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EDM Electrode Design and Analysis to Enhance Process Performance

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Abstract: Electric discharge machining (EDM) is regarded as one of the most energy-efficient manufacturing processes for exceptionally accurate processing of any electrically conductive material, regardless of mechanical properties. EDM is a non-contact process utilized in various industries, including aerospace, industrial, instruments, molds, dies, and medical tools; also, it is beneficial for hard materials with simple or proficient geometries and shapes. Although EDM is for machining "difficult to machine" metals, such as those used in the mold and die industries, metal properties indicate potential capability in the domain of surface modification due to the electrical spark between the tool and the work material. This paper investigates the machining of Alloy steel X210 by using the most affecting parameters and how electrode angles contribute to responses, as MRR, Electrode wear ratio, and surface finish, which the manufacturing industry uses to make die tools, molds, automotive parts, and other products. Electrodes with angles of 0° and 90° are used to machine workpieces using WEDM (dk7740). Electrode Angle, peak discharge current, pulse-on time, and pulse-off time were controllable parameters in this study. While all other criteria are constant, variables have been studied. The effects of the four aspects on the four variables were statistically analyzed using ANOVA by MINITAB. Regression models for the responses were developed. Regression mathematical models have been developed for Alloy steel X210 workpieces to increase productivity and industry results.

تصميم وتحليل أداء الألكترودات في مكائن القطع بالشرارة الكهربائية لتحسين عملية التشغيل

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الخلاصة

تعتبر مكائن التشغيل بالشرارة الكهربائية (EDM) واحدة من أكثر مكائن التشغيل كفاءة في عمليات التصنيع في استخدام الطاقة خصوصاً تلك الصناعات التي تتطلب الدقة العالية ولأي مادة موصلة للكهرباء، وبغض النظر عن الخصائص الميكانيكية للمواد. في هذه العملية التي لا تلامس العدة المشغولة فهي منتشرة وتُستخدم في كثير من الصناعات، بما في ذلك صناعة الطيران، العدد والقوالب، والأدوات الطبية، وهي مفيدة بشكل خاص للمواد الصلدة ذات الأشكال الهندسية البسيطة أو المعقدة. على الرغم من استخدام مكائن EDM في تشغيل المعادن "التي يصعب تشغيلها" مثل تلك المستخدمة في صناعات القوالب. إلا أن خصائص المعدن تشير الى الامكانية المحتملة في مجال معالجة السطح بسبب الشرارة الكهربائية التي تحدث بين الألكترود ومادة المشغولة. في هذا البحث تم دراسة الصلب السبائكي X210 باستخدام معظم المتغيرات المؤثرة وكيف يمكن أن تساهم زوايا الألكترود على المخرجات مثل: معدل ازالة المعدن، نسبة تآكل الألكترود، والخشونة السطحية، والتي تستخدمها المصانع لصنع عدد القوالب، وأجزاء السيارات، وغيرها. أُستخدمت الألكترودات بزوايا ٥° و ٩٠٥ في تشغيل العينات، استخدمت مكائن سلك الشرارة الكهربائي(dk7740) WEDM لتصنيع الألكترودات. متغيرات هذه الدراسة كانت: زاوية الألكترود، التيار، وتيار تفريغ النبضة، وتيار توقف النبضة، في حين أن جميع المتغيرات الأخرى ثابتة، أُجريت دراسة على هذه المتغيرات ثم أُجري تحليل تأثيرات المتغيرات الأربعة على المخرجات إحصائيًا باستخدام مبدأ ANOVA باستخدام برنامج MINITAB. تطوير نماذج الانحدار للمخرجات. تم تطوير النماذج الرياضية الانحدارية لعينات الصلب السبائكي X210 لزيادة الإنتاجية.

الكلمات الدالة: مكائن التشغيل بالشرارة، الشكل الهندسي للألكترود، الخشونة، معدل ازالة المعدن، النمذجة.

