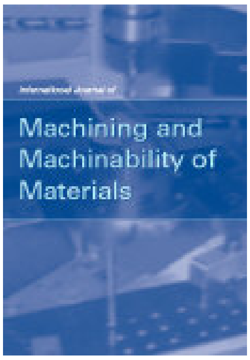

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Effect of tool size and cavity depth on response characteristics during electric discharge machining: an experimental investigation

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Abstract: In the present investigation, AISI304 material has been selected as the workpiece, and electrolytic copper as the tool electrode. For systematic investigation and understanding of the effect of tool size in terms of tool diameter and cavity depth along with other important electrical parameters namely, peak current, pulse-on-time, and gap voltage have been varied at three different values. The experiment has been designed using the fractional factorial (Taguchi) method. The effect of parameter settings is observed for material removal rate (MRR), tool wear rate (TWR), and surface roughness (R_a). Results reveal that a larger tool diameter yielded 13% more MRR and there is no significant effect of cavity depth on MRR, TWR, and surface quality. To perform experiments with other parameters set, smaller cavity depth can be used which can reduce the cost and time of experiments. Further, statistical analysis has been carried out to identify the interaction effect between the parameters.

Keywords: electrical discharge machining; EDM; AISI304; material removal rate; MRR; surface roughness; tool wear; tool size.

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1 Introduction

Electrical discharge machining (EDM) is a non-traditional method of machining in which thermal energy is used for machining instead of mechanical force like the traditional machining process. In this process, the material is removed from an electrically conductive workpiece using an electrode. The electric spark generated between the small gap of electrode and workpiece removes the material through melting and vaporisation of the material. During the process, the workpiece and electrode need to be submerged in dielectric fluid. The continuous flow of dielectric fluid helps to reduce the heating of the material, controls the spark, and easily removes the debris from the working gap.

EDM easily processes shapes and depths that are impossible to process using a cutting tool. Deep processing is a usual application of EDM where the tool length to diameter ratio would be very high. Some imperative uses of EDM are sharp internal corners, deep ribs, and narrow slots. The performance of electrodes predominantly depends on the design and material of the electrode (Jha et al., 2011). The selection of shape and size from the designing aspect is very important because the performance of EDM will depend on both basic parameters. The best tool geometry for high material removal rates (MRR) and low tool wear rate (TWR) is circular followed by triangular, rectangular, and square cross-section (Sohani et al., 2009) and as per size is concerned for circular shape tool, i.e., cylindrical electrode; diameter and height are the two parameters that need to be considered during the designing process. Machining parameters like MRR, TWR, and R_a vary according to the shape of the electrode. To investigate the performance of EDM by changing the shape of the tool Khan et al. (2009) selected round, triangular, square, and diamond shape tools of 64 mm^2 constant cross-section area. In this study, machining was done on mild steel and a cylindrical tool of 9.027 mm diameter was used for the generation of a 2 mm deep cavity. The use of round shape electrodes provides various benefits compared to other shape electrodes. It was also confirmed by Sohani et al. (2009) and Kumar et al. (2016) that circular shape tools are best to obtain high MRR and low TWR. The diameter of the cylindrical electrode depends on the shape and geometry of the tool. Different types of tools used for machining are solid cylindrical, thin-wall tube electrodes, one eccentric hole, two eccentric holes, complex shape electrodes, and special purpose electrodes.

The machining performance of the EDM process can be improved by modifying the tool design. Wang and Yan (2000) used an electrode of 12.7 mm diameter having an eccentric through-hole for the machining of Al composite material. By making changes in the tool design major improvements can be seen in the results. If the electrode has an eccentric hole and is employed for machining with a rotary motion to the electrode then higher MRR and TWR can be obtained. Vibratory motion to the tool helps to attain high MRR. From the experimental analysis of Ghoreishi and Atkinson (2002), it was observed that high-frequency vibration and electrode rotation of the tool increases MRR, TWR, and R_a. For the comparative study between rotary, vibratory, and vibro-rotary, a 12.7 mm diameter tool was used for the machining. Later, the author Abdullah and Shabgard (2008) studied the effects of tool vibration in the EDM process. In this investigation, experimental results confirmed the results obtained by (Ghoreishi and Atkinson, 2002), which were ultrasonic vibration to the tool improves MRR four times higher than the conventional EDM, TWR and Ra also increases.

Several studies have been reported on the EDM machining process discussing electrical parameters that influence the MRR, TWR, and R_a of the machined cavity. Some other factors which can influence the MRR, TWR, and R_a are electrode material, electrode design, and tool motion. In the investigation done by Mohan et al. (2002), to find the effect of various parameters on MRR, TWR, and R_a, brass and copper electrode of 12 mm diameter was selected for the machining of SiC reinforced aluminium alloy during the machining of a blind hole of 10 mm deep. From the results, it was observed that MRR is more for the brass electrode and the same was observed for the rotary electrode and then for the copper and stationary electrode. Upadhyay et al. (2018) used copper electrodes for the investigation of MRR, TWR, R_a, and surface crack density by selecting controllable process parameters and similarly, Rahul et al. (2018) also used copper electrodes for the machining. In this investigation surface characteristics of the EDMed workpiece were analysed and different types of cracks formed during the machining were also observed.

To understand the MRR mechanism in the powder mixed EDM (PMEDM) Kumar and Davim (2011) used a copper electrode of 5 mm diameter for the machining of metal matrix composite (MMC). To study the MRR and tool wear ratio on PMEDM, Kung et al. (2009) used a copper electrode of 25 mm diameter. In both studies, it was concluded that MRR increases with an increment in powder concentration up to a certain level, and after an appropriate level MRR decreases. However, the effect of cavity depth or tool diameter was not included. A different aspect of tool design is material selection for the electrode. Machining titanium and its alloys are very difficult from the conventional machining process because it has high-temperature strength, high strength-to-weight ratio, low electrical and thermal conductivity. To find the best suitable electrode material for the machining of titanium and its alloys Sivakumar and Gandhinathan (2013) performed several experiments with different electrode materials of 7 mm diameter and machining was done up to 5 mm depth. The best suitable electrode material found for the machining of titanium alloy is copper impregnated graphite. The experimental results revealed that MRR and overcut are the most affected by pulse-on-time and discharge current.

