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Investigations into Performance of Dry EDM Using Slotted Electrodes

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Dry EDM is an emerging EDM technology, which uses gas as dielectric fluid. Due to low density of gaseous dielectric, the process experiences i) unconstrained plasma expansion thereby reducing the effective material removal rate (MRR) and ii) inefficient disposal of debris. This work proposes use of electrodes with peripheral slots to provide more space for the flow of dielectric for effective debris disposal and consequently improve MRR. In this regard, a comprehensive experimentation using Taguchi L_{16} orthogonal array has been planned initially to optimize the number of peripheral slots on the electrodes, and then to understand the effect of the slots on material removal, tool wear, oversize and depth achieved as a function of processing conditions. It is observed that the optimum number of peripheral slots on electrode for effective debris evacuation is four for the electrode configuration used in this work. The statistical analysis shows that in dry EDM, discharge current (I), gap voltage (V), rotational speed (N) and pulse off-time (T_{off}) control MRR. Also, use of slotted electrodes significantly reduces the electrode wear rate, and attachment of debris particles on the electrodes.

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1. Introduction

EDM is a widely known machining technology for effective machining of ‘difficult-to-machine’ materials. It has a large number of applications in die and aerospace industries for manufacturing of components with high precision. Dry electrical discharge machining is a new EDM technique, which uses gas as a dielectric fluid, instead of conventional liquid dielectric.[1-8] During a spark erosion process, carbon particles, debris particles and certain amount of waste products are generated. They disturb the erosion process causing frequent short circuits.[1,2]

It is known that the flushing of waste products in EDM can be done by controlling dielectric flow in the inter-electrode gap. In the case of dry EDM, controlled flow of gaseous dielectric through a pipe tool electrode carries away debris particles from the inter-electrode gap.[1] However, due to i) low density of the gaseous dielectric and ii) insufficient space for flow of gaseous dielectric, the debris disposal is not fully effective. In dry ED groove machining, clogging of the groove with debris particles, even with high velocity air flow was observed.[3] In addition, severe reattachment of debris particles occurs while generating blind holes.[4] Table 1 lists the research efforts in the past to enhance the process capability of the dry EDM.

In dry EDM, few attempts have been done, for achieving faster debris removal. Rotation and planetary motion provided to the tool electrode helps debris removal to some extent.[1] Tao *et al.*[3] used external gas supply in the form of a jet, in addition to flushing through the electrode, which slightly improved the debris removal. In another investigation, ultrasonic vibration was found to be little effective in removing debris particles from the inter-electrode gap.[2] Therefore, achieving a high process MRR (material removal rate) along with high precision remains a big challenge in dry EDM.

In view of this, the approach used in this work is to modify the geometry (face shape) of the tool electrode, by providing peripheral slots on it. The dry EDM experiments were conducted with the electrodes having varying number of peripheral slots. The slotted electrodes were provided rotation during cutting operation. It is anticipated that the slotted electrodes would improve the process by helping better escape of gaseous dielectric and debris disposal, thereby improving the MRR.