1.INTRODUCTION

Recent advancements in electronic products, such as mobile phones, PDAs, and handheld media players, have proven the need for items with intricate and undercut designs. Electro-discharge machining (EDM) is a material removal process that uses electric spark discharges to machine conductive materials [1]. Alloy steel compressor and gas turbine fabrication are examples of promising applications besides producing tools and molds from hard materials, such as high-hardness materials. The electrode (tool) and the workpiece are submerged in a fluid (dielectric) that carries an electrical current. During the process, the anode and the cathode are placed very close to one another, creating a plasma stream [1, 2]. The process's essence is converting electrical energy in the form of sparks into thermal energy. The electric spark occurs when the distance between the tool and the electrode is close enough to create a micro-conductive ionized channel [3]. Alloy tool steel is used for various purposes, from cutting tools and hammers to stamping and metalworking molds and machine parts. The enormous demand for tools, tooling, dies, and molds is due to the extensive use of these items in production. How likely a discharge is determined by how easily electricity can be broken down within the spark gap [4, 5]. Any point between the two electrodes will experience a more severe electrical breakdown if debris is present. This debris can cause unstable electrical conditions; thus, flushing is performed under standard machining settings to remove it from the cutting gap [6, 7]. Debris granules in the gap are crucial for establishing steady machining conditions by improving spark position distribution, and a dielectric that is too clean can lead to uncontrolled sparking [8]. This investigation presents an overview of the modern technologies using the EDM process. Shukry works with electrodes made of carbon steel CK 60 for the workpiece and brass for the tool, and these electrodes can have flat, conical, or spherical geometries. The material removal rate was shown to be most affected by the duty factor, i.e., the percentage of the ratio between pulse duration and total cycle time, and current in experiments. According to the results of this research, the electrode form using a flat tool produced the highest MRR compared to other electrode shapes [1]. Nadeem et al. modified a standard tool design, including relief angles in the electrodes. The workpiece and electrode were made of WC and copper, respectively; when it came to relief, the angled tool electrodes behaved better than their cylindrical counterparts. The machining time has been cut by 49% due to the relief-angled electrodes [4]. Electric machining of tool steel by Hanan et al. analyzed the effect of the tip angle and tip radius of a copper electrode tool (AISI D2). Compared to other electrodes, it was discovered that the conical electrode with a radius of 1 mm delivered the highest MRR, while the conical electrode with a radius of 0 mm offered the lowest EWR [9]. Uhlmann et al. explored how changing the electrodes' exterior shape on cylindrical tools could improve the efficiency of electric discharge drilling. Brass electrodes with helical flutes along the shank were compared to the standard form of a cylindrical rod electrode to determine which is more effective at clearing out waste. The drilling EDM method might be improved by setting a minimum flute depth and angle[6, 10]. By employing the EDM method of cutting high-speed steel, Asaad and Maan investigated the impact of various parameters on the material removal and wear rates with five forms of electrode tool (triangle, square, circular, cylindrical solid, and polygon). The results indicated that the rectangular geometry of the electrode holes was the most effective electrode shape. With the same form, the best electrode wear ratio was added. The electrode with the square hole had the highest MRR [11]. Micro precision in mold manufacture was investigated by Pellicer et al., who examined the impact of different EDM machining parameters and tool steel electrode shapes. Various electrode geometries, i.e., flat, depth, slope, and width, and AISI H13 workpieces were studied. Regular polygons like rectangles and squares best illustrated high precision in groove processing due to their high EWR and stable machining. Due to rapid wear along the electrode's triangular edges, this tool is ineffective [12]. Pani and Masanta investigated a copper-based hexagonal electrode tool through a series of tests. A plate made from Al alloy (A6063) was used in the production process. This study's findings were used to refine the regression method, and RSM was employed to highlight the connection between stimulus and effect. A giant crater was created, and the rate at which material was removed, as the high current and spark output, was increased. No interaction between the duty factor and pulse-on-time affects the removal rate [13]. Tool steel P20 was the workpiece for Shailesh Kumar's presentation of a hollow U-shaped copper electrode tool with an internal flushing mechanism; this steel is crucial in the fabrication of mold steel. Taguchi analysis was used to determine the optimal values for three machining parameters, i.e., pulse on time, tool diameter, and discharging current. This study demonstrated that current significantly affected MRR, increasing MRR with current. Tool wear can also be affected by the presence of current. The current discharge has a far more significant effect on overcut than the pulse on time [14]. Kamlesh and Patel utilized an ANOVA analysis with a few factors. Four copper electrode tool shapes were employed with steel (AISI) H13 utilized primarily in tooling dies: rectangular, square, triangle, and round. Electrode shape was an essential aspect affecting performance evaluations. Electrode shape contributed between ten and twenty percent to analyses of variance and signal-to-noise ratios [15]. For drilling large holes, Jamkamon and Janmanee relied on a copper tool with a stepped cylindrical shape consisting of a (body), "shank," and "neck," and a workpiece of AISI P20 (Step-cylinder). The percentage of wear was lower, and the MRR was higher than conventional electrode instruments. Electrodes with a higher surface roughness than the normal shape [16]. According to Naveed et al., a Taguchi L9 array was used for multiple positive-voltage electrodes, i.e., graphite, aluminum, copper, and brass. Also, a Taguchi L9 array was utilized for many negative-voltage electrodes. Consequently, 72 separate trials were conducted. To obtain the lowest possible levels of tool wear and overcut (OC) around the machined surfaces, it is necessary to study the nature of these responses. A tool with common tool polarity was selected as optimal to achieve the assessment approach of least tool wear and minimal level OC [17]. The height of re-sticky particles decreased with increasing lift distance, as previously observed by Shih-Hsien and Wang and throughout the current investigation. However, the finished product exhibited a slight degree of material re-stickiness. However, almost 90 μm of height was generated. Further, after a piece of the electrode was cut from the base of the trash re-sticky to the cylinder rod along its longitudinal axis, the machined surface would gradually diminish. When the width of a specialized electrode was 0.6D, re-sticky debris was also minimized. The issue completely vanished [18]. Kliuev investigated a method to capture high-speed, microscopic images of an EDM drill bit in action. The average workpiece speed in the electrode's outflow area was 0.9 m/s, while the electrode was nearing the condition. In the second scenario, the electrode was situated inside the eroded cavity, and the average gap velocity was 0.75 m/s [19].