EDM is the most appropriate technique of machining for hard-to-machine materials and to generate complicated shapes and curves (Gupta et al., 2020). To find the best suitable tool material Pavan and Sateesh (2021) performed some experiments using brass, copper, and copper tungsten material. Various process parameters were optimised on the performance of MRR and TWR for different material electrodes of 10 mm diameter. Taguchi method was employed in the investigation for the optimisation of process parameters. The results obtained after conducting various experiments showed that the copper tungsten material for the electrode is best to obtain high MRR and low TWR.

Various tool designs have been used for machining with the help of the EDM process. Some extensively used tool designs are tube electrodes and electrodes having eccentric holes. Teimouri and Baseri (2013) investigated dry EDM using brass and copper electrode of 10 mm diameter having an eccentric hole in the electrode. From the results, it was inferred that two eccentric holes can provide high MRR and low R_a than the one eccentric hole. Yan and Wang (1999) used a rotating tube electrode of 22 mm outer diameter and 19 mm inner diameter to find the machinability of EDM in the terms of MRR, TWR, and R_a. The study revealed that the use of rotary tube electrodes is beneficial to getting higher MRR. Although the TWR was also higher, overall advantages were still greater which makes it an acceptable tool. To find the contribution of process parameters for MRR and R_a Rajesha et al. (2012) performed some experiments with copper tube electrodes of 12 mm diameter. It was revealed that I_P influences the MRR and R_a more compare to other process parameters. Haron et al. (2001) investigated the influence of electrode diameter and supply current on machining parameters. Copper electrodes of 9.5, 12 and 20 mm diameter were selected for the investigation to create blind holes in the tool steel plate of 40 mm thickness. The results revealed that the 20 mm diameter tool at 6.5 A current provides better performance compared to other settings. If there is a need for machining with a small diameter electrode then a low current will be suitable and machining with a big diameter electrode high current will be suitable.

Peak current shows a directly proportional relationship with the machining parameters like MRR, TWR, and R_a (Fatatit and Kalyon, 2021). Similar results were obtained by Hussain and Khan (2018), in which process parameter effects on TWR and MRR have been investigated. The results and confirmation test indicated that peak current influences TWR and MRR majorly. Perumal et al. (2021) also investigated the effects of discharge current, pulse-on-time, and voltage on machining parameters MRR and TWR. For the experiments, three copper electrodes of 6mm, 8mm, and 10 mm diameter were used. The investigation was done to optimise the electrical machining parameters of the EDM process. Hence, for the machining in the EDM process, pulse-on-time and discharge current are the most influential factors for better MRR. MRR increases with the increment in I_p values. To get optimum TWR, a better combination of pulse-on-time, current, and diameter needs to be selected because these three factors influence TWR significantly. The influence of peak current, pulse-on-time, and tool diameter on the performance of EDM was studied by Koteswararao et al. (2017) on alloy steel using a copper electrode. Two electrodes of 6mm and 8mm were used for the experiments. It has been found that peak current influences the machining parameter MRR and TWR more compare to T_{on} and then followed by diameter.

Ghazi (2020) investigated the TWR and MRR of copper electrodes having 15 mm diameter and workpiece material of 4 mm thick for the EDM process. The results obtained from the investigation revealed that pulse-on and off-time highly influence the TWR and MRR. Increasing the current or pulse on-time results in a high value of response for tool wear and material removal and increasing pulse-off-time provides adverse effects. Ahmad et al. (2018) studied the effect of process parameters on MRR and R_a for the machining of SS 304. It was observed that MRR and R_a both are greatly influenced by current density. For high MRR, a higher value of current is desirable and for better surface finish of machined workpieces lower current and pulse duration are desirable with high gap voltage. In the EDM process, MRR is the most critical parameter because it is directly related to the machining cost therefore it should be carefully analysed and investigated. Further, EDM can generate a good surface finish without having contact between electrode and workpiece, because of this it can be used for surface modification of metallic medical implants, where high performance of implants is desirable (Singh et al., 2021).

By referring to various research papers it has been observed that limited researches are available on the effect of electrode diameter and depth of machining in the EDM process. The majority of the researchers have done a study about the influence of machining parameters by considering single electrode diameter on MRR, TWR, and R_a. Very limited research papers discussed the effect of machining depth on the MRR, TWR, and R_a. The diameter of an electrode may influence the EDM machining performance, and very few studies have been found on this subject. For a better understanding of the effect of tool diameter in the EDM process, tool diameter is selected as one of the parameters. The present research paper discusses the effect of different tool diameters along with the other machining parameters like peak current, pulse-on-time, and gap voltage during machining of a blind cavity of different depths, i.e., 2.5 mm, 5.5 mm, and 8.5 mm. There is a need to understand the effect of machining depth on the performance of the EDM process, as machining depth is related to the machining time and hence machining cost also.

2 Machine and materials

In this study, AISI304 is selected for workpiece material and on this material experiments have been conducted with a copper tool with Electronica make EDM. The commercially available EDM dielectric fluid is used for experiments. The operational accuracy of axes movement is up to 1μm. The weight of the workpiece and electrode is measured before and after machining to find the weight loss after machining using a precision electronic weight balance having 300 gm maximum weighing capacity and 1mg least weight count. The surface roughness of the machined surface is measured using a Mitutoyo SJ-210 surface tester. Surface roughness is measured at six different locations on the cavity wall and the average of all measurements is considered as average surface roughness and is expressed in R_a. The cavity is generated on a split workpiece of 10 × 15 × 10 mm to study the cavity surface. Copper electrodes of 8, 10 and 12 mm diameter are selected to create a cavity at different depths.

