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Investigation into the Electrical Discharge Machining Parameters of DIN 2767 Tool Steel Using Taguchi Method

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Abstract

Electrical discharge machining (EDM) is one of the most crucial non-traditional machining methods used in molds and dies manufacturing, and conductive materials machining, which are difficult to machine by traditional methods. The EDM performance is affected by several machining parameters with different contribution percentages. In this study, the experimental investigations were conducted on DIN 2767 tool steel using CuCrZr, Cu and CuCo1Ni1Be (CNB) electrodes. The most influential process parameters were focused on to improve the EDM performance. The value of the process parameters and their levels were discharge current (6, 12 and 25 A), pulse-on time (50, 200 and 800 µs) and pulse-off time (50, 200 and 800 µs). Optimal levels of machining process parameters were obtained by employing the Taguchi L_{27} orthogonal arrays. The experimental results showed that the optimal combination of the machining parameters for maximum material removal rate was $A_3B_2C_1$ using a CNB electrode. For minimum tool wear rate, the optimal parametric combination was $A_1B_3C_1$ and Cu electrode. The optimal parametric combination was $A_1B_3C_3$ and CuCrZr electrode for minimum surface roughness. The study further revealed the relation and interaction effect between process parameters for the performance measures. Lastly, the process parameters affected and changed the DIN 2767 tool steel workpieces' surface integrity as evidenced by the scanning electron microscopy images.

***Keywords**: EDM, Taguchi method, DIN 2767 tool steel, copper, CuCrZr*

1. Introduction

The industrial development has witnessed the challenge of new materials characterized by superior properties such as high hardness, strength and toughness. There is also a growing need for manufacturing accuracy and precision in manufacturing intricate shapes and 3-dimensional (3-D) shapes that cannot be achieved by conventional machining. Electric discharge machining (EDM) is one of the non-conventional machining processes in which electrical energy is converted into very high thermal energy. This energy is created as a spark between the electrode and workpiece in a tiny area making it melt or vaporize.

The use of EDM began during the 1940s after two Russian scientists (Boris and Natalya Lazarenko) discovered that electric contacts' erosion was more precisely controlled if the electrodes were submerged in a dielectric fluid. They succeeded in controlling and maintaining the gap between the electrode and the workpiece and reducing the electric discharge (Schumacher *et al.*, 2013). EDM can machine any conductive materials with high accuracy, reasonable removal rates, and good surface finish, regardless of the material's mechanical properties making it widely used in many fields involving medical, aerospace, automotive, electronics and other industries (El-Hofy, 2005).

The performance and efficiency of the sinking EDM depend on many process parameters. These parameters are classified into electric process parameters and nonelectric parameters. Electric process parameters include discharge current, pulse-on time, pulse-off time, duty factor, gap voltage, intensity and pulse frequency. Nonelectric process parameters encompassed the electrode material, electrode shape, rotation of the electrode, workpiece material, dielectric fluid type, and flushing system (Patil and Jadhav, 2016).

Among the most influencing parameters are peak current, pulse-on time, pulse-off time and electrode material. The peak current (I_p), known as pulse current, is the most significant parameter affecting EDM's performance because of its relation to the spark energy applied to the workpiece. The pulse duration or pulse-on time (T_{on}) expresses the time length of the spark in microseconds. Actual machining only occurs during the pulse-on time. The longer pulse-on time will make the energy higher; therefore, the machining rate is faster. Nevertheless, after a specific value of pulse-on time, the material removal rate starts to reduce as the plasma is created in the gap hindering the energy transfer (Guitrau, 1997). Pulse-off time (T_{off}) is commonly referred to as pulse interval or pause time (time between two sparks). At this time, neither discharge voltage is applied between electrodes nor does discharge current flow between them. Pulse-off time must be long enough to allow the dielectric fluid's deionization and flushing debris away from the gap spark.

The electrode material is the significant property of an electrode with high electric conductivity and high melting temperature. The selection of particular electrode material based on five significant factors: material removal rate (MRR), tool wear rate (TWR), surface roughness (R_a), fabrication electrode cost and raw material cost. The EDM process performance is assessed by the achievement of high MRR, low TWR and good surface finish. In addition, some other outputs have less importance such as white layer thickness, heat affected zone, surface crack density (SCD) and residual stress.

Several research studies and experiments on EDM machining have been carried out to provide information on machining factors and their effect on the responses that significantly reduce effort, time, cost, and achieve satisfying results (required quality). This has made manufacturing by EDM a large research field and still in progress (Ho and Newman, 2003).