2.EXPERIMENTAL WORK

This experimental investigation determines the effects of varying the electrode angle, current, pulse-on, and pulse-off times for an Electric Discharge Machine while machining an Alloy steel X210 workpiece (see Fig. 1). A detailed research technique is offered, including guidelines for conducting experiments, analyzing data, and drawing conclusions. As a result of its high efficiency, copper was selected as the electrode material for this experiment (see Fig. 2). (CM 323C+50N) EDM machine was used in this study. Chemical composition was analyzed by an ARL spectrometer in North Gas Company (NGC)-Kirkuk/Iraq. The X210 Alloy tool steel employed in the present investigation is the subject of the possible process parameters for the objective response parameters. The chemical elements of Tool steel X210 alloy are provided in Table 1. Electrodes with 0° and 90° angles have been produced.

Table 1 Chemical Composition (%) of Workpiece Alloy Steel X210.

Material	% Weight
C	1.9
Cr	11.71
Mn	0.49
Cu	0.36
Zn	0.15
Mo	0.24
Sn	2.22
Fe	81.82

Fig. 1 Machined Workpiece by EDM Process.

Fig. 2 Copper Electrode with a Transverse Hole.

3.ANGLED ELECTRODE

A copper electrode was selected as the material electrode, and the process parameters that might yield the desired value of response variables were identified. Two electrodes, one at an angle of 0° and the other at an angle of 90°, were designed, and a transverse hole was drilled into them. Throughout this work, Fig. 3 displays a comparison between the conventional and the novel electrodes [20].