3 Experimental procedures

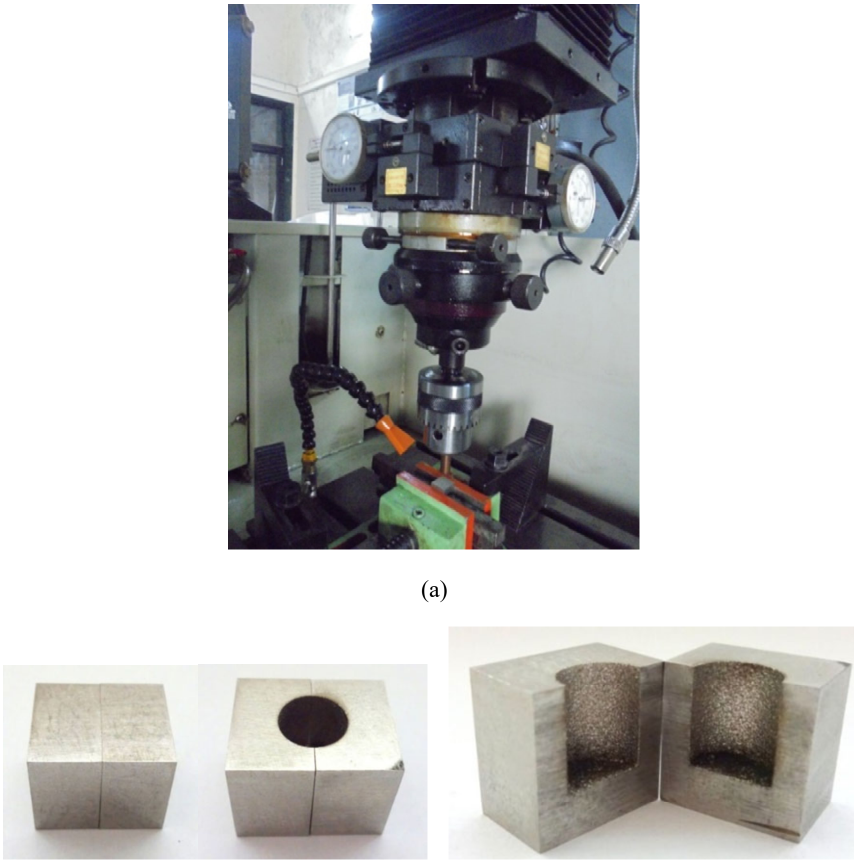
After weighing the workpiece and electrode, two blocks of the workpiece are clamped together on the clamping vice to create a hole using a copper electrode. An electrode tool connected with positive polarity is fixed in the chuck of the EDM head and the workpiece is connected with negative polarity. The tool electrode and workpiece are submerged in the dielectric fluid and also pressurised dielectric fluid through the nozzle is supplied at the machining zone. In this study, three different diameter electrodes of 8, 10, and 12 mm are used for machining up to a depth of 2.5, 5.5 and 8.5 mm. Figure 1 shows the position of the tool electrode with the workpiece in the experimental setup of EDM.

After setting up all the basic necessary equipment, machining has been started and the machining parameters like MRR, TWR, and R_a have been studied. The experiments are designed and conducted using the Taguchi design methodology and significant parameters are determined using analysis of variance (ANOVA).

3.1 Input parameter

EDM process is very complex in nature; a large number of factors can affect the machining process (Singh and Ghosh, 1999; Patil and Jadhav, 2016). However, important factors like peak current, pulse-on-time, and gap voltage are considered input parameters. In addition to the electrical parameters, two geometrical parameters namely cavity depth and tool diameter are considered. Thus, five input parameters at three levels are selected for this experimental analysis. All the parameters and their corresponding levels are shown in Table 1. For such types of combinations, Taguchi L27 orthogonal array is found to be suitable (Ross, 2005; Phadke, 1995), as shown in Table 2.

Figure 1 (a) Set up of workpiece, (b) Split workpiece and cavity, (c) Cavity surface (see online version for colours)



(a)

(b) (c)

Table 1 Input parameters and their corresponding levels

Parameters	*Symbol*	*Units*	*Levels*		
			1	*2*	*3*
Peak current	I_p	A	10	20	30
Pulse on time	T_{on}	µs	200	300	400
Gap voltage	S_v	V	80	100	120
Cavity depth	d	mm	2.5	5.5	8.5
Tool diameter	D	mm	8	10	12

3.2 Response parameters

MRR and TWR are calculated by finding the weight difference between the tool and workpiece. Weight of tools and workpiece are measured before machining and after machining using weighing balance having 1 mg least count. Surface roughness (R_a) is the third parameter which is expressed as the average R_a. Equations (1) and (2) are used for the calculation of MRR and TWR.

$$MRR = \left(\frac{W_{wb} - W_{wa}}{\rho_w \times t} \right) \tag{1}$$

$$TWR = \left(\frac{W_{tb} - W_{ta}}{\rho_w \times t} \right) \tag{2}$$

where W_{wb} = workpiece weight before machining, W_{wa} = workpiece weight after machining, W_{tb} = tool weight before machining, W_{ta} = tool weight after machining, ρ_w = density of workpiece AISI 304 (8 gm/cm^3), ρ_t = density of copper electrode (8.94 gm/cm^3), t = time of machining.

In this method, all the responses are recorded in the form of S/N ratio. The higher value of S/N ratio is all the time desirable regardless of quality characteristics. The most suitable condition is found by the higher value of S/N ratio. The core objective of this experimental investigation is to find the machining conditions required to accomplish maximum MRR and minimum TWR and R_a. Therefore, larger the better-quality response characteristic has been used for MRR and smaller the better characteristic has been used for TWR and R_a.

4 Analysis of result

In the study, each experiment is replicated twice under the same machining condition to obtain variability within the experiment. The machining time required to machine a workpiece is noted using the stopwatch. This machining time is used for the calculation of MRR and TWR as written in equations (1) and (2). Each response is converted into a signal-to-noise ratio (S/N) using larger the better characteristics for MRR and smaller the better for TWR and R_a, as discussed in equations (3) and (4), respectively.

$$\eta_{LB} = -10 \log_{10} \left(\frac{1}{n} \sum_{j=1}^{n} \frac{1}{y_{ij}^2} \right) \tag{3}$$

$$\eta_{SB} = -10 \log_{10} \left(\frac{1}{n} \sum_{j=1}^{n} y_{ij}^2 \right) \tag{4}$$

where y_{ij} represents the response of i^{th} quality characteristics at j^{th} experimental run and n represents the total number of repetitions of a run.

