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An investigation into performance of electric discharge milling using slotted tools

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Abstract The flushing of by-products from the interelectrode gap (IEG) of a few microns is the major concern in the electrical discharge machining (EDM). The inadequate removal of debris from the gap causes short-circuits and reduces machining efficiency. Researchers have explored different techniques to enhance debris flushing from the gap. In electrical discharge milling (ED milling), the rotation of the tool along with linear travel is the major driving force for the debris flushing. In this paper, the application of an improvised tool to enhance rotation induced debris flushing is proposed. The flow-fields of dielectric and debris were modeled using computational fluid dynamics (CFD). The simulations results were utilized to optimize the tool geometries. A comparative study of the cylindrical and improvised tool in terms of material removal rate (MRR), tool wear rate (TWR) and surface finish was calculated. Relative to conventional cylindrical tools, the improvised tool enhanced the MRR by 150 %.

1. Introduction

Electrical discharge machining (EDM) is a popular technique for machining intricate and precise geometry. It can cut high aspect ratio slot and a hole in the microdomain. The probability of the occurrence of a spark is greater where the interelectrode gap (IEG) is minimum. However, this small IEG creates a problem in machining performance. The by-products of the EDM process pollute the IEG and must be efficiently removed from the IEG. The effective flushing of debris from the IEG avoids secondary discharge and improves machining efficiency. A high-velocity dielectric fluid is injected through a nozzle for flushing the debris from the gap. Many researchers have proposed different flushing methods to improve flushing efficiency. The rotation of the tool and high electrode jump is an effective method of debris flushing from the gap. A simple cylindrical tool is modified by a slotted tool to enhance flushing and improve material removal rate (MRR).

The various shapes of tools used by different researchers for various machining processes are given in Fig. 1. Kunieda and Masuzawa proposed horizontal EDM and rotary horizontal EDM. It is observed that the buoyancy of bubbles is responsible for flushing of debris from the gap. Also, rotation of the tool and the workpiece together improved machining accuracy and performance [1]. Nastasi and Koshy utilized slotted tools for electrical discharge drilling (EDD) of high aspect ratio holes and observed a 300 % increase in MRR as compared to cylindrical tools [2]. Puthumana and Joshi used electrodes with peripheral slots to improve MRR, reduce tool wear rate (TWR) and radius overcut (ROC) by dry EDM in gas [3]. Li et al. proposed a new tool containing bunched hollow electrode to improve flushing efficiency. The dielectric fluid velocity increased tenfold, reducing the debris in the gap and uniform distribution of debris particles was also observed [4]. Pei et al. used tubular tools in electric discharge milling (ED milling) and observed that the machining error was controlled within 2 % and surface fluctuation was less than 4 μm, improving the accuracy and the efficiency of the process [5]. Flaño et al.

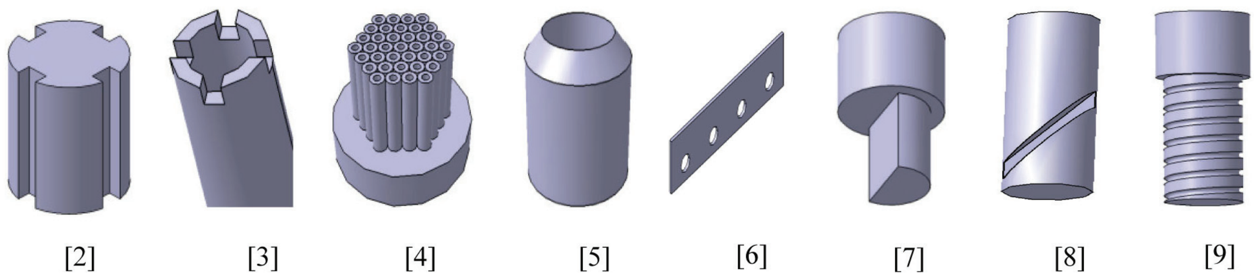


Fig. 1. Various shapes of tools [2-9].