2. Experimental procedure

2.1 Theme and Design of experiments

A schematic of the mechanism of dry EDM process using

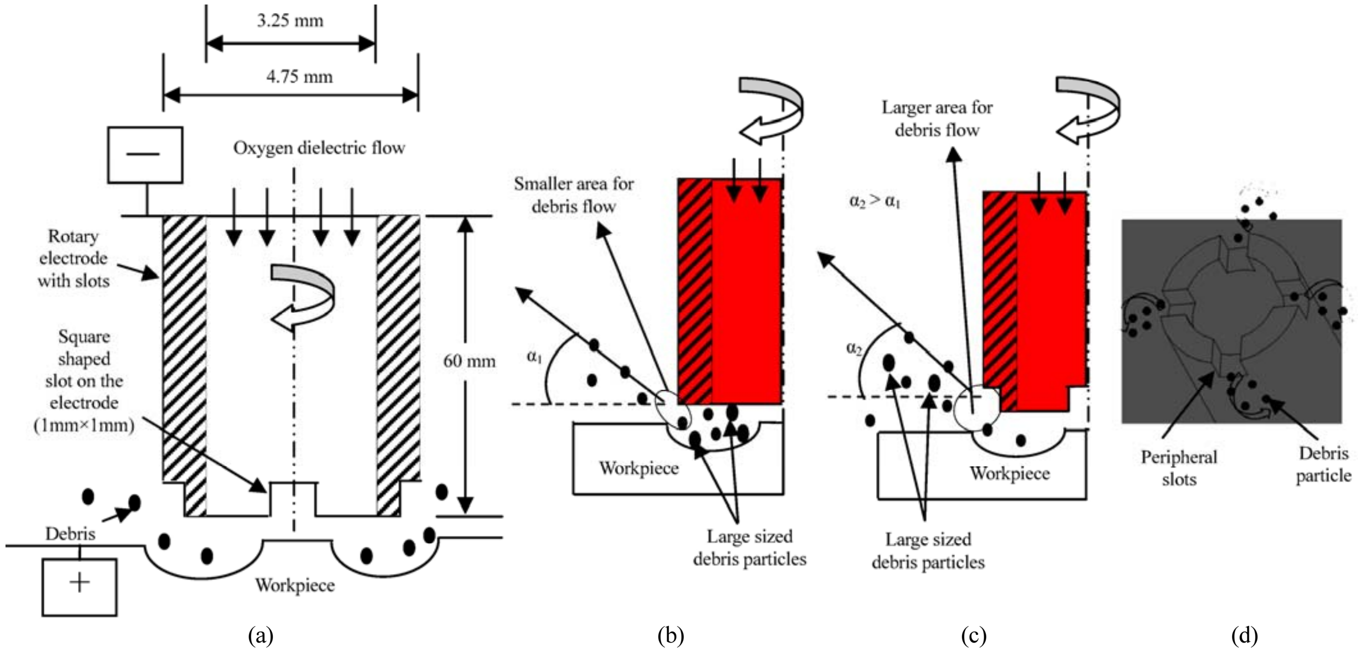

Fig. 1 (a) Schematic illustration of principle of dry EDM with slotted electrodes and principal dimensions, and Physical model of dry EDM indicating the effect of peripheral slots provided on the electrode on debris flow for (b) plane electrode and slotted electrode (c) 2-D and (d) 3-D

Table 1 Summary of major investigations on dry EDM

Objective of the work	Key findings
1. To generate 3D surfaces[1]	• Tool wear is near to zero. • MRR improves by increasing oxygen concentration.
2. Ultrasonic assisted EDM in gas to improve MRR and stability.[2]	• A higher MRR achieved using UEDM in gas.
3. Use of a quasi-explosion mode for high MRR, and intake method to improve accuracy and reduce tool wear.[5]	• A quick method of milling 3D cavities though not very accurate. • Intake method gave a better accuracy up to 0.3 mm depth.
4. Machining 3D geometries on 'difficult-to-cut' cemented carbide.[6]	• Tool wear ratio in dry EDM is 66% and 75% lower than die sinking and oil EDM, respectively.
5. Comparison of wet, dry and near dry EDM drilling processes.[4]	• Dry EDM has low efficiency, deposits more debris and causes taper on holes.
6. Effect of dielectric and electrode material on dry and near-dry EDM.[3]	• O_2 as dielectric and Cu as electrode for dry EDM.
7. Effect of dielectric, electrode and pulse energy on MRR and surface finish.[7]	• Kerosene mist with air is the best dielectric media and Cu-infiltrated graphite as electrode.
8. Analysis of MRR, Ra and TWR (tool wear rate).[8]	• Current, duty factor, pressure and spindle speed influence MRR. Pulse on-time influences surface finish, Ra.

slotted tool electrode is shown in Fig. 1(a). It is anticipated that slots on the periphery of the tool electrode (see Fig. 1(a)), would help in the mechanism of material removal in dry EDM in the following way:

Table 2 Input parameters for optimization experiments

(a) Parameters of optimization experiments					
Expt. No.	Slots (1x1) mm^2 each	V (V)	I (A)	P (MPa)	N (rpm)
1	0	65	9	0.15	100
2	1	65	9	0.15	100
3	2	65	9	0.15	100
4	3	65	9	0.15	100
5	4	65	9	0.15	100
6	5	65	9	0.15	100
7	6	65	9	0.15	100
8	7	65	9	0.15	100
9	8	65	9	0.15	100

- The slots would replenish the dielectric strength in the inter-electrode gap after a discharge at a faster rate, which is important in dry EDM.[1]
- The slots would facilitate effective circulation of dielectric, thereby quicker and easier debris evacuation from the sparking region occurs at the end of a discharge.
- The slots would help in cooling of the wall region of the pipe electrode surrounding the spark, which could minimize debris deposition[3] due to a large flow of oxygen dielectric.
- It is observed that in slotted electrodes, larger area for flow of debris particles helps improve its flushing.