Arunkumar *et al.* (2012) investigated the influence of electrode material on the performance characteristics of electrical discharge machining of EN31 (air-hardened steel). It was observed that the copper electrode provided less TWR, higher MRR, less taper value and variation in the average R_a compared with aluminum and EN 24 electrodes. Haron *et al.* (2001) examined the effect of discharge current and electrode diameter on MRR and TWR when machining AISI 1045 tool steel. Low discharge current was found to be appropriate for small diameter electrodes, while high discharge current was apt for large diameter electrodes. Venkatesh *et al.* (2015) studied the influence of electrode material on EDM performance. Their work materials are EN 31, EN 8, and HCHCr; three electrodes were used, namely copper, brass and chromium-copper. The results showed that higher MRR and lower TWR were achieved by chromium-copper electrode followed by copper and then brass. R_a was directly proportional to the I_p. Chromium-copper electrode produced good dimensional accuracy, and R_a was lower than the copper electrode. The brass electrode gave a good surface finish but TWR was high, and MRR was low. The performance characteristics were affected by workpiece material and electrode material.

Patil and Jadhav (2016) discussed the influence of process parameters on the EDM performance. They reported that the I_p had the greatest influence on MRR, while T_{on} and voltage had considerable influence on MRR. TWR was mainly affected by I_p and T_{on}. R_a increased with I_p and T_{off}'s increase, whereas the T_{on} at a higher values improved the surface finish. Haron *et al.* (2008) investigated the effect of the process parameters on MRR and TWR of XW-42 tool steel using graphite and copper electrodes. The results revealed that the increase in the I_p and electrode diameter reduced the TWR and MRR. Another EDM experiment was conducted by Chandramouli and Eswaraiah (2018) on 17-4 PH steel, wherein the copper-tungsten electrode was used; L_{27}, based on the Taguchi method, was applied to plan experiments and parameters optimization. The input parameters were I_p (9, 12, 15 A), T_{on} (50, 100, 200 µs), T_{off} (20, 50, 100 µs), and lift time (10, 20, 50 µs). However, I_p and T_{on} had a significant effect on both MRR and R_a, while T_{off} had a lower effect than I_p and T_{on}. T_{on} had the highest contribution effect on MRR and R_a followed by I_p; the contribution of T_{off} and lift time were negligible. The optimal parametric combinations of MRR and R_a were I_p = 15 A, T_{on} = 50 µs, T_{off} = 100 µs, and lift time = 10 µs; and I_p = 9 A, T_{on} = 200 µs, T_{off} = 20 µs, and lift time = 10 µs, respectively.

Nikalje *et al.* (2013) carried out EDM experiments on MDN 300 steel using a copper electrode to obtain the effect of input parameters on EDM responses. Taguchi technique L_9 orthogonal arrays were applied for planning the experiments and optimizing the response measures. It was found that I_p had a greater influence than T_{on} for MRR and TWR but T_{on} was more significant than I_p for TWR and R_a. T_{off} had a low impact on all performance measures. Lower I_p and shorter T_{on} gave less surface damage. Sihore and Somkuwar (2019) performed EDM works on SS316H using a copper electrode, and statistical techniques (Taguchi L_9 and analysis of variance [ANOVA]) were used for optimization and results confirmation. The minimum R_a was at low I_p and T_{on} values, whereas the maximum MRR was at high I_p and T_{on} values. For R_a, the most significant process input parameter was T_{on} followed by T_{off}, and for MRR, the most influential factor was I_p, followed by T_{on}.

Ahmad and Lajis (2013) accomplished experiments on Inconel 718 with a copper electrode. The EDM process parameters were at high values: I_p = 20, 30, and 40 A; T_{on} = 200, 300, and 400 µs; and voltage = 120 V. The study found that the MRR increased with the increase in I_p and decrease in the T_{on}. The maximum MRR was at I_p = 40 A and T_{on} = 200 µs. The minimum TWR was at low I_p (20 A) with a high value of T_{on} (400 µs). The optimum surface finish was achieved at the lowest value of I_p and T_{on}. Kumar (2012) investigated the EDM performance of three different electrodes (copper-chromium, brass, and copper) of machining OHNS die steel and discharge current ranging from 6 to 12 A. It was concluded that the copper-chromium electrode produced higher MRR, better surface finish, lower TWR, and slightly higher surface micro-hardness than other electrodes. Similarly, Nallusamy (2016) performed an experimental study of MRR and TWR on OHNS using EDM with copper and brass electrodes. The results revealed that MRR and TWR increased with the increase of I_p for both electrodes. The copper electrode yielded a higher MRR than the brass electrode. The copper electrode was appropriate for both rough and finish machining and brass electrode for rough machining.