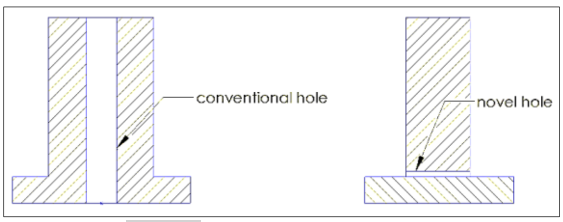


Fig. 3 Angled Electrodes.

4.EXPERIMENTAL DESIGN

Many aspects of the EDM process are under control; however, to keep the scope of this study manageable, only a small subset of these aspects was changed. Table 2 displays these adjustable parameters and their respective set points. The copper was chosen in the electrodes for its high efficiency and high quality. The main characteristic of copper electrodes is their Electrolytic nature.

Table 2 Process Parameters.

Parameter	Unit	Levels	
		Min	Max
Electrode Angle	Degree	0°	90°
Current	Ampere	15	35
Pulse-on time	Micro Second	60	300
Pulse-off time	Micro Second	20	140

5.RESPONSE-BASED VARIABLE

Material Removal Rate quantifies the efficacy of any machining technique, including electrical discharge machining (EDM). The EDMs' ability to calculate a volume cut-to-machining-time ratio allowed for accurate estimation of material removal. Therefore, mathematically [21].

$$MRR = \frac{W_i - W_f}{t.\rho} \quad \textbf{(1)}$$

where W_i = initial weight before machining (gm), W_f = final weight after machining (gm), t = machining time (min), and ρ= density of workpiece (gm/mm3).

As in the MRR procedure, the workpiece replaced an electrode. The equation for Electrode wear ratio (EWR) is stated according to [21]:

$$EWR = \frac{W_{ie} - W_{fe}}{\rho_e t} \quad \textbf{(2)}$$

where W_{ie} = initial weight of electrode before machining (gm)

W_{fe} = final weight of electrode after machining (gm), t = machining time, and ρ_e = electrode density (gm/mm3).

The essential parameter Ra was used to quantify the roughness of a surface; it is obtained from the ratio of the highest and lowest points on a surface, which is then averaged over a given length [22]. In this study, Ra was measured using a Pocket Surf III/ PMD 90101 from the (Mahr Federal) company in the USA, with an accuracy of 0.05. All the acquired variables for each controlled parameter set are listed in Table 3. Minitab's analysis of variance (ANOVA) is a standard tool for examining potential differences in the response parameters' standard deviations. The central hypothesis of ANOVA argues that any changes made to the controllable variables or interactions would result in similar changes to the parameters measuring the mean response [23]. The results showed that the parameters' and interactions' impact on the variables was negligible. The hypothesis suggested a significant discrepancy between the means of the response parameters. Due to the variety of available methods, it is essential to consider how various input parameters and their interactions affect the independent variables [24]. The estimated response and its influencing data, variables, and parameters were entered into the statistical analysis Minitab program. The software then developed a design of experiment (DOE) formula, which was used to examine and evaluate the results.

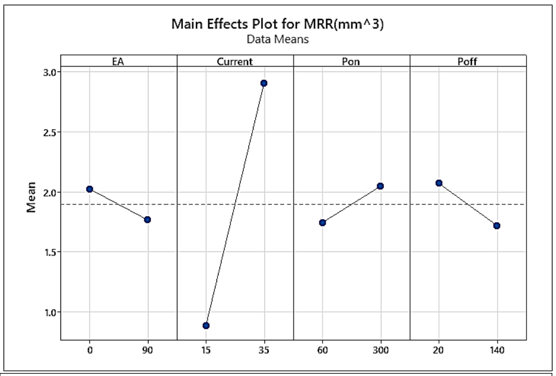
Table 3 Measurable Parameters of the Mean Response.