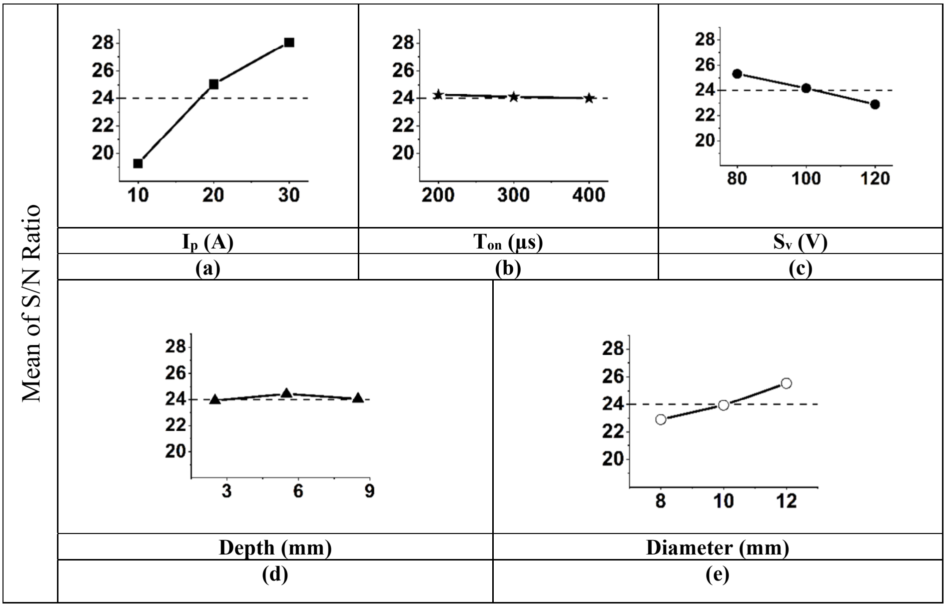
Table 2 Experimental plan of L27 orthogonal array and their respective S/N ratios

Exp. run	A	B	C	D	E	S/N ratios		
	Peak current	Pulse on time	Gap voltage	Depth	Diameter	η_{MRR}	η_{TWR}	η_{Ra}
1	10	200	80	2.5	8	20.164	22.051	–9.883
2	10	200	100	5.5	10	21.119	35.085	–15.221
3	10	200	120	8.5	12	18.926	17.027	–14.283
4	10	300	80	5.5	10	21.343	29.278	–15.608
5	10	300	100	8.5	12	20.701	22.578	–17.301
6	10	300	120	2.5	8	16.155	30.699	–8.704
7	10	400	80	8.5	12	21.589	27.656	–15.284
8	10	400	100	2.5	8	16.808	44.055	–10.764
9	10	400	120	5.5	10	16.564	45.868	–14.699
10	20	200	80	5.5	12	27.473	–2.405	–17.887
11	20	200	100	8.5	8	23.659	8.421	–17.042
12	20	200	120	2.5	10	23.173	19.810	–20.282
13	20	300	80	8.5	8	24.496	7.046	–17.919
14	20	300	100	2.5	10	23.854	31.004	–20.831
15	20	300	120	5.5	12	25.452	6.450	–20.536
16	20	400	80	2.5	10	26.340	19.141	–21.438
17	20	400	100	5.5	12	26.990	10.957	–20.137
18	20	400	120	8.5	8	23.916	15.878	–19.618
19	30	200	80	8.5	10	28.036	5.387	–20.582
20	30	200	100	2.5	12	29.466	–12.286	–20.740
21	30	200	120	5.5	8	26.451	–5.621	–20.539
22	30	300	80	2.5	12	30.905	–6.574	–20.897
23	30	300	100	5.5	8	26.933	–2.209	–17.866
24	30	300	120	8.5	10	27.041	14.907	–18.929
25	30	400	80	5.5	8	27.479	0.346	–19.635
26	30	400	100	8.5	10	27.993	15.617	–17.293
27	30	400	120	2.5	12	28.316	1.911	–23.034

4.1 Analysis of MRR

After the selection of the L27 orthogonal array, S/N ratio (η_{MRR}) for MRR was calculated for all 27 trials as recorded in Table 2. A higher value of η_{MRR} means better performance of parameters. In Figure 2 main effect plots have been drawn between each level of parameters on the X-axis and the mean of S/N ratio (η_{MRR}) on the Y-axis. The examination of S/N ratio indicates that optimal performance parameters for MRR are peak current 30 A (I_p) (level 3), pulse-on-time 200 μs (T_{on}) (level 1), gap voltage 80 V (S_v) (level 1), depth 5.5 mm (d) (level 2) and tool diameter 12 mm (D) (level 3).

Figure 2 Main effect plot for MRR

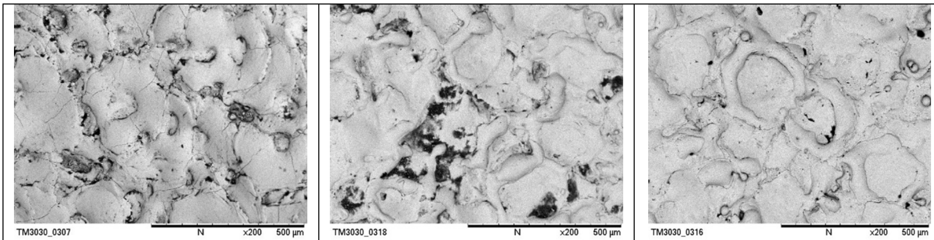


Peak current is found most affecting parameter in determining MRR, it has the highest F-value, as indicated in Table 3. The MRR value increases by increasing the peak current level. A higher value of I_p discharges high energy between the tool electrodes (Sundaram et al., 2005; Ahmad and Lajis, 2013; Kalyon, 2020: Nallusamy, 2016; Kuppan et al., 2008). High discharge energy creates a bigger and deeper crater per spark which leads to higher metal removal per unit time. This can be identified from the craters formed on the machined cavity surface, as shown in Figure 3. To observe the effect of peak current on crater size, micro images are shown in Figures 3(a), 3(b), and 3(c) at 10 A, 20 A, and 30 A of peak current respectively. The craters formed at lower peak current is smaller as compared with those at higher peak current.