Fikri *et al.* (2017) experimentally evaluated the effect of process parameters on EDM performance (MRR and R_a) on AISI P20M steel. Graphite, copper and brass were used as electrodes; the results were verified statistically. It was observed that the graphite electrode was the most influential on R_a followed by the brass and copper electrodes. Graphite electrode had the highest electrical conductivity followed by brass and copper. Also, the results confirmed that higher I_p led to higher R_a. Similarly, another study of Koteswararao *et al.* (2017) investigated the influence of EDM machining parameters (I_p, T_{on}, and electrode diameter) on EN 31 alloy steel utilizing copper electrode. L_{18} orthogonal array based on Taguchi design experiments was conducted. The results showed that the I_p was the most influential parameter on both MRR and TWR followed by T_{on} and then the electrode diameter.

More recently, Kalyon (2020) optimized the machining parameters in EDM of Caldie plastic mold tool steel using the Taguchi method. Experiments were performed with graphite and copper electrodes, and the process parameters were I_p (6, 12 and 25 A) and T_{on} (50,100 and 200 µs). ANOVA was used for analyzing the effect of process parameters. Results revealed that the optimal parametric combination for MRR was the copper electrode (25 A and 200 µs) and the optimal parametric combination for R_a and TWR are graphite electrode (6A and 50 µs). Additionally, Mahajan *et al.* (2020) investigated the effect of EDM performance parameters on the MRR and R_a of Co-Cr alloy employing the Taguchi L_{18} orthogonal array. Two dielectric fluids (deionized water and EDM oil) and three electrodes (graphite, tungsten and tungsten-copper) were used. It was found that the most critical factors affecting R_a were T_{on} followed by I_p and electrode material, and for MRR, the dielectric had the highest influence than I_p and electrode material. T_{off} exhibited as an insignificant parameter for both responses. Moreover, Panda *et al.* (2015) investigated the EDM of S304 grade stainless steel using the copper electrode. Experimental results showed that the I_p, T_{on} and dielectric flashing pressure significantly affected the MRR and TWR, while I_p and T_{on} affected the R_a.

The previous studies handled the effect of the process parameters on the EDM responses of different types of materials and optimized parameters for best EDM performance. However, it can be noticed that no considerable work has been performed to determine the effect of process parameters using pure copper, hot-rolled CuCrZr and CuCo1Ni1Be (CNB) copper electrode materials on the DIN 2767 tool steel. Hence, the current study was carried out to investigate the effect of discharge current, pulse-on time, pulse-off time and electrode material on MRR, TWR, and R_a in EDM of DIN 2767 tool steel.

2. Methodology

2.1 Experimental Work

The experiments were conducted on the FURKAN M25A sinker electrical discharge machine. Pure copper, hot-rolled CuCrZr and CNB copper were selected as electrode materials. The electrode diameter was 16 mm, and its polarity was negative. The chemical compositions of electrodes are shown in Tables 1 and 2.

Table 1. Chemical composition (wt%) of copper CuCrZr electrode

Cu	Cr	Zr	Others
Base	1.00	0.10	0.20

Table 2. Chemical composition (wt%) of copper CNB electrode

Cu	Be	Co + Ni	Others
Base	1.00	2.00	0.50

The cross-section (face) of the electrodes were polished on silicon carbide paper with grit sizes of 150, 240, 320, 400, 600 and 800 before each experiment was carried out. The work material was DIN 2767 tool steel. This type of steel has an actual industry application such as cutting and bending tools, plastic molds, drawing jaws, gears requiring shock resistance, heavyduty shafts, and axles. The chemical composition of DIN 2767 tool steel is presented in Table 3. Each workpiece's size was 50 x 25 x 12 mm, and its surface was milled and finish grinded before performing the EDM experiments.

Table 3. Chemical composition (wt%) of DIN 1.2767

C	Si	Mn	Cr	Mo	Ni	Fe
0.45	0.25	0.35	1.35	0.25	4.05	Balance

The EDM selected controllable factors (process parameters) such as electrode material, I_p, T_{on} and T_{off}; their levels are shown in Table 4. The kerosene was used as a dielectric fluid with lateral flushing pressure of 0.25 bar. The EDM machining time of each experiment was 60 min. Figure 1 exhibits the CuCrZr electrode and workpieces after machining.

Table 4. Process parameters and their levels

Process Parameters	Parameter Notation	Levels		
		Level 1	Level 2	Level 3
Electrode Type	E	CuCrZr	Cu	CNB
I_p	A	6	12	25
T_{on}	B	50	200	200
T_{off}	C	50	200	800

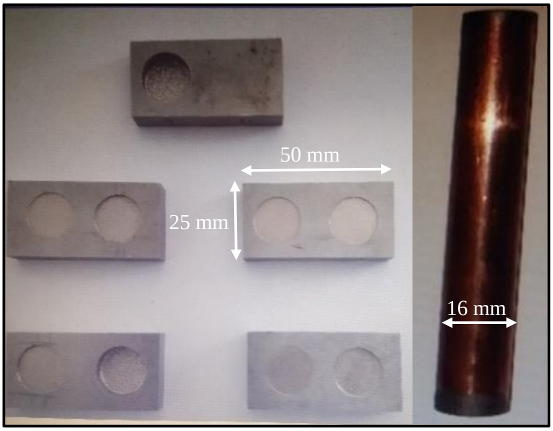

Figure 1. Electrode and workpieces after machining

The electrodes and the workpieces were weighed before and after performing the experiments to calculate MRR and TWR using Equations 1 and 2, respectively.