Run	EA	Current	P_{on}	P_{off}	MRR	EWR	SR
1	90	35	300	20	0.220	0.019	4.454
2	90	35	60	140	0.542	0.089	4.265
3	90	15	300	20	1.111	0.007	3.168
4	0	15	60	140	1.168	0.224	3.981
5	0	35	300	140	1.896	0.033	5.667
6	0	35	60	20	2.418	0.536	3.679
7	0	35	20	20	3.792	0.045	6.081
8	0	15	20	20	1.046	0.022	3.856
9	90	15	20	20	0.833	0.039	4.058
10	90	35	140	140	0.560	0.134	3.088
11	0	15	140	140	0.729	0.005	5.459
12	90	15	140	140	0.433	0.102	4.941

EA (Electrode Angle). P_{on} (Pulse-on time). P_{off} (Pulse-off time).

Table 4 ANOVA for Material Removal Rate.

Parameter	DOF	Adj. SS	Adj. MS	F-Value	P-Value
Electrode Angle (degree)	1	0.1985	0.1985	1.37	0.032
Current (C)	1	12.2061	12.2061	84.21	0.000
Pulse-on Time (P-on)	1	0.2728	0.2728	1.88	0.0212
Pulse-off Time (P-off)	1	0.3669	0.3669	2.53	0.156
Error	7	1.0146	0.1449		
Lack-of-Fit	6	1.0077	0.1679	24.27	0.154
Pure Error	1	0.0069	0.0069		
Total	11	14.0590			



0, 90: EA (degree)
15, 35: Current (A)
60,300: P_{on} (µs)
20,140: P_{off} (µs)

Fig. 4 Main Effect Plots of Mean MRR [25].

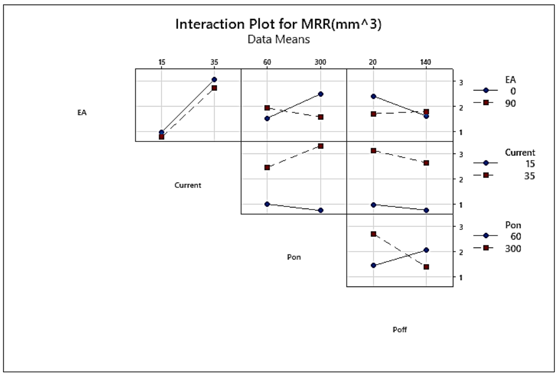


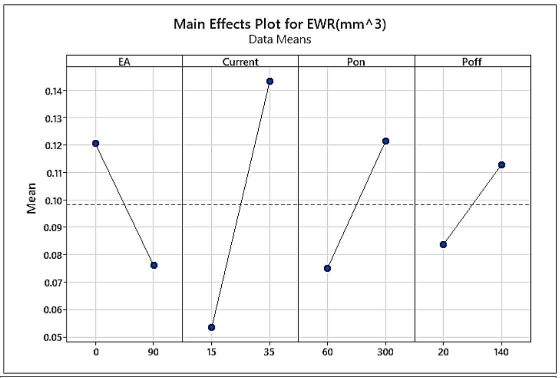
Fig. 5 Interaction Effect Plots of Mean MRR.

6.MATERIAL REMOVAL RATE

Increasing the pulse on time and peak current increased MRR, as seen in Fig. 4. Conversely, decreasing the pulse of time and using an angled electrode (90°) decreased MRR. Unlike the standard vertical hole, which left a mark on the workpiece, the transverse hole electrode left no trace due to increased discharge energy and enhancements in pulse on and peak current, resulting in a faster MRR for (0°). Reduced MRR results from fewer discharges occurring in a particular period due to more extended periods of inactivity between pulses. Table 4 displays the results of an analysis of variance performed on the MRR by changing the observable parameters. Meanwhile, the changing effect of these characteristics and their interactions on the mean MRR is shown in Figs. 4 and 5. The MRR was significantly impacted by electrode angle and current, as shown in Table 4 (also see Fig. 4) (P-value less than 0.05) [26]. Fig. 5 demonstrates that interactions between the current and the electrodes at an angle of 90 degrees also affected the MRR. Along the length of the cut at an electrode angle of 0 degrees, the MRR varied from minimum to maximum (see Fig. 4), leading to a mean MRR that was greater than the mean MRR at an electrode angle of 90 degrees. As shown in Fig. 5 and Table 4, MRR increased significantly as the electrode angle and current simultaneously altered, particularly for the 90° electrode angle. As seen in Fig. 5, increasing the current reduced the MRR considerably, whereas increasing the pulse-off duration had the opposite effect. The mean MRR was the smallest at a 90° electrode angle.