From Figure 2(a), the noticeable fact is that the change in MRR between 10 A and 20 A peak current is more than the change between 20 A and 30 A. It indicates a rise in peak current from 10 A to 20 A has generated higher MRR as compared to peak current from 20 A to 30 A. This may be because of unstable machining at a higher peak current. At a high peak current, a relatively large volume of material is eroded in each spark which may accumulate in the working gap between the tool and the working surface. This may lead to secondary discharge and unstable machining, resulting in slightly lower MRR.

The plot between means of S/N ratio and pulse-on time (T_{on}) for MRR [as shown in Figure 2(b)] reveals that MRR is decreasing with increase in T_{on}. Higher T_{on} may become a reason to distribute the heat energy of spark that affects the MRR adversely. However, Ton is varied within the short range of 200 to 400 µs therefore its variation effect on MRR is minimal. Statistically, it can be observed in ANOVA Table 3, As it has a very low F-value. Hence, T_{on} is an insignificant parameter for the analysis of MRR.

Figure 3 SEM image of cavity generated at, (a) 10 A (b) 20 A and (c) 30 A



(a) (b) (c)

Table 3 ANOVA of S/N ratio for MRR

Source	*DF*	*Adj SS*	*Adj MS*	*F-value*	*P-value*
I_p	2	360.236	180.118	632.40	0.000
T_{on}	2	0.349	0.174	0.61	0.586
S_v	2	26.499	13.249	46.52	0.002
d	2	1.284	0.642	2.25	0.221
D	2	31.810	15.905	55.84	0.001
I_p * T_{on}	4	6.863	1.716	6.02	0.055
I_p * S_v	4	4.998	1.250	4.39	0.091
T_{on} * S_v	4	1.517	0.379	1.33	0.394
Error	4	1.139	0.285		
Total	26	434.695			

The effect of gap voltage (S_v) on MRR is illustrated in Figure 2(c). It is observed that MRR reduces with an increase in gap voltage. Gap voltage is an indirect measurement of the gap between the electrode and workpiece in terms of potential difference. Smaller gap voltage may increase the discharge energy in the working zone which leads to higher material removal. Gap voltage is found to be statistically significant, as shown in Table 3, its P-value is less than 0.05.

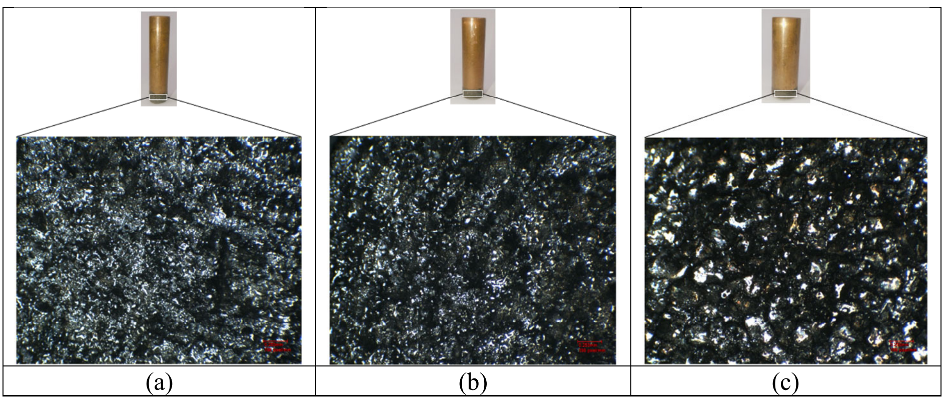
Variation in MRR with the depth of cavity is negligible, as plotted in Figure 2(d). It implies that the machining process remains stable through the machining depth varies between 2.5 to 8.5 mm. In other words, the effect of dielectric flushing is nearly the same at 2.5 mm, 5.5 mm, and 8.5 mm depths. This also signifies that the nature of machining could be identified even at smaller cavity depths. A smaller depth of machining requires less time as well as less machining cost.

In this investigation, it has been found that tool diameter is a major affecting parameter based on the ANOVA Table 3. MRR proportionally increases with tool size. A larger tool size provides a large surface area which generates relatively large number of sparks per cycle in comparison to the smaller tool. The higher sparks at a time produce higher discharge energy into the machining zone, which helps to increase the MRR. The results of the present work are in good agreement with the earlier reported research work Ahmed et al. (2018), Kalyon (2020) and Ahmad and Lajis (2013).

4.2 Analysis of TWR

In the EDM process, wear of tool is inevitable because ions of plasma channel, during the breakdown, collide with tool electrode also. Analysis of tool wear is very important in the EDM process because it confirms the final cavity characteristics. Mainly, wear on the tool is observed in the form of tiny craters. The size and depth of craters depend upon the intensity of discharge energy at the time of sparking. Higher the spark energy larger the crater size and hence higher the tool wear. The crater formations can be easily observed on the cylindrical as well as the bottom surface of the tool electrode as shown in Figure 4. Increasing the peak current, higher discharge energy is generated and this leads to higher TWR. From Figure 4, it can be noticed that crater size is getting large with higher peak current.

Figure 4 Variation in crater size with peak current, (a) 10 A (b) 20 A (c) 30 A (see online version for colours)