In dry EDM using electrode with plane geometry, gaseous dielectric is supplied through the electrode. The flowing gaseous dielectric carries a portion of debris particles, and removes them from the inter-electrode gap, to the atmosphere. However, small clearance for this flow results in incomplete debris removal. Therefore, in dry EDM with slotted electrodes, debris particles will get easily escaped from the inter-electrode gap at a larger angle ($\alpha_2 > \alpha_1$) as shown in Fig. 1(b), (c) and (d).

In this study, experiments are designed to understand the effect

Table 3 (a) Assignment of input variables to L16 orthogonal array and (b) average values of response variables

(a) Parameters and their levels of main experiments						(b) Responses of the main experiments			
Expt No.	V (V)	I (A)	T_{off} (μs)	P (MPa)	N (RPM)	MRR (mm^3/min)	TWR (mm^3/min)	ROC (μm)	Depth achieved, Z (μm)
1	50	9	66.6	0.1	100	0.375	0.002	230	80
2	50	12	40	0.15	200	0.833	0.002	312.5	290
3	50	15	18.1	0.2	300	1.12	0.004	311.5	320
4	50	18	0	0.25	400	1.497	0.004	252.5	370
5	60	9	0	0.15	300	0.49	0.002	252	210
6	60	12	18.1	0.1	400	0.70	0.002	251.5	270
7	60	15	40	0.25	100	0.79	0.004	305.5	320
8	60	18	66.6	0.2	200	1.04	0.002	305	310
9	70	9	40	0.2	400	0.540	0.002	309.5	140
10	70	12	66.6	0.25	300	0.832	0.002	330	230
11	70	15	0	0.1	200	0.832	0.004	242	240
12	70	18	18.1	0.15	100	0.998	0.006	240.5	250
13	80	9	18.1	0.25	200	0.345	0.002	267.5	300
14	80	12	0	0.2	100	0.49	0.006	211	80
15	80	15	66.6	0.15	400	0.832	0.006	359.5	200

of peripheral slots on the response variables like, MRR, TWR, depth achieved and ROC (radius of overcut). Initially, a set of screening experiments was performed to optimize the number of slots, as per the specifications shown in Table 2.

It is further known that the major factors influencing the energy of a pulse in an EDM process are: voltage, V and current, I. Also, the importance of varying pulse off-time (T_{off}) is well understood.[5] At the same time, gas pressure, P and spindle speed, N influence the flushing conditions and stability of the process. It is thought that varying all the above mentioned factors at four levels would help better identification of their influence. Therefore, experiments with input parameters at four levels have been conducted in a random order, based on L_{16} (4^5) Taguchi orthogonal array,[9] as per parametric conditions listed in Table 3(a). The responses of dry EDM experiments are presented in Table 3(b).

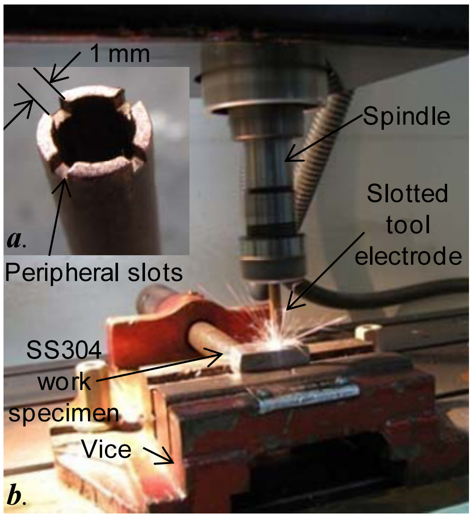

Fig. 2 (a)-(b) Photograph of the (a) slotted electrode and (b) dry EDM experimental set-up

2.2 Slotted electrode and workpiece preparation

Copper pipes (each of length: 60 mm, OD: 4.75 mm and ID: 3.25 mm) were finish turned, ground at the ends, for their use as the tool electrodes in this experimentation. Further, geometry of the electrodes was modified by generating equi-spaced square cut-outs of size 1 mm x 1 mm at the bottom (near the discharge gap), along the periphery (see Fig. 2(a)).

The slots were machined using end milling cutters of Ø500 μm on a high precision CNC Mikrotools Micromachining Center that has a resolution of 0.1 μm and an accuracy of 1 μm. Slots were deburred manually by needle files. The bottom face of the electrodes and the slots were further finished using silicon carbide polishing papers.