$$MRR\ (mm^3/min) = \frac{w_i - w_f}{t \times \rho} \tag{1}$$

$$TWR\ (mm^3/min) = \frac{T_i - T_f}{t \times \rho} \tag{2}$$

where:

W_i = initial weight of the workpiece
W_f = final weight of the workpiece
T_i = initial weight of the electrode
T_f = final weight of the electrode
ρ = density
t = machining time (min)

In EDM, the individual machining spark creates individual craters on the workpiece surface. The size and the distribution of these craters affect R_a. Mitutoyo digital surface roughness tester was used to measure surface roughness as shown in Figure 2. Three measurements were taken at different locations and the average surface roughness was calculated. The Taguchi method, using the L_{27} orthogonal array, was applied to design experiments and obtain the optimal machining parametric combination for MRR, TWR and R_a.

Figure 2. Surface roughness measurement

2.2 Data Analysis

Many researchers have applied the Taguchi method and ANOVA technique to investigate and optimize EDM process parameters (Nikalje *et al.*, 2013; Chandramouli and Eswaraiah, 2018; Sihore and Somkuwar, 2019; Kalyon, 2020; Mahajan *et al.*, 2020). In Taguchi technique, signal to noise ratio (S/N ratio) was used to determine the effect of factors on performance, the individual impact of each factor and the possible interactions between factors. The S/N ratio was a combined measure of mean and variance. Calculating the S/N ratio depended on the condition of optimization (Krishnaiah and Shahabudeen, 2012; Kalyon *et al.*, 2018). For example, in the "larger the better", S/N was calculated according to Equation 3, which was used in calculating MRR. To calculate TWR and R_a, the lower value was preferred "smaller the better"; the S/N ratio was given by Equation 4. In these equations, Y_i is the performance response, i is the observation value and n is the number of tests in an experiment.

$$S/N = -10log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{3}$$

$$S/N = -10log\left[\frac{1}{n}\sum_{i=1}^{n}y_i^2\right] \tag{4}$$

Table 5. Design of experiments and values of response variables

Exp. No.	Variables	MRR (mm^3/min)	TWR (mm^3/min)	R_a (µm)
1	$E_1A_1B_1C_1$	1.40	0.04	4.026
2	$E_1A_1B_2C_2$	0.81	0.02	4.071
3	$E_1A_1B_3C_3$	0.23	0.02	2.069
4	$E_1A_2B_1C_2$	1.91	0.25	5.380
5	$E_1A_2B_2C_3$	1.97	0.27	4.989
6	$E_1A_2B_3C_1$	2.93	0.02	2.210
7	$E_1A_3B_1C_3$	3.12	1.74	5.921
8	$E_1A_3B_2C_1$	28.07	0.48	9.404
9	$E_1A_3B_3C_2$	19.16	0.08	9.455
10	$E_2A_1B_1C_1$	1.57	0.02	4.099
11	$E_2A_1B_2C_2$	0.97	0	3.822
12	$E_2A_1B_3C_3$	0.21	0.02	2.290
13	$E_2A_2B_1C_2$	2.06	0.19	4.681
14	$E_2A_2B_2C_3$	2.40	0	8.128
15	$E_2A_2B_3C_1$	2.42	0.02	5.375
16	$E_2A_3B_1C_3$	3.40	1.24	6.092
17	$E_2A_3B_2C_1$	25.75	0.18	11.454
18	$E_2A_3B_3C_2$	17.61	0.03	9.687
19	$E_3A_1B_1C_1$	2.78	0.19	4.198
20	$E_3A_1B_2C_2$	1.59	0.02	3.165
21	$E_3A_1B_3C_3$	0.44	0	1.997
22	$E_3A_2B_1C_2$	4.44	1.80	7.497
23	$E_3A_2B_2C_3$	7.27	0.14	10.006
24	$E_3A_2B_3C_1$	3.97	0.02	2.847
25	$E_3A_3B_1C_3$	3.50	0.26	6.424
26	$E_3A_3B_2C_1$	22.99	2.43	10.334
27	$E_3A_3B_3C_2$	24.60	0.11	10.600

Optimization in Taguchi's technique relied on determining the best level for the process parameters, which minimized the influence of noise. The best levels of process parameters were those that maximized the S/N ratio. ANOVA was used to reveal the combined effects (interaction) of process parameters on the performance measure. The interaction effect between process parameters for a response was present when one parameter's impact was based on the other parameter level (Krishnaiah and Shahabudeen, 2012). The experimental design and experimental results are presented in Table 5.