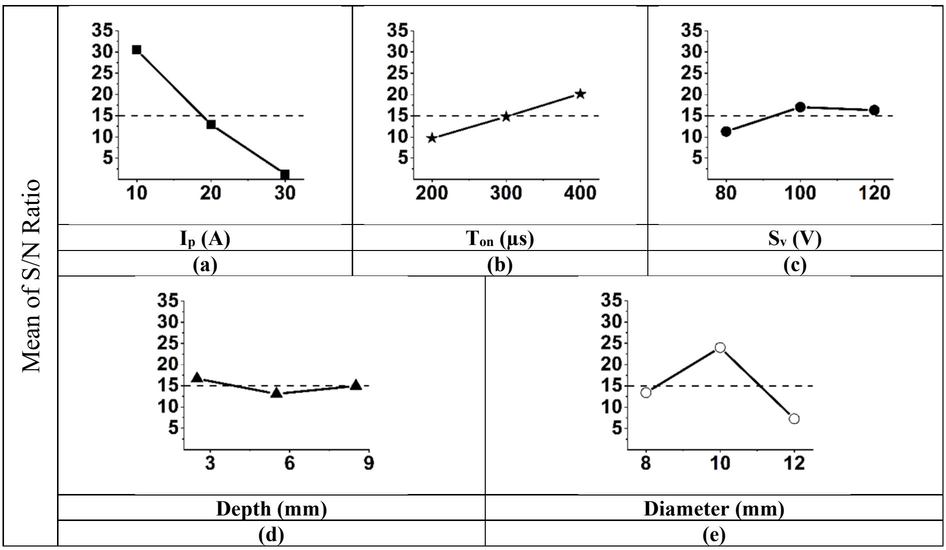


A lower value of TWR is desirable therefore the S/N ratio for TWR (η_{TWR}) is calculated using lower is better characteristics, as per equation (3). A higher S/N ratio of TWR (η_{TWR}) means better performance of parameters. The main effect plot (as shown in Figure 5) of S/N ratio shows that optimal performance parameters for TWR are peak current at 10 A (I_p) (level 1), pulse-on-time 400 µs (T_{on}) (level 3), gap voltage 100 V (S_v) (level 2), depth 2.5 mm (d) (level 1) with tool diameter 10 mm (D) (level 2).

Figure 5(b) is showing the mean plot of the S/N ratio and pulse-on-time for TWR. It is observed that means of S/N ratio is minimum at 200 µs pulse-on-time and maximum at 400 µs pulse-on-time, which infers that increasing the pulse-on-time reduces the TWR. During the experiments, it has been observed that spatial current density decreases due to increasing the pulse on time and the tool surface is protected by the deposition of carbon particles that guards the electrode surface against wear, and the same observations are made by Sohani et al. [2]. ANOVA illustrated in Table 4 shows that pulse-on-time is a significant parameter for TWR and it is having F-value of 63.69.

In the analysis of TWR, P-value obtained for gap voltage (S_v) is less than 0.05 which indicates that gap voltage is statistically significant. The means of S/N ratio is found minimum at a lower value of gap voltage (80 V) then S/N ratio increases up to 100 V after this shows negligible changes up to 120 V. The changes for the means of S/N ratio from 80 V to 100 V are more compared to the gap voltage from 100 V to 120 V. At lower gap voltage higher tool wear is observed because of high discharge energy generated on the tool produces a higher heating effect of tool which results into higher tool wear. At high gap voltage, low tool wear is observed because of the less heating effect of the tool.

Figure 5 Main effect plot for TWR



The relation between means of S/N ratio and depth of machining is illustrated in Figure 5(d). At the machining depth of 2.5 mm, S/N ratio for TWR is found maximum and at the depth of 5.5 mm S/N ratio is found minimum. For the analysis of TWR, depth is also a significant factor but the variations are very less and influence TWR slightly. For the machining, up to 2.5 mm depth, sparking time will be less, which leads to low TWR compared to machining depths of 5.5 mm and 8.5 mm.

Table 4 ANOVA of S/N ratio for TWR

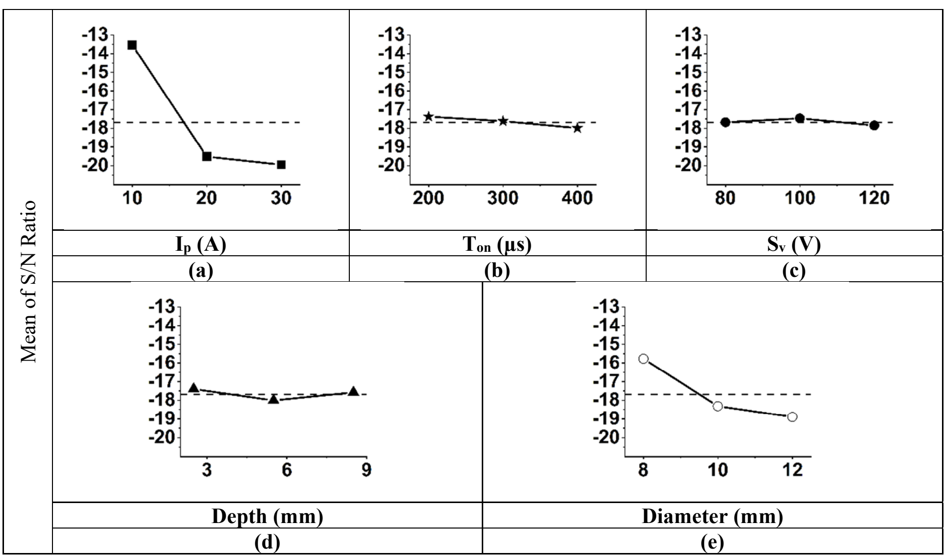
Source	*DF*	*Adj SS*	*Adj MS*	*F-value*	*P-value*
I_p	2	3889.79	1944.89	504.96	0.000
T_{on}	2	490.59	245.29	63.69	0.001
S_v	2	173.93	86.97	22.58	0.007
d	2	57.15	28.57	7.42	0.045
D	2	1292.86	646.43	167.84	0.000
$I_p * T_{on}$	4	103.68	25.92	6.73	0.046
$I_p * S_v$	4	65.95	16.49	4.28	0.094
$T_{on} * S_v$	4	38.84	9.71	2.52	0.196
Error	4	15.41	3.85		
Total	26	6128.20			

Diameter is one of the most significant parameters for the analysis of TWR. F-value obtained for the diameter is 167.84, which infers that the diameter of the tool electrode influences the TWR significantly. The means of S/N ratio for TWR is found maximum at 10 mm diameter and found minimum at 12 mm diameter. As the tool diameter increases, more surface area will be in contact for machining and more tool wear will occur. The results of the present research are in good agreement with the earlier reported work of Ahmad and Lajis (2013) in which the best conditions for TWR are at lower I_p and higher value of T_{on}. After analysing the results of the present investigation, it has been noticed that significant parameters to optimise the TWR are peak current, pulse on time, gap voltage, depth, and diameter of the electrode.