Work specimens made of SS304 were of size 27 mm x 14 mm x 10 mm. The top faces of the specimen were initially machined using a precision surface grinder. All the six faces of the specimen were machined using a precision surface grinder. All the six faces of the specimen were polished using SiC polishing papers followed by lapping. Workpieces were clamped to the machine table using a table vice.

2.3 Experimental procedure

Dry EDM drilling experiments were performed on SS304 workpieces using tubular copper tool electrodes, which had four slots, equispaced around the periphery (see Fig. 2(a)). DC power supply was provided to the electrodes with the electrode being at negative (-ve) polarity and workpiece at the positive (+ve) polarity. The flow of oxygen gas dielectric into the inter-electrode gap was provided through the slotted electrode (see Fig. 2(b)). Each experiment was conducted for half an hour.

After the dry EDM experiments, MRR, TWR, depth achieved and radius of overcut were determined. The weight differences (in g) of workpieces and tool electrodes before and after the experiments were measured using Sartorius CP 4235 precision balance. The depth achieved and radii of holes generated were measured using Nikon MM-400 microscope. Radius of hole generated was measured at twenty locations for each sample, to determine the overcut, and the average values were used for the analysis.

3. Results and discussion

3.1 Number of slots on electrode periphery

Variation of response variables with the number of slots on the electrode, observed in the initial experiments is shown in Fig. 3(a)-(d). The optimum values of response variables, viz., maximum MRR, minimum TWR, minimum ROC and maximum depth achieved are found corresponding to four slots on the periphery of the tool electrode. With an increase in number of slots beyond four, the MRR values show relatively larger decrease as compared to the case when the number of slots is varied between 1 to 4 (see Fig. 3(a)). Also, lower value of TWR is observed in the case of a plane electrode as well, when the number of slots on electrode is four (see Fig. 3(b)).

The overcut in hole dimensions is maximum (430 μm) for a plane electrode with no slots. The overcut is lower for electrodes with 3,5 and 4 number of slots, the lowest value (415 μm) being at four number of slots (see Fig. 3(c)). Average depth achieved follows a trend similar to that of the MRR, see Fig. 3(d).

3.2 Results of main experiments

The results of the experiments including the average values of response variables (MRR, TWR, ROC and depth achieved are presented in Table 3(b). In order to analyze the influence of input parameters on the response variables, statistical analysis using ANOVA (analysis of variance) has been applied (see Table 4). The means tables, main effect plots were also prepared based on AOM (analysis of means) using MINITAB 15 software.[9]

3.2.1 Analysis of MRR

The values of MRR presented in Table 3(b) shows that the highest average MRR (1.497 mm^3/min) was obtained in the 4^{th} trial (50 V, 18 A,0 μs, 0.25 MPa, 400 rpm) and the lowest average MRR (0.345 mm^3/min)was in 13^{th} trial (80 V, 9 A,18.1 μs, 0.25 MPa, 200 rpm). The statistically significant parameters (based on ANOVA table presented elsewhere) that influence the MRR are as shown in Table 4. The corresponding AOM plots are shown in Fig. 4(a)-(d).

Discharge current (I) is the most significant parameter controlling MRR, at 95% confidence level. The MRR increases linearly with I (see Fig. 4(a)). It is known that with an increase in current, discharge energy increases, resulting in a higher MRR.[10,11]

Spindle speed (N) is the second statistically significant parameter controlling MRR. Normally in a liquid dielectric EDM process[11-13] and in dry EDM process using,[10] the contribution of spindle speed to MRR is only after voltage (V) and current (I). However, in dry EDM using slotted electrodes, spindle speed (N) appears to be more significant in controlling MRR than the voltage. The electrode rotation provides a blowing action to the molten debris particles.[8] The flowing oxygen gas dielectric in a circular path generates a centrifugal force on a debris particle, proportional to the square of the outward velocity of the debris particle given by,