3. Results and Discussion

3.1 Effect of Input Parameters on MRR

The main effect plot for S/N ratios explained the effect of each parameter on the response. As shown in Figure 3, if the line for a particular parameter has the highest inclination, that line will have the most significant effect on the response. Figure 3 and Table 6 show that I_p was the most significant parameter followed by T_{off}, T_{on} and the least electrode material.

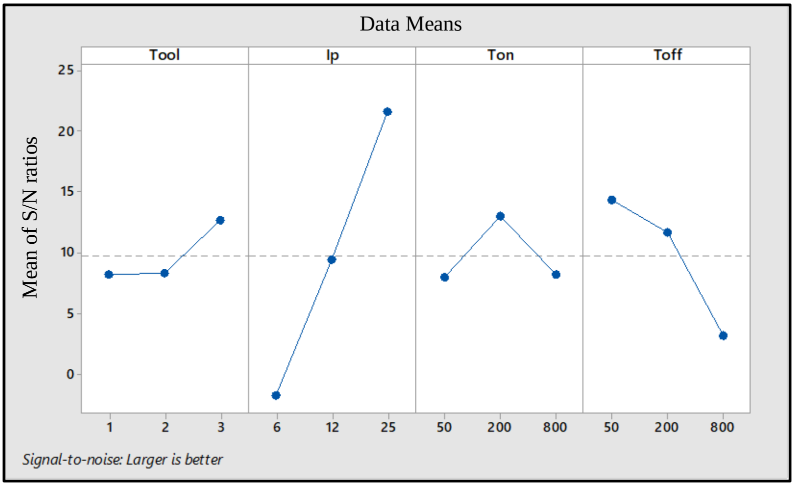

Figure 3. Main effects plot for S/N ratios of process parameters on MRR

This sequence is desirable to follow and focused on the most influential variables to improve the removal rate. MRR was directly proportional to I_p

and inversely proportional to T_{off}. The discharge energy was proportional to the peak current as the rise of the current resulted in the highest temperature; hence, more MRR was achieved (Dastagiri and Hemantha Kumar, 2014). At longer T_{off} time, the MRR was low which was attributed to the lesser time application of discharge energy. MRR rose with an increase of T_{on} until the second level and subsequently decreased. This was due to the excessive T_{on} leading to the expansion of the electric plasma channel, which reduced MRR and R_a (Lee *et al.*, 2004). Although the electrode material type did not impact the removal rate, the CNB electrode had a higher effect on MRR than CuCrZr and copper electrodes giving close results. The optimal combination of parameters for MRR was $E_3A_3B_2C_1$.

Table 6. Response for S/N Ratio of MRR

Level	Electrode	I_p	T_{on}	T_{off}
1	8.186	1.755	7.996	14.347
2	8.380	9.395	13.008	11.685
3	12.651	21.576	8.213	3.185
Delta	4.466	23.332	5.012	11.162
Rank	4	1	3	2

The interaction effects of parameters for MRR are illustrated in Figure 4. In the interaction plots, if the lines are parallel, there is no interaction between the parameters. On the other hand, if the lines are non-parallel, an interaction exists between the parameters. It is clear that there was slight interaction between the electrode materials and the process parameters for MRR.

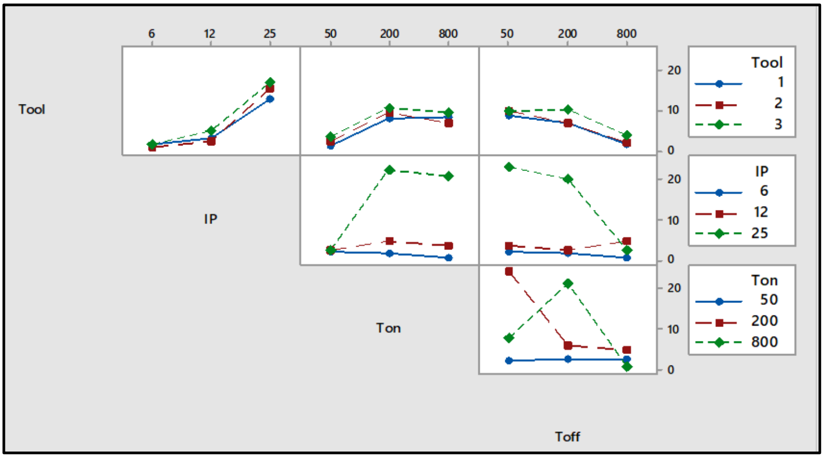

Figure 4. Interaction plot for MRR

A moderate interaction between I_p and T_{on} for MRR at low values of T_{on} and did not affect T_{on}'s high values. No interaction occurred between I_p and T_{off} at low levels of T_{off}, whereas strong interaction was maintained at longer T_{off}. Also, there was a strong interaction effect of T_{on} at 200 and 800 µs and T_{off}. However, the effect of T_{on} at 50 µs and T_{off} at high values was moderate.