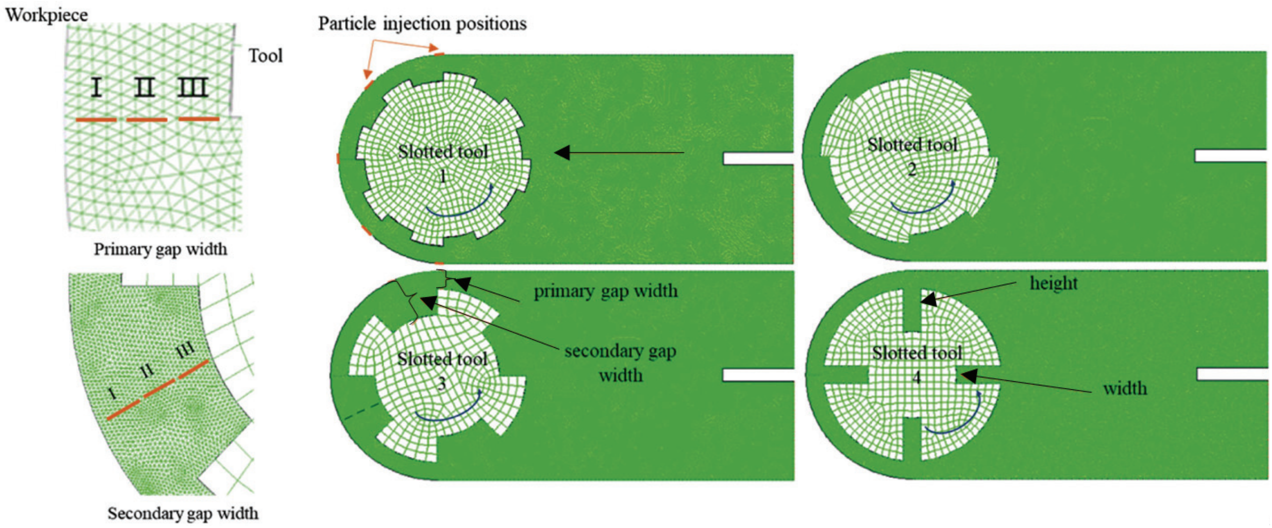


Fig. 2. Schematic diagram representing the slotted tool and analysis points.

studied the effect of size and position of the holes on the lateral surfaces of the electrode to machine high aspect ratio slots using EDM. It reduced the machining time considerably and improved the machining stability [6].

Yang et al. investigated the machining characteristics of micro holes using a semi-cylindrical tool with and without ultrasonic vibrations in microelectrochemical machining (μECM). The semi-cylindrical tool provided more flow space for the electrolyte, which resulted in 76 μm hole at a depth of 300 μm on stainless steel. In addition to that with ultrasonic vibrations, machining is more effective with a reduction in machining time [7]. Kumar and Singh studied response characteristics of micro EDD of holes by using slotted tools with inclined micro slots. The need for flushing was eliminated and the slotted tool acted as a self-flushing electrode, which further eliminates the occurrence of arcing and short-circuiting. The slotted electrode improved MRR, TWR, taper angle, corner radius and aspect ratio at tool speed of 1000 rpm [8]. Hsue and Chang proposed a hybrid synchronized process for precision drilling and polishing using the micro-EDM grinding process (micro-EDMG). The helical micro-tool improved penetration and surface quality of the machined micro-hole. The Ra value achieved was 0.107 μm and the difference between the entrance and exit diameters of the through micro-hole was 5 μm with a depth of 300 μm [9]. It is observed that in deep hole EDM, high electrode jump motion at high speed resulted in effective flushing of debris from the gap [10, 11]. Computational fluid dynamics (CFD) is used by most of the researchers to analyze the flow field and debris movement in the gap [10-14].

The objective of this paper was to study the effect of the slotted tool and compare it with the cylindrical tool in machining the channel using ED milling. The effect of slot size, number of slots, and tool speed on the removal rate was investigated. CFD simulation was used to get useful insights into the flow fields and to assess and optimize the slot size to improve the MRR. The scanning electron microscope (SEM) micrographs were used to assess the surface topography of the machined channel and the tool wear.