$$F_{cd}= m_d V_d^2 / r_f =(4\pi^2/3600)\, m_d\, r_f^2 N_d^2 \quad (1)$$

$$V_d = r_f \cdot (2\pi N_d/60) \quad (2)$$

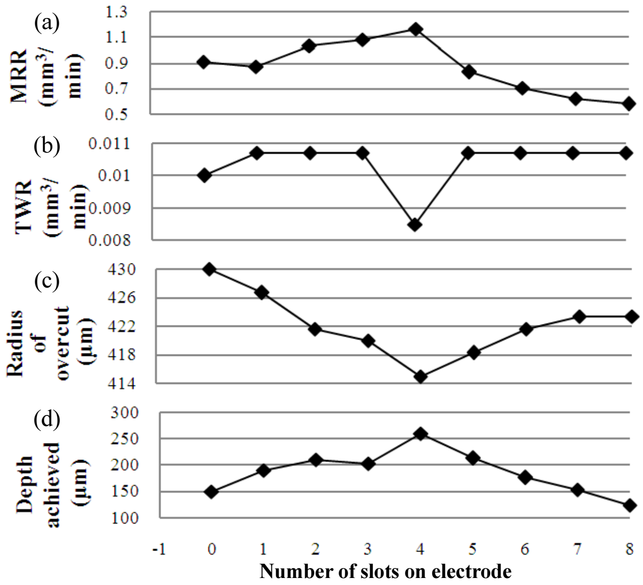

Fig. 3 (a)-(d) Results of screening experiments for optimization of response variables

Table 4 Statistical significance of input parameters

Response variable	*V* (V)	*I* (A)	T_{off} (μs)	*P* (MPa)	*N* *(RPM)*
MRR	√	√	√	×	√
TWR	×	×	×	×	×
ROC	×	√*	×	×	×
Depth	√	√	×	×	×

√ - statistically significant at 95% confidence level
√* - statistically significant at 90% confidence level
× - not statistically significant

where, 'F_{cd}' is the outward centrifugal force on a debris particle, 'm_d' is the mass of a debris particle flushed out, 'V_d' is the outward velocity of the debris particle, 'r_f' is the radius of flow of the debris particle and 'N_d' is the speed of rotation of a debris particle.

The AOM plot presented in Fig. 4(b) shows that there is a linear increase in MRR with speed (N). However, very high spindle speed is found to hamper MRR, as it causes difficulties in debris removal causing short circuits (see Fig. 4(b)).

ANOVA results (Table 4) show that voltage (V) is the third significant parameter at 95% confidence level, after current (I) and spindle speed (N). The main effect plots (see Fig. 4(c)) reveal that there is an overall decrease in MRR with voltage. In a dry EDM process, sparking occurs when the effective electric field (E) given by,

$$E = V / d \quad (3)$$

(where, 'V' is the gap voltage and 'd' is the inter-electrode gap) exceeds the dielectric strength of the gaseous medium.[8] With an increase in voltage (V), gap distance for initiation of a discharge increases. This reduces the velocity of the oxygen gas striking the workpiece surface.[8,10] It is known that in liquid dielectric EDM,[11] the discharge energy (E_d) varies as the square of the voltage given by,