4.3 Analysis of surface roughness (R_a)

Since erosion of material in the EDM process occurs in the form of a hemi-spherical cavity, therefore machined surface obtained is a matt finish. In this study, surface roughness is measured at six different locations approx. 60 degrees apart from each measurement on the surface of the cavity. The average of all six roughness values is represented as the R_a value.

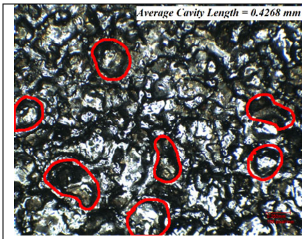
Figure 6 Main effect plot for R_a

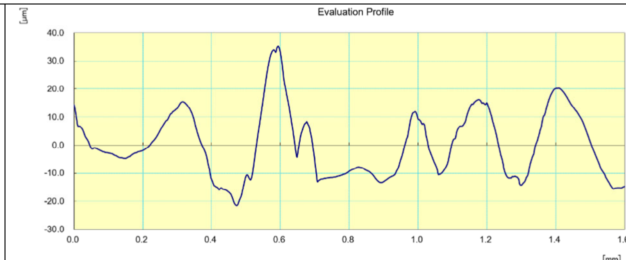


A higher value of η_{Ra} means better performance of parameters. In the mean effect plot of peak current on the surface roughness, the means of S/N ratio decreases by increasing the value of peak current. It indicates that the R_a value increases by increasing the peak current. A higher peak current makes the surface rougher than a lower peak current. In the EDM process, the size of minute craters depends upon the discharge energy of sparks. Distinctive images of machined surfaces can be seen in Figure 7. At the lower value of peak current (10 A), the crater size is comparatively smaller [Figure 7(a)] than the crater size obtained at the highest peak current (30 A) [Figure 7(c)]. A higher value of peak current generates deep and more uneven craters that resulted in higher R_a. Average cavities length obtained in Figures 7(a), 7(b) and 7(c) is 0.4268 mm, 0.5229 mm and

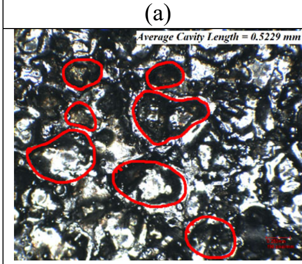
0.8673 mm respectively. It can be said that increasing the peak current increases the cavity size which further increases the surface roughness. For, a better understanding, micrographs of the R_a profile is included which show the variation in peak to valleys heights.

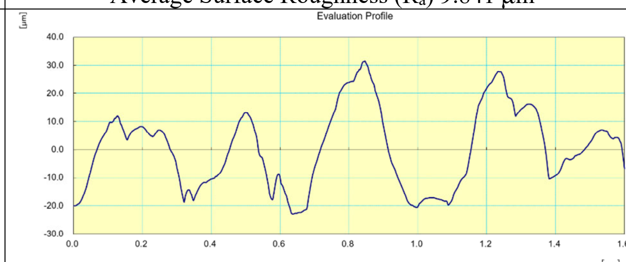
Figure 7 Machined surface at, (a) 10 A (b) 20 A (c) 30 A (see online version for colours)



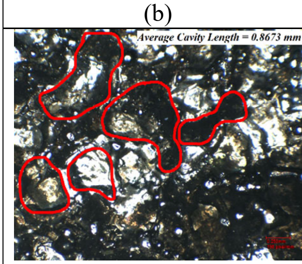


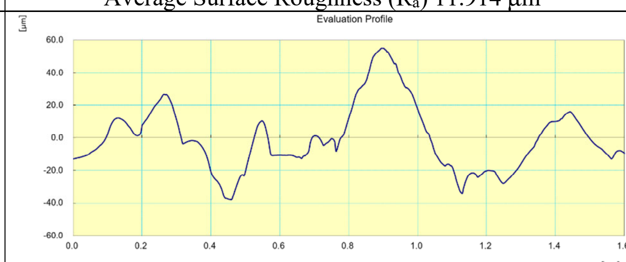
(a) Average Surface Roughness (R_a) 9.841 µm





(b) Average Surface Roughness (R_a) 11.914 µm





(c) Average Surface Roughness (R_a) 15.635 µm

Table 5 is showing the results of ANOVA for R_a. This indicates that peak current is having a major contribution to the analysis of surface roughness and it is the most significant parameter for R_a analysis.

From Figures 6(b), 6(c), and 6(d), it can be observed that variation in the means of S/N ratio between lower and higher levels is negligible or minimal which indicates that the effect of T_{on}, S_v, and depth of machining has minimal influence on surface roughness. This can also be observed from the ANOVA Table 5, P-value for all these factors is more than 0.05, and their F-value is very less compared to peak current and diameter.

The diameter of an electrode has a major effect on surface roughness. Increasing the diameter of electrode means of S/N ratio decreases gradually. This means a lower value of R_a is obtained at a lower diameter (8 mm) and working with a larger diameter of tool electrode provides more surface roughness. Smaller diameter electrodes are better to get lower surface roughness for the machined workpiece. From ANOVA Table 5, it can be noticed that diameter is a significant parameter having F-value of 67.66.

Table 5 ANOVA of S/N ratio for R_a

Source	*DF*	*Adj SS*	*Adj MS*	*F-value*	*P-value*
I_p	2	231.917	115.959	315.41	0.000
T_{on}	2	1.671	0.835	2.27	0.219
S_v	2	0.657	0.329	0.89	0.478
d	2	1.803	0.902	2.45	0.202
D	2	49.752	24.876	67.66	0.001
I_p * T_{on}	4	8.295	2.074	5.64	0.061
I_p * S_v	4	14.517	3.629	9.87	0.024
T_{on} * S_v	4	35.567	8.892	24.19	0.005
Error	4	1.471	0.368		
Total	26	345.649			

In this work, best-desired conditions for good surface finish are peak current 10 A (I_p) (level 1), pulse on time 200 μs (T_{on}) (level 1), gap voltage 100 V (S_v) (level 2), depth 2.5 mm (d) (level 1) and tool diameter 8 mm (D) (level 1). As per ANOVA Table 5, peak current and diameter, both are significant for the analysis of surface roughness. Other parameters which have minimal influence on the surface roughness are pulse on time (T_{on}), gap voltage (S_v), and depth of machining. These results are in good agreement with the earlier reported work Ahmed et al. (2018), Ahmad and Lajis (2013) and Gostimirovic et al. (2012).