2. Computational fluid dynamics

The dielectric fluid flow governs the movement of debris particles in the gap. Hence, the fluid flow and debris particles trajectory in the gap was simulated using ANSYS Fluent software. The schematic diagram showing various slotted tool is shown in Fig. 2. The geometrical model of the study is a 2D represen-

Table 1. Tool geometry and µchannel size.

Tool No.	Tool dia. (µm)	No. of slots	Slot width (µm)	Slot height (µm)	µchannel width (µm)
1	500	8	98	25	600
2	500	4	197	25	600
3	500	4	197	75	600
4	500	4	50	125	600

tation of the cutting process by µED-milling. This is shown as partially cut straight channel with rotating tool positioned in the direction of machining. The tool is represented as a solid circular domain and the µchannel excluding the tool represents the fluid domain which is finely meshed. Since the major flow behavior changes happen in the fluid domain, it has been meshed with structured triangular elements. A solid domain is the group of cells for which only a heat conduction equation is solved and no flow equations are solved and hence it is meshed with quadrilateral elements. The accuracy of results improved with fine grid size, and with increasing the count of elements above 60000 the results did not improve considerably. The time independency check shows that considerable change in the output result was not observed with the decrease in the time step. Hence, to reduce the total simulation time the time step of 0.01 sec was used. The metrics of the generated mesh is reasonably good to be adopted for the CFD model.

As shown in Fig. 2, four different tools of various shapes, represented as slotted tool 1, slotted tool 2, slotted tool 3, and slotted tool 4, were selected for simulation. The shape of the tool was varied by changing the number of slots and the size of slots. The details of different shapes of tool in terms of number of slots, slot width, slot height are listed in Table 1. The width represents the circumferential distance of slot and the height represents the depth of slot. The diameter of the tool, µchannel width and gap width are 500, 600 and 50 µm, respectively, and they are kept constant. The gap between the external surface of the tool and workpiece surface is represented as primary gap width (IEG) and the gap between bottom surface of the slot and the workpiece surface is represented as secondary gap width (IEG + slot height). The primary and secondary gap width was divided into equal divisions and the average dielectric velocity was measured at three different positions as shown in Fig. 2.

The fluid domain is filled with kerosene (dielectric) and to ensure a sufficient quantity of dielectric in the gap, it is supplied through inlet cross-section with a velocity of 0.01 cm/s. The excess dielectric after circulating through the IEG flows out through the outlet cross-section. The wall is provided in the simulation model to differentiate inlet and outlet cross-section and its presence does not affect the flow field. The moving reference frame is used to provide angular rotation to the tool where the tool is rotating in counter-clockwise direction. The velocity inlet and pressure outlet conditions are set to inlet and outlet cross-section, respectively. The walls of tool and workpiece are set with the no-slip condition. The effectiveness of flushing is investigated by injecting spherical steel particles from the workpiece surface and by tracking their movement out of the IEG. The Euler-Lagrange approach is used to track the particles (discrete phase) and one-way coupling is used as the volume of particles is very less as compared to the dielectric (continuous phase). The Schiller-Naumann drag model is used to calculate momentum transfer between the fluid and the particles. The CFD parameters used for simulation of fluid flow and discrete phase modeling are summarized in Table 2. The assumptions made for the simulation are listed below:

Table 2. CFD parameters.

Solver type	Pressure based 2D double precision, no gravity effect
Velocity formulation	Absolute
Turbulence model	Realizable k-epsilon turbulence model
Pressure-velocity coupling	SIMPLE (semi-implicit method for pressure-linked equations)
Gradient option	Least squares cell-based
Pressure	Standard
Particle treatment	Unsteady particle tracking
Drag law	Spherical
Injection type	Surface
Particle type	Inert

1. The effect of gravity of the particles is neglected.
2. The effect of particles on the dielectric fluid flow is neglected as quantity is low.
3. No-slip condition is applied to workpiece surfaces.