$$E_d = \tfrac{1}{2} C V^2 \quad (4)$$

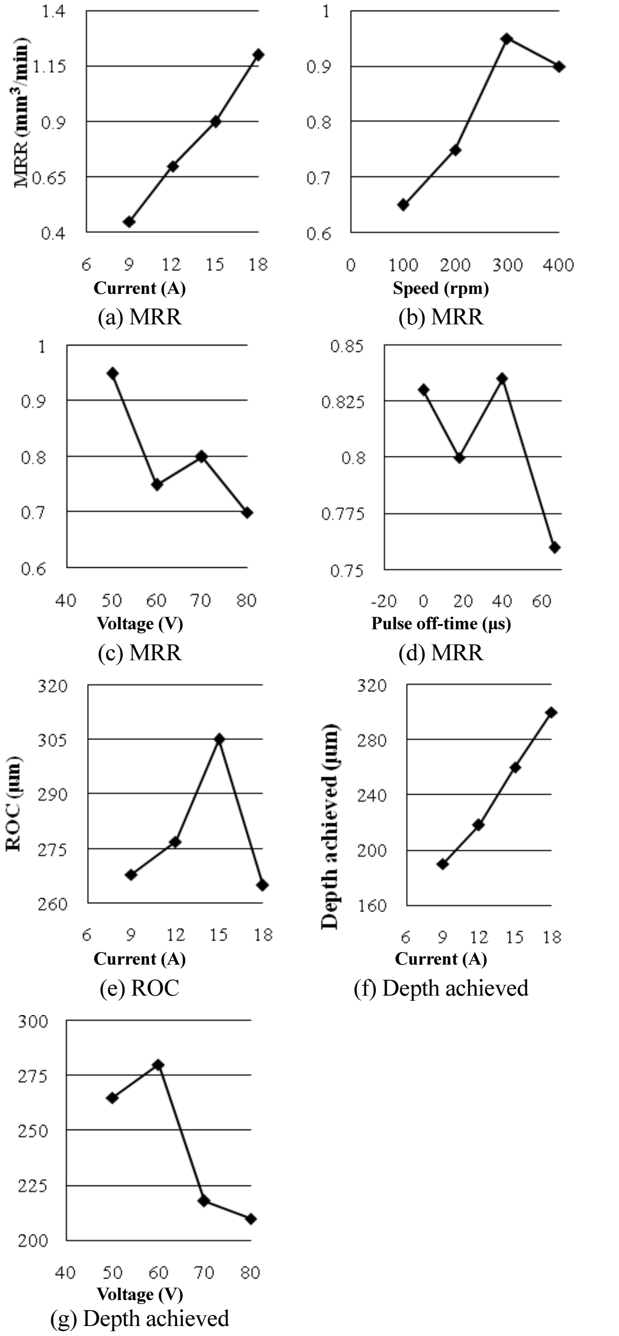

Fig. 4 (a)-(g) AOM plots for statistically significant parameters influencing

where, 'C' is the capacitance of the oxygen gas dielectric in the inter-electrode gap and 'V' is the gap voltage. However, opposed to this effect, in dry EDM with plane electrode, an increase in voltage causes a decrease in MRR.[10] An increase in voltage causes an increase in gap of sparking, which reduces velocity of gaseous dielectric at work surface. As a result, the flushing action on debris particles becomes less effective which causes arcing. This appears to be valid in the case of dry EDM using slotted electrode too (see Fig. 4(c)).

Statistical analysis using ANOVA shows that pulse off-time (T_{off}) is the fourth significant parameter in influencing MRR at 95% confidence level (see Table 4). From the AOM plots (Fig. 4(d)), it is observed that beyond a pulse 'off-time' of 40 μs, the MRR decreases linearly. Hence, the highest MRR is observed close to the well-known 'quasi-explosion' point at which pulse 'off-time' is one-sixth of pulse 'on-time'.[5] This strongly supports the earlier investigations on dry EDM under 'quasi-explosion' mode.[3,5]

3.2.2 Analysis of TWR, ROC and depth achieved

The statistical significance of the input parameters on the other response variables, viz. TWR, ROC and depth achieved are shown in Table 4. The trends followed by the statistically significant parameters in AOM plots are shown in Figs. 4(e), (f) and 4(g).

3.2.2.1 Analysis of TWR

Average values of TWR are presented in Table 3(b). The statistical significance of input parameters on TWR is shown in Table 4 indicates that none of the parameters are statistically significant at 95% confidence level.

Nevertheless, the values of TWR are observed to be close to zero or positive (0.002 to 0.006 mm^3/min). This indicates that with peripheral slots, the debris deposition on tool electrode is completely eliminated. However, the process of making slots on electrode periphery reduces the effective cross-sectional area supporting the thermal load. This sometimes causes minor wear on the electrode. In a liquid dielectric EDM, TWR is controlled by current (I), voltage (V) and pulse 'on-time' (T_{on}).[11] Thus, slotted electrodes help in

- minimizing the attachment of a fraction of molten workpiece material to the tool electrode, which normally occurs in dry EDM.
- maximizing the access of oxygen gas to entire region of tool electrode close to discharge locations, so as to protect the electrode from wear, by formation of an oxide layer around the tool electrode.[1]
- Cooling the walls of the slots on the tool electrode, so as to reduce thermal damage and chances of arcing, unlike in the case of dry EDM.[3,4,10]

3.2.2.2 Analysis of radius of overcut (ROC)

The ANOVA results for radius of overcut (ROC) of dry EDMed holes are presented in Table 4. The highest ROC (359.5 μm) was corresponding to 15th trial (80 V, 15 A, 66.6 μs, 0.15 MPa, 400 rpm), and the lowest (211.0 μm) corresponds to 14th trial (80 V, 12 A, 0 μs, 0.2 MPa, 100 rpm).

ANOVA results show that none of the input parameters are statistically significant in influencing ROC at 95% confidence level. Discharge current (I) however is the only parameter influencing ROC, but at 90% confidence level (see Table 4). The main effects plot (shown in Fig. 4(e)) indicates that the largest ROC is observed at a current of 15 A.