3.2 Effect of Inputs Parameters on TWR

In Figure 5 and Table 7, the S/N ratio results showed that I_p was the most influencing factor on TWR followed by T_{on}, electrode material and then T_{off}. TWR was directly proportional to I_p and T_{off}. TWR was inversely proportional to T_{on}. This was linked to the deposition of carbon resulting from the dielectric burning on the electrode at a high temperature for a more extended T_{on}. The deposited carbon forms a protective layer that reduces TWR (Kumar, 2012).

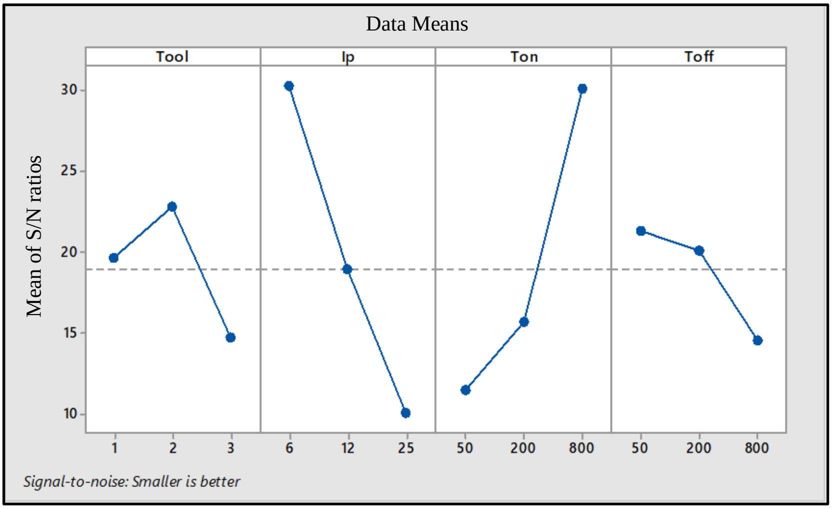

Figure 5. Main effects plot for S/N ratios of process parameters on TWR

As for the electrode, Cu was less wearing than the other two electrodes. The optimal combination of process parameters for TWR was $E_2A_1B_3C_1$. To confirm the optimal combination result, an experiment was performed, and the TWR was zero. In the previous studies, it was mentioned that electrode wear was affected by the type of electrode material (Nallusamy, 2016; Fikri *et al.*, 2017; Koteswararao *et al.*, 2017; Mahajan *et al.*, 2020) and that the most important and most influential variables were I_p followed by T_{on} (Muthukumar *et al.*, 2014; Koteswararao *et al.*, 2017; Kalyon, 2020). As for T_{off}, its effect was non-significant (Reddy *et al.*, 2015). To obtain a low TWR, I_p and T_{off}

should be set at a low level and the T_{on} at a high level and focused on the most profound effect parameters.

Table 7. Response for S/N ratio of TWR

Level	Electrode	I_p	Ton	Toff
1	19.65	30.33	11.42	21.32
2	22.84	18.97	15.71	20.11
3	14.69	10.02	30.18	14.49
Delta	8.15	20.31	18.77	6.83
Rank	3	1	2	4

The combined effects (interaction) of input parameters on TWR is shown in Figure 6. There was a moderate interaction between the electrode material and I_p, T_{on} and T_{off} for all levels except the interaction between the electrode and T_{off} from 200 and 800 μs, which was shown to be stronger. The combined effects of any of the two parameters of I_p, T_{on} and T_{off} on TWR strongly depended on the other parameters' level. This is evidenced by the lack of parallel between the lines and the presence of intersections.