5 Confirmation tests

After conducting several experiments with different setting parameters, their results need to validate and verify by selecting particular setting parameters, where optimum performance is obtained in the previous set of experiments. The steps involved to conduct the confirmation test are:

1 selection of the preferred arrangement of process parameter levels

2 calculate the estimated mean of the preferred arrangement of levels

3 calculate the confidence interval value

4 calculate a confidence interval for the true mean around the estimated mean

5 conduct the tests considering the preferred arrangement of parameters

6 compare the results of the confirmation experiment with the confidence interval for the true mean.

An optimum combination of process parameters is selected by analysing the parameters at different levels for MRR, TWR, and R_a in Sections 4.1, 4.2, and 4.3 respectively.

5.1 Estimation of predicted means

Calculation of the predicted mean of MRR, TWR, and R_a is determined using equation (5) given below (Ross, 2005).

$$\eta_P = T + \sum(\eta_i - T) \tag{5}$$

where T represents the overall mean of the response parameter, η is an average value of significant parameters.

The confirmation tests are conducted with the optimal parameter settings. The values of predicted and experimented S/N ratios are illustrated in Table 6. The results obtained by setting optimum parameters for the experimental test are very near to the predicted S/N ratios. For all three responses, significant parameters are chosen for the prediction of the S/N ratio in the confirmation test.

The probable mean of MRR response characteristic is calculated using the equation as follows:

$$\eta_{MRR} = A_3 + C_1 + E_3 - 2T \tag{6}$$

where T is the overall mean of MRR, A_3 is the mean value of MRR at the third level of peak current, C_1 is the mean value of MRR at the first level of gap voltage and E_3 is the mean value of MRR at the third level of diameter. Similarly, the probable mean of TWR and R_a is calculated using the equations (7) and (8).

$$\eta_{TWR} = A_1 + B_3 + C_2 + D_1 + E_2 - 4T \tag{7}$$

$$\eta_{R_a} = A_1 + E_1 - T \tag{8}$$

The statistically insignificant parameters are not considered for the estimation of the mean S/N ratio in the confirmation test because these are less effective.

The values of predicted optimal S/N ratios for MRR, TWR, and R_a are 30.67059 db, 48.75037 db, and –11.637 db respectively as shown in Table 6.

In the confirmation experiment 95% confidence interval (CI) is computed using equation (9):

$$CI_{CE} = \sqrt{F_{(\alpha;1;f_e)} * v_e \left[\frac{1}{\eta_{eff}} + \frac{1}{R}\right]} \tag{9}$$

where $F(\alpha; 1; f_e)$ is the F-ratio at a CI of (1-α) at one degree of freedom (DOF), f_e is the value of error DOF, V_e is the value of error variance, R is the number of times the experiment is repeated and η_{eff} can be calculated by the following equation:

$$n_{eff} = \frac{N}{1 + [\text{Total degree of freedom associated with items used in } \eta \text{ estimate}]} \tag{10}$$

Using the equations stated above, CI for the confirmation experiment is calculated. The estimated optimal range for the confirmation test is

$$\eta_{MRR} / \eta_{TWR} / \eta_{Ra} - CI_{CE} < MRR / TWR / R_a < \eta_{MRR} / \eta_{TWR} / \eta_{Ra} + CI_{CE}$$

The 95% CI of the estimated MRR, TWR, and R_a mean is,

- $29.378 < MRR < 31.961$
- $43.558 < TWR < 53.941$
- $-13.030 < R_a < -10.243$.

5.2 Confirmation experiments

The requirement of a confirmation test is to confirm the conclusions obtained during the analysis of results. The confirmation test is conducted for MRR, TWR, and R_a considering the optimum and significant factors. The mean values of S/N ratio after the conduction of the experimental run for MRR, TWR, and R_a are 31.578, 50.914, and –12.029 respectively. All these experimental S/N ratio values lie within the 95% CI of the estimated optimum factors.

Table 6 Confirmation test result

Responses	*Optimum level*	*Predicted S/N ratio (η_P)*	*Experimental S/N ratio (η_E)*	*% Prediction error* $\left\lvert \frac{\eta_E - \eta_P}{\eta_E} \times 100 \right\rvert$
MRR	A3C1E3	30.67059	31.578	2.88%
TWR	A1B3C2D1E2	48.75037	50.914	4.25%
R_a	A1E1	–11.637	–12.029	3.265%

6 Conclusions

In this study, the influence of five parameters on three response characteristics is observed using ANOVA and mean effect plots. Further, experimental results are confirmed using confirmation tests. Following conclusions may be drawn:

1 Higher discharge energy creates a bigger and deeper size of cavities, which leads to higher MRR. However, it also increases the average surface roughness of the machined cavity.

2 Peak current is the most influencing parameter for MRR as compared to other process parameters. Pulse-on-time and cavity depth do not have a significant effect on the MRR.

3 Variation in MRR with the depth of cavity is very small and it is found to be statistically insignificant for MRR. Hence, it can be concluded that the nature of machining in particular settings could be easily identified even at a smaller depth of cavity.

4 To conduct the experiments using the EDM process, a smaller depth can also be used for machining purposes. It will significantly reduce the machining time and save the cost of the experiments.

5 To reduce the tool wear, a lower value of peak current and a higher value of pulse-on-time is desirable.

6 All the parameters excluding the depth of cavity show some measurable change to TWR. Depth of machining influences TWR slightly.

7 Mainly peak current and tool diameter influence the surface roughness of the machined workpiece.

8 A lower value of peak current and smaller tool diameter is helpful to get lower surface roughness for the machined workpiece.

9 A larger tool diameter yields more MRR and cavity depth is found to be insignificant for MRR, TWR, and surface quality.

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