINING PARAMETERS

For the evaluation of the optimal machining response, there are many input factors to be considered in the process. It is noticed that pulse duration time and pulse pause time greatly influence machining outputs. At the beginning and before machining the main EDM experiments, many experiments are accomplished to reveal the best range for the working factors. The values of other process factors are listed in **Table 3.**

Table 3. Machining parameters with their levels.

Factor	Level1	Level2	Level3
Pulse duration (µs)	100	150	200
Current (A)	12	18	24
Pulse pause (µs)	25	50	75

5. RESULTS AND DISCUSSION

The practical outputs of machining O1 tool steel according to the L_{20} orthogonal mixed array are given in **Table 4.** In the machining responses, Ra in µm and MRR in mm^3/min, the roughness of the surface is the most dependable consideration to explore the process performance. In the present work, a portable stylus-type profile meter pocket surf (Maher Federal) was utilized to measure surface roughness, which is available in the measurements laboratory in Production Engineering and Metallurgy Department. The Metal Removal Rate *MRR* (in mm^3/min) was calculated according to the relation below:

$$MRR = \frac{Wi - Wf}{\rho . t} \qquad (1)$$

where:
Wf is the weight of the sample after machining (g).
Wi is the weight of the sample before the machining (g).
ρ is workpiece density (g/mm^3)
T is cutting time (min).
The accuracy of the used electronic balance was (0.05%+0.20g).

Table 4. Measured values of surface roughness and metal removal rate.

Run Order	Blocks	Current (A)	Pulse Duration (µs)	Pulse-off time (µs)	Ra (µm)	MRR (mm^3/min)
1	1	18	150	50	4.18	6.963
2	1	24	200	25	7.08	10.897
3	1	18	100	50	5.04	7.877
4	1	12	100	25	3.63	5.262
5	1	24	100	75	4.31	5.987
6	1	18	150	50	4.70	7.698
7	1	12	200	25	4.75	6.979
8	1	12	100	75	2.32	3.522
9	1	18	150	25	4.82	6.891
10	1	18	200	50	5.70	9.114
11	1	18	150	50	4.16	6.499
12	1	18	150	50	5.57	8.077
13	1	12	150	50	3.67	5.480
14	1	24	150	50	7.13	10.483
15	1	24	100	25	5.91	8.958
16	1	24	200	75	3.84	6.399
17	1	18	150	50	4.76	7.328
18	1	12	200	75	2.93	4.437

19	1	18	150	75	2.41	3.598
20	1	18	150	50	4.90	6.996

5.1 Ra Results

Fig. 3 illustrates the main effects of controllable parameters on the Ra. From this Figure, it is observed that Current (Ip), Pulse Duration (Ton), and Pulse-off time (Toff) have an important impact on the Ra, and Ip represents the most influential factor among all of the variables of the process. The Ra is directly proportional to the Ip, as evinced in **Fig. 3**. The Ip represents the most influential factor exhibiting a sharp increase in the average of Ra of (1.16) µm in the case where the Ip rises from (12 to 18Amp). At the same time, it reveals a sharp increase of (1.03) µm when the Ip rises (18 to 24 Amp). One of the potential explanations for that might be that increased Ip causes an increase in the intensity of the discharge spark, striking the workpiece surface, and resulting worsened erosion effect results in an increase of the molten materials. Part of that molten material is flushed away with the dielectric, while overheated material evaporation results in the formation of a large crater, which is why the rough surface is produced.

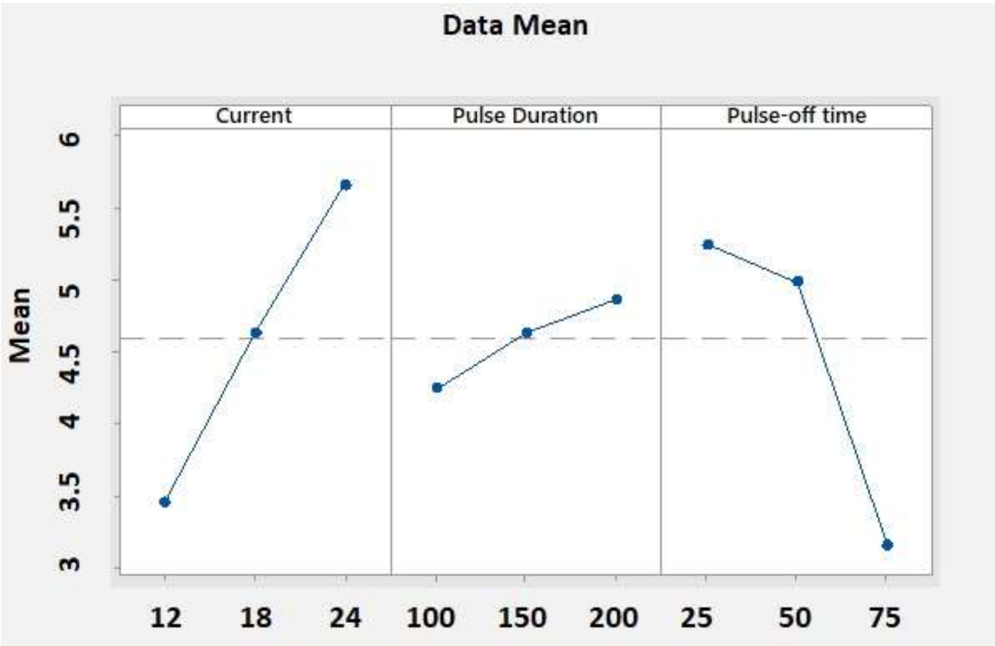

Figure 3. Main effect plot for Ra.