Table 5 ANOVA for Electrode Wear Rate.

Parameter	DOF	Adj. SS	Adj. MS	F-Value	P-Value
Electrode Angle (degree)	1	0.005916	0.005916	1.57	0.020
Current (C)	1	0.024091	0.024091	6.40	0.039
Pulse-on Time (P-on)	1	0.006403	0.006403	1.70	0.023
Pulse-off Time (P-off)	1	0.002534	0.002534	0.67	0.043
Error	7	0.026358	0.003765		
Lack-of-Fit	6	0.024226	0.004038	1.89	0.505
Pure Error	1	0.002132	0.002132		
Total	11	0.065303			



0, 90: EA (degree)
15, 35: Current (A)
60,300: P_{on} (μs)
20,140: P_{off} (μs)

Fig.6 Main Effect Plots of Mean EWR.

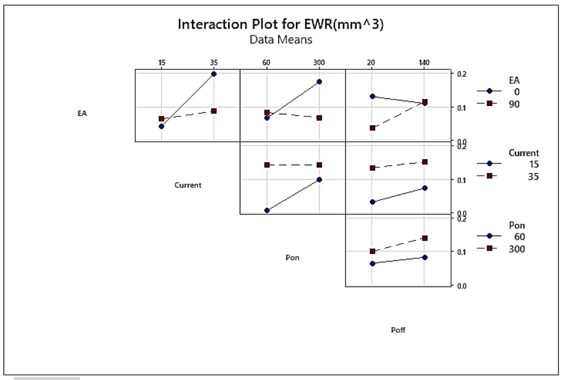


Fig.7 Interaction Effect Plots of Mean EWR.

7.ELECTRODE WEAR RATE

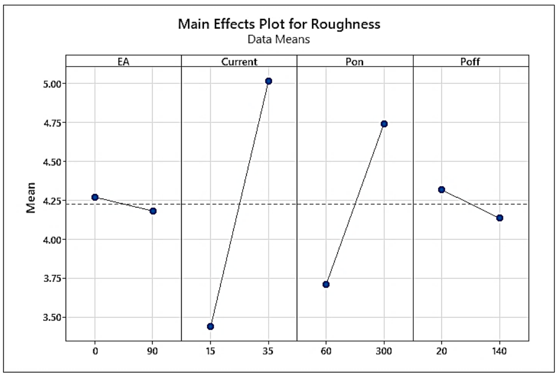
The results of the ANOVA performed on the electrode wear ratio acquired during the EDM process in the Alloy tool steel X210 workpiece are shown in Table 5. Compared to the other variables, the F-value of 6.40 demonstrates that the current influence was the most important. As a result, it had a far more significant impact than the other variables. Fig. 7 demonstrates that when electrode angles increased, EWR decreased because more surface area was exposed to erosion. Because the sparks were spread out across a wider region, the electrodes wear out faster. The EWR rose due to the increased erosion rate within the exposed area brought on by the more significant current.

8.SURFACE ROUGHNESS

With a rise in current, the surface roughness of Alloy steel X210(F value 26.28) also increased, as shown in Table 6. An increased EDM current was detrimental to the surface finish. When the electrode was at a zero-degree angle to the surface of the workpiece, the mean surface roughness was most significant. As a result, the surface roughness of the Alloy tool steel X210 increased due to its non-uniform melting. Electrode angle, current, and pulse-on alone considerably impacted surface roughness; however, when combined, they had an even more significant impact. The surface finish deteriorated as the pulse off was turned.