3.2.2.3 Analysis of depth achieved (Z)

The highest depth (370 μm) was achieved during the 4th trial (50 V, 18 A, 0 μs, 0.25 MPa, 400 rpm) whereas the lowest depth (80 μm) was found in the 1st (50 V, 9 A, 66.6 μs, 0.1 MPa and 100 rpm) and 14th (80 V, 12 A, 0 μs, 0.2 MPa, 100 rpm) trials. The result of ANOVA for depth achieved is shown in Table 4.

Table 5 Optimum parametric conditions

Objective function	Value	V (V)	I (A)	T_{off} (μs)	P (MPa)	N (rpm)	Expt No.
Maximization of MRR (mm^3/min)	1.497	50	18	0	0.25	400	4
Minimization of TWR (mm^3/min)	0.002	50	9	66.6	0.1	100	1
		50	12	40	0.15	200	2
		60	9	0	0.15	300	5
		60	12	18.1	0.1	400	6
		60	18	66.6	0.2	200	8
		70	9	40	0.2	400	9
		70	12	66.6	0.25	300	10
		80	9	18.1	0.25	200	13
Minimization of ROC (μm)	211	80	12	0	0.2	100	14
Maximization of depth achieved (μm)	370	50	18	0	0.25	400	4

The volume of crater generated in a dry EDM drilling process using plane electrode can be approximately expressed as a function of depth achieved as,[10]

$$V_c = 1/3\ \pi\ R_c^2 z \tag{5}$$

where, 'V_c' is the volume of a single crater, 'R_c' is the radius of a crater and 'z' is the depth achieved. Thus, MRR in a dry EDM varies directly with 'z'. It is felt that this relation holds good for dry EDM using a slotted electrode too.

Statistical analysis using ANOVA reveals that discharge current (I) is the most significant parameter controlling the depth achieved (Z), at 95% confidence level (see Table 4). It is evident that with an increase in current (I), there is a linear increase in depth achieved (see Fig. 4(f)). ANOVA results show that the gap voltage (V) is another statistically significant parameter at 95% confidence level in controlling the depth achieved (Z) (see Table 4). The AOM plots presented in Fig. 4(g) show that though there is an initial increase in depth achieved with voltage (V), further, an overall decrease in depth has been observed.

It may be noted that the slotted electrode would be effective as long as the depth of hole is less than the depth of slots on the electrode. Once the depth of hole exceeds the depth of holes on the electrodes, there may not be any difference in the performance of slotted as well as solid electrodes.

4. Optimum parametric conditions

The optimum parametric conditions for the response variables, viz., MRR, TWR, ROC, depth achieved and surface finish are presented in Table 5.

The highest MRR (1.497 mm^3/min) and depth achieved (211 μm) were observed corresponding to lowest voltage (50 V) and pulse off-time (0 μs), and the highest conditions of other parameters (18 A, 0.25 MPa and 400 RPM).

The dominant phenomenon on the tool electrode was 'positive wear of the tool electrode' close to zero, and lowest value of tool wear was 0.002 mm^3/min, corresponding to half (8 trials) among entire 16 trials (Trials: 1, 2,5,6,8,9,10 and 13). The lowest radius of over-cut (211 μm) was found in 14th trial, high-voltage (80 V), low-current (12 A) and low-speed (100 rpm) condition.

5. Conclusions

Based on the results of this experimentation, the following conclusions can be drawn:

- The use of electrodes with peripheral slots helps flush debris particles more effectively and hence promotes improvement in MRR.
- The initial experiments show that with four peripheral slots on electrodes help achieve maximum MRR and depth, and at the same time, minimize TWR and ROC. This can be attributed to inefficient debris disposal when the number of slots is less than four and excessive blowing of plasma column by gaseous dielectric when the number of slots are more than four.
- Statistical analysis on results of experiments with four peripheral slots on electrode show that MRR is controlled by voltage (*V*), current (*I*), pulse off-time (T_{off}) and speed (*N*). The MRR decreases with voltage (*V*), but linearly increases with current (*I*) and speed (*N*). This shows that besides current, the spindle speed also controls the MRR in dry EDM.
- The use of slotted electrodes in dry EDM reduces the TWR and the occurrence of debris attachment on the tool electrodes.
- The depth achieved and ROC are mainly controlled by current and to some extent by voltage in dry EDM.

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