3. Experimental work

The objectives of the experimental work were to investigate the effect of geometric features of the tool on the machining performance. The geometric features include peripheral longitudinal slots on the cylindrical tools. The effect of slot size and the number of slots was explored. The tool is of copper with a nominal diameter of 2 mm and the workpiece is EN31 die steel material with a thickness of 4 mm. The main aim of the author was to investigate the effect of peripheral slots on ED milling of slots in microdomain. But with the present manufacturing scenario, it is difficult to cut straight slots on the periphery of cylindrical tools with a diameter below 1 mm. Hence for the present study, a tool with a diameter of 2 mm was used for experimentation and the CFD simulation was used to study the flushing efficiency of the similar tool with a diameter of 0.5 mm.

The slots of various dimensions were machined on the cylindrical tool using CNC controlled wire-EDM machine. The wire material was brass with a diameter of 0.25 mm. The three basic tool shapes considered for study were cylindrical, slotted and deep slot. The slotted tool consisted of four equispaced radial slots on the periphery, each of width 0.4 mm and height

0.5 mm. The deep slot tool consisted of a single radial slot of width 0.4 mm and a height of 1 mm which is the radius of the tool. The effect of slot width and height on the removal rate was considered taking two different cases. In the first case, the slot width is varied by three values 0.5, 0.75 and 1 mm keeping the slot height constant at 0.4 mm. In the second case slot height was varied similarly by three values 0.5, 0.75 and 1 mm keeping the slot width constant at 0.4 mm. The effect of number of slots was also studied by considering one, two, three, and four slots. Further increasing the number of slots would weaken the tool due to its small size. Table 3 shows the various shapes of the tool used for experimentation. The experiments were performed on a Hyper-15 micromachining machine. Hyper-15 is a tabletop type integrated multi-process CNC machine tool. The tool is mounted rigidly on the spindle using the collet to avoid wobbling during rotation. The workpiece is clamped on the machine table using a fixture. Necessary care is taken to ensure the top surface of the workpiece to be horizontal. The tool is rotated with a speed of 800 rpm and the depth of cut is 1 mm. The dielectric is conventional EDM oil and is supplied through a nozzle to ensure continuous recirculation of the fluid. The experimental setup and different tools are shown in Fig. 3 and the experimental parameters are given in Table 4. The cause and effect diagram showing relation between output parameters such as TWR, MRR with various input parameters is represented in Fig. 4.

Table 3. Various tool geometry [*slot width (w) and slot height (h)].

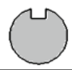
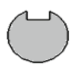
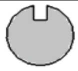
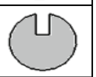
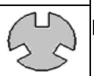
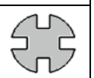
Tool No.	Tool dia. (mm)	No. of slots	*(w) (mm)	*(h) (mm)	Tool shape	Parameter
1	2	1	0.5	0.4		Effect of width
2	2	1	0.75	0.4		
3	2	1	1	0.4		
4	2	1	0.4	0.5		Effect of height
5	2	1	0.4	0.75		
6	2	1	0.4	1		
7	2	2	0.4	0.5		Effect of no. of slot
8	2	3	0.4	0.5		
9	2	4	0.4	0.5		

Table 4. Parameters used and its specification.

Sr. No.	Description	Values
1	Workpiece	EN31 (4 mm thick)
2	Tool	Copper (ϕ 2 mm)
3	Dielectric	EDM oil
4	Capacitance	10000 pF
5	Voltage	150 V
6	Speed	500, 800 rpm
7	Feed	0.6 mm/min
8	Length of cut	1 mm
9	Depth of slot	1 mm