As illustrated in **Fig. 3**, the Ra increased by (0.39) µm when the Ton is maximized from 100 μs to 150 μs. It increased by (0.22) µm when the Ton increased from 150μs to 200μs. This could be because the initial Ton level results in maximizing spark density in the plasma channel due to not allowing the expansion of such channel as it has been explained earlier, which result in the heat energy amount that is transferred to the workpiece surface increasing which is why, more material will melt. If molten material isn't flushed away by the dielectric medium from the machined surface, it will be solidified and create a re-solidified layer with a surface roughness deterioration. As can be seen by observing **Fig. 2**, the main Toff effects have an inverse tendency. Ra has been slightly reduced by (0.25) μm when the Toff is maximized from 25 μs to 50 μs and sharply decreased by (1.82) μm when the Toff is increased from 50 μs to 75 μs. It seems possible that this result is due to increasing the Toff, unwanted dissipation of the heat, and the machined surface temperature will be decreased, which results in decreasing the molten material amount and small crater produced, which is why the roughness of the surface has been decreased.

5.2 Results for MRR

MRR represents one of the most important criteria to evaluate the performance of the EDM Process. **Fig. 4** illustrates the main effects plot of the MRR, from which it may be observed that Ip, Ton, and Toff have an important impact on MRR.

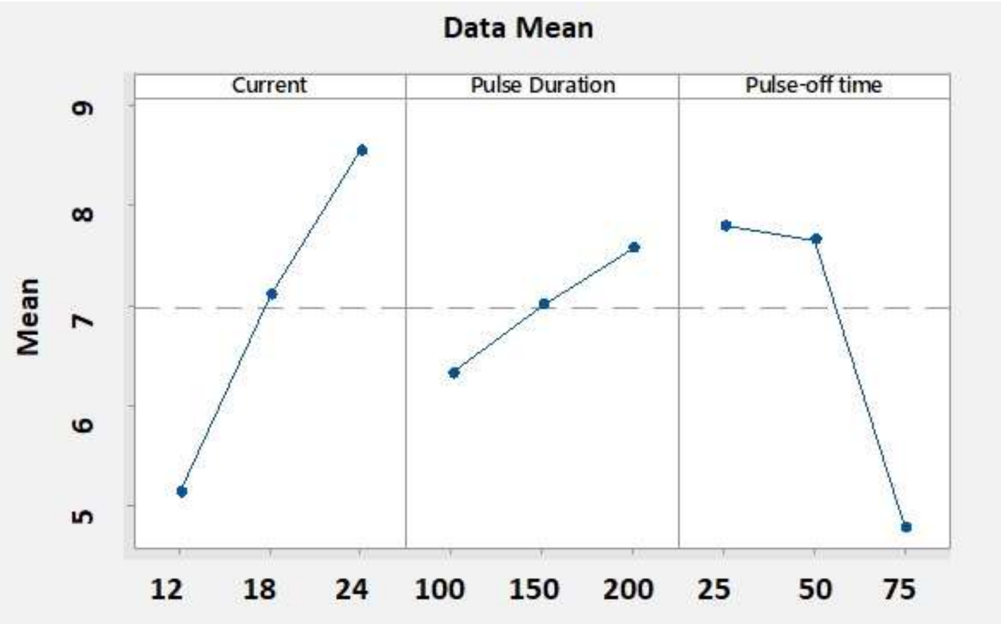

Figure 4. Main effect plot for the MRR

From the **Fig. 4** above, it has been noted that MRR value is directly proportionate to current, Ip represents the most influential factor, and it shows a sharp increase of (1.97 mm^3/min) and (1.44 mm^3/min) in an average of the MRR when Ip increases from (12 to 18Amp) and (18 to 24Amp), respectively. One of the potential explanations for that could be increasing the working current at constant values of Toff and Ton. Spark Energy has been increased, which will result in a stronger spark with a higher level of thermal energy produced, thermal energy that has been transferred to electrode tool and work-piece, and presenting high impact force in the spark gap results in causing more molten material, thus, increased the MRR amounts. As can be seen from **Fig. 4**, MRR has been increased by (0.68 mm^3/min) when the Ton is increased from 100μs to 150μs, whereas it increased by (0.56 mm^3/min), when Ton has been increased from 150μs to 200μs. It appears

possible that those results are because even though spark energy has been increased with the increase in the value of Ton, MRR has been increased due to the expansion of the plasma channel at higher Ton values. The expanded plasma channel resulted in the production of higher levels of energy density. Such occurrence results in forming larger molten material that leads to a higher value of the MRR.
Additionally, the key impacts of Toff have a similar tendency. MRR has been decreased slightly by (0.14 mm^3/min) when the Toff is maximized from 25 μs to 50 μs and sharply decreased by (2.87 mm^3/min) when the Toff is maximized from 50 μs to 75 μs. This is because increasing Toff results in an increasing time gap between successive spark and spark contact time with the work-piece has been decreased, resulting in a decrease of MRR.

6. CONCLUSIONS

Based on the results obtained from the experimental investigation of the impact of input machining parameters of the EDM process on the MRR and Ra, the main conclusions achieved can be summarized as follows:

- The main impacts of the controllable parameters (Ip, Ton, Toff) were found to be highly dominating in affecting the MRR and SR.
- Surface roughness is maximized by maximizing current and pulse duration while decreasing pulse pause time.
- MRR increased by increasing current and pulse duration time while decreased by increasing pulse pause time.

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