Table 6 ANOVA Surface Roughness.

Parameter	DOF	Adj. SS	Adj. MS	F-Value	P-Value
Electrode Angle (degree)	1	0.0238	0.02376	0.08	0.078
Current (C)	1	7.4387	7.43873	26.28	0.001
Pulse-on Time (P-on)	1	3.1951	3.19507	7.19	0.012
Pulse-off Time (P-off)	1	0.0990	0.09901	0.68	0.573
Error	7	1.9816	0.28308		
Lack-of-Fit	6	0.7271	0.12118	0.75	0.982
Pure Error	1	1.2545	1.25453		
Total	11	12.7382			



0, 90: EA (degree)
15, 35: Current (A)
60,300: P_{on} (μs)
20,140: P_{off} (μs)

Fig. 8 Main Effect Plots of Mean SR.

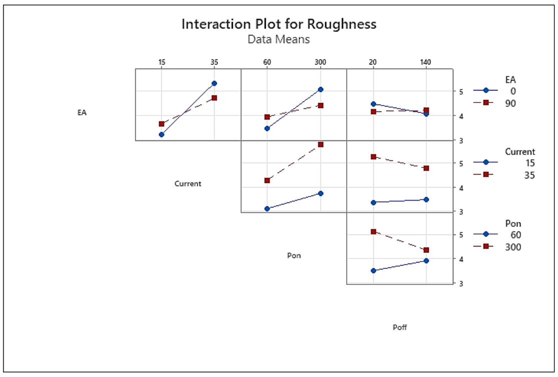


Fig. 9 Interaction Effect Plots of Mean SR.

The results of an ANOVA performed on the surface roughness achieved by the EDM process in the Alloy steel X210 workpiece are displayed in Table 6. Current and pulse on both had P-values smaller than 0.05, indicating that their influence was likely more noticeable than chance suggests. Fig. 8 shows that the roughness of a surface was most affected by the current. Compared to the F-value of 7.19 for the pulse-on, which indicated a less significant influence, the F-value of 26.28 for the current indicated a more significant influence. A correlation exists between the current used in the EDM process and the surface roughness produced (F-value 26.28), supporting the ANOVA for SR (Table 6). The electrode at 0 degrees had the most significant effect on the workpiece's mean surface roughness.

9.CONCLUSIONS

This investigation presents EDM process parameters that affected the final products made from Alloy steel X210. During the EDM cutting of Alloy tool steel X210, the results of altering the parameters over the selected process variables are presented. The following conclusions are drawn from the experimental findings and analysis:

- The MRR of Alloy tool steel X210 components was extremely sensitive to electrode angle, current, pulse-off time, pulse-on time, and their interactions. The magnitude of the change in MRR was primarily attributable to the current.
- As the time required to recharge potential energy during the discharging process increased, the MRR and the pulse-off value tended to move in opposite directions. While the erosion rate increased with a higher current, it continued to rise. As the pulse-off time increased, the erosion rate decreased, and as a result, the temperature in the erosion zone dropped.
- Surface roughness was negatively correlated with pulse-on time and current in electrical discharge machining (EDM) of Alloy tool steel X210. However, the surface roughness was positively affected by a 90° electrode angle and a longer pulse-off time.
- There was a high degree of sensitivity of MRR to all critical variables. Since a greater erosion area was exposed at a 90° electrode angle and for a more extended pulse-off time, the mean relative reduction in MRR was negatively correlated with these two variables. In contrast, the increased erosion rate associated with higher currents increased it.
- During electrical discharge machining (EDM) of stainless steel X210, significant factors influencing the electrode wear rate were observed with current, pulse-on, and pulse-off.
- The electrode wear rate was lowest at an electrode angle of 90°, while current negatively affected the electrode wear rate (EWR).

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