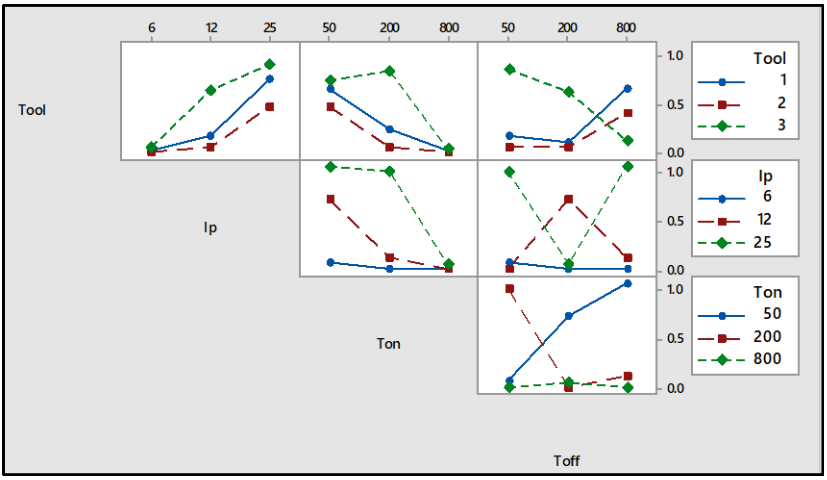

Figure 6. Interaction plot for TWR

3.3 Effect of Inputs Parameters on Surface Roughness

The main effects plot for the S/N ratio and the response for the S/N ratio of R_a are explained in Figure 7 and Table 8. I_p had the highest effect on R_a and played a significant role to achieve minimal R_a followed by T_{on} and electrode material, while T_{off} was the lowest. The surface roughness decreased as the I_p

increased. As T_{on} and T_{off} increased from level 1 to level 2, R_a increased and decreased thereafter.

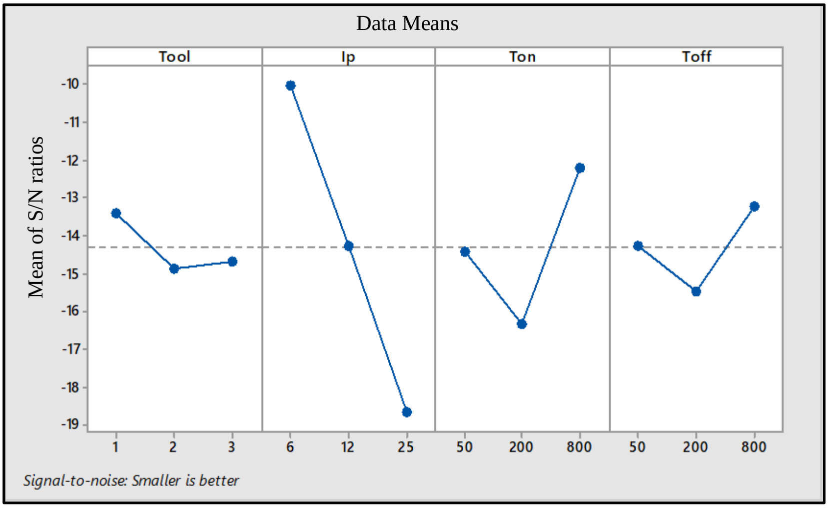

Figure 7. Main effects plot for S/N ratios of process parameters on R_a

The optimal combination of parameters for R_a was $E_1A_1B_3C_3$. However, according to a previous study (Keskin *et al.*, 2006), the type of electrode material affected both the R_a and the surface crack density (SCD). Chandramouli and Eswaraiah (2018) observed that T_{on} and I_p had a significant effect on both MRR and R_a, while T_{off} had a lower effect than I_p and T_{on}. Gupta *et al.* (2016) explained that with the excessive length of T_{on}, the electric plasma channel expands, which reduced the MRR and R_a. Ponappa *et al.* (2019) mentioned that I_p was more influential parameter in affecting MRR, TWR and R_a. The minimal surface roughness can be achieved by setting the machine parameters to low pulse energy (Mahajan *et al.*, 2020).

Table 8. Response for S/N ratio of R_a

Level	Electrode	I_p	T_{on}	T_{off}
1	-13.39	-10.02	-14.4	-14.26
2	-14.88	-14.25	-16.33	-15.46
3	-14.67	-18.66	-12.21	-13.22
Delta	1.49	8.64	4.12	2.24
Rank	4	1	2	3

Figure 8 shows that the interaction between the electrode material and other parameters was slight, while the interactions among other parameters were more influential.

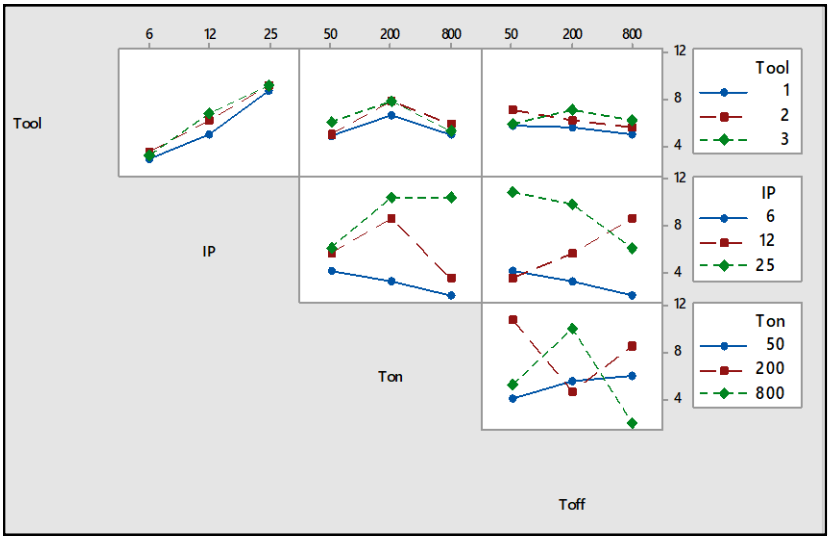

Figure 8. Interaction plot for R_a

When machining with EDM, the metal surface is exposed to high heat and rapid cooling multiple times causing significant changes in surface morphology (Guitrau, 1997). Figure 9a shows that at machining with machining parameters, $E_1A_1B_2C_2$, the micro-cracks were wider and larger. Figures 9a to 9c disclose that machining with the parameters $A_1B_2C_2$ and either electrode produced denser and larger micro-cracks and fewer craters and pockmarks compared with machining with parameters $A_2B_1C_2$ (Figures 9d to 9f). By increasing the discharge current from 6 to 12 A and reducing the pulse-on time from 200 to 50 µs, it was possible to obtain a surface with lower crack density. The values of SCD reported by Bhattacharyya *et al.* (2007) were minimal at I_p and T_{on} in 18-22 A and 20-100 µs, respectively. Likewise, Rizvi and Agarwal (2016), who worked on a range of lower process parameters, noted that increasing I_p and shortening T_{on} effectively reduced SCD.

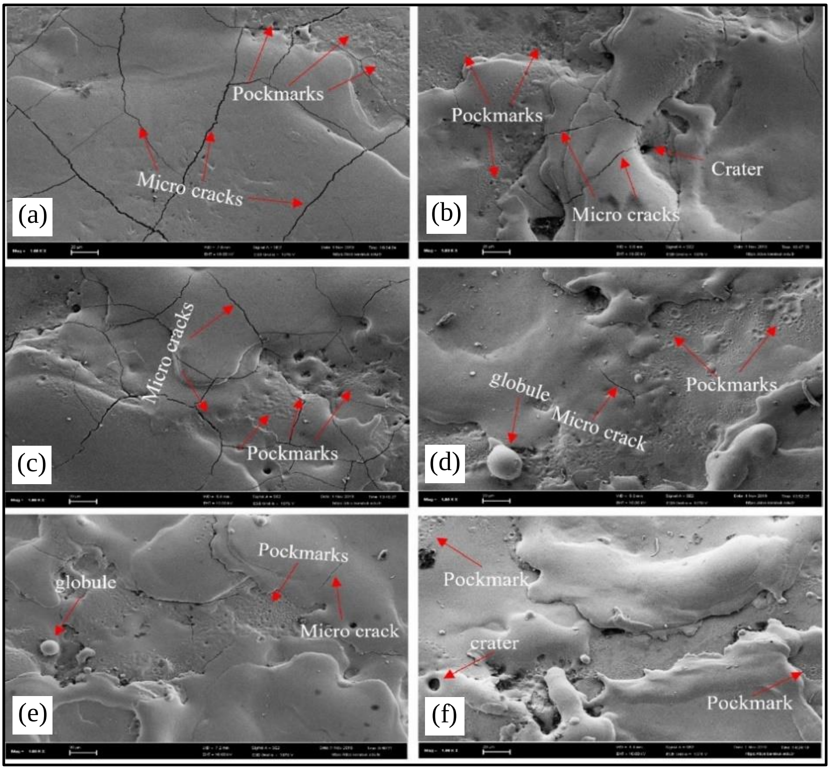

Figure 9. Effect of process parameters on surfaces $E_1A_1B_2C_2$ (a), $E_2A_1B_2C_2$ (b) $E_3A_1B_2C_2$ (c), $E_1A_2B_1C_2$ (d), $E_2A_2B_1C_2$ (e) and $E_3A_2B_1C_2$ (f)

4. Conclusion

In this paper, the effect of the process parameters and the optimization of DIN 2767 tool steel on the EDM was investigated using the Taguchi technique. It was found out that I_p was directly proportional to MRR, TWR and R_a, and it was the most influential parameter among them. The increase in T_{on} caused TWR to decrease and MRR and R_a to increase. This increase of MRR and R_a was up to the second level and then decreased until the third level of T_{on}. The increase in T_{off} led to decrease in MRR and raise in TWR. R_a increased with T_{off} from the first to the second level and declined until the third level. Taguchi optimization results revealed that the optimal combinations of machining parameters for MRR, TWR and R_a were $E_3A_3B_2C_1$, $E_2A_1B_3C_1$ and $E_1A_1B_3C_3$, respectively. There were slight interaction effects between the tool and the process parameters for MRR and R_a. In contrast, the other interaction effects between the other parameters were more substantial. SEM images showed micro-cracks, craters, pockmarks and globules of debris resulting from EDM high temperature and quenching. SCD can be reduced by machining at high peak current and short pulse-on time.

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