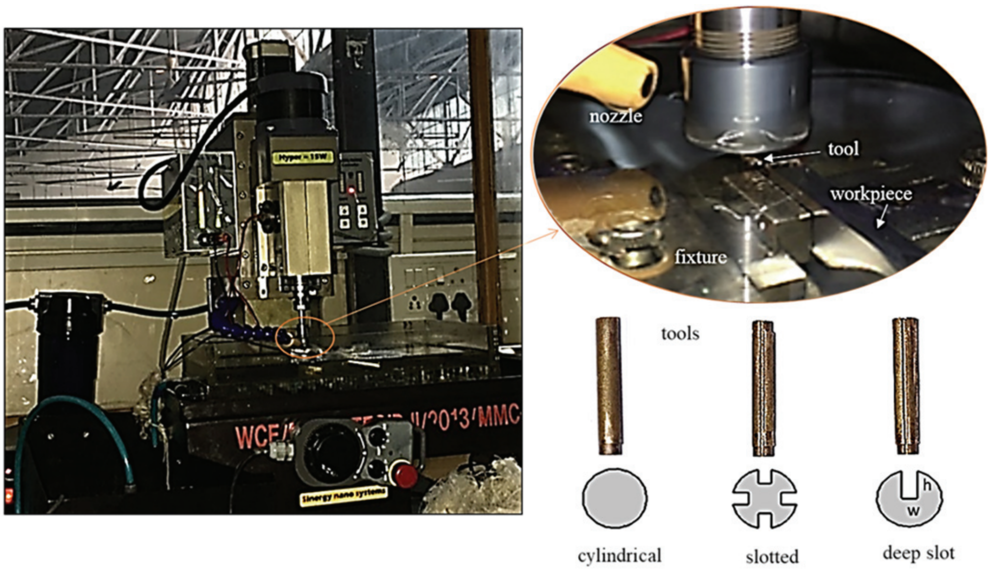


Fig. 3. Experimental setup showing different types of tool.

4. Results and discussion

4.1 Dielectric flow-field

The velocity contour plot shows large variation of velocity in the slot and it is observed that the velocity near the tool surface is maximum. The velocity at the corners of the slot is less due to inability of the dielectric to flow in that region. Fig. 5 shows the velocity vector and the values of the average dielectric velocity in the gap at a tool speed of 800 rpm. The average velocity at the primary gap is greater as compared to secondary gap for all the tools. The dielectric velocity in the gap varies due to slot size and the number of slots. When the number of slots is greater (slotted tool 1), the velocity is minimum due to sudden change in the flow direction of the fluid. The reduction in the number of slots keeping the slot size constant (slotted tool 2) increases the average velocity in the gap. However, increasing the height of slot decreases the average velocity in the gap. In case of slotted tool 4 where the height of slot is considerably more than the width, the average velocity near the workpiece is maximum and it is minimum at the center. The vortex flow is also observed in the slot as shown in Fig. 5.

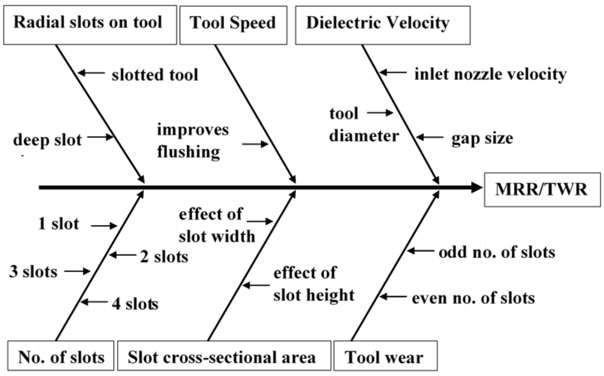


Fig. 4. Cause and effect diagram.

4.2 Debris particles

The time taken by the particles and the percentage of particles removed from the gap for different slotted tools is shown in Fig. 6. Total 28 particles were injected for 10 ms with a velocity of 0.8 m/s normal to the workpiece surface. Few particles were injected to keep track of individual particles and to avoid flooding of particles in the gap. The time taken by the particles from the injection point to move out of the gap outlet was considered as the removal time and was calculated for different tool speeds. It is observed from Fig. 6(a) that with the increase in tool speed the time required to remove the particles from the gap was reduced and it happened for all the tools. This is due to higher dielectric velocity at higher tool speed. Minimum time was taken by slotted tool 2 to remove the particles from the gap at a tool speed of 800 rpm. However, all the particles were not removed from the gap and 10 % of the particles remained in the gap as shown in Fig. 6(b). Among all the tools, slotted tool 4 was able to remove all the particles from the gap irrespective of the tool speed.

4.3 Effect of geometry of the tool

The performance of tool geometric features on the machining performance was analyzed and compared with the cylindrical tool. The comparison of three shapes of the tool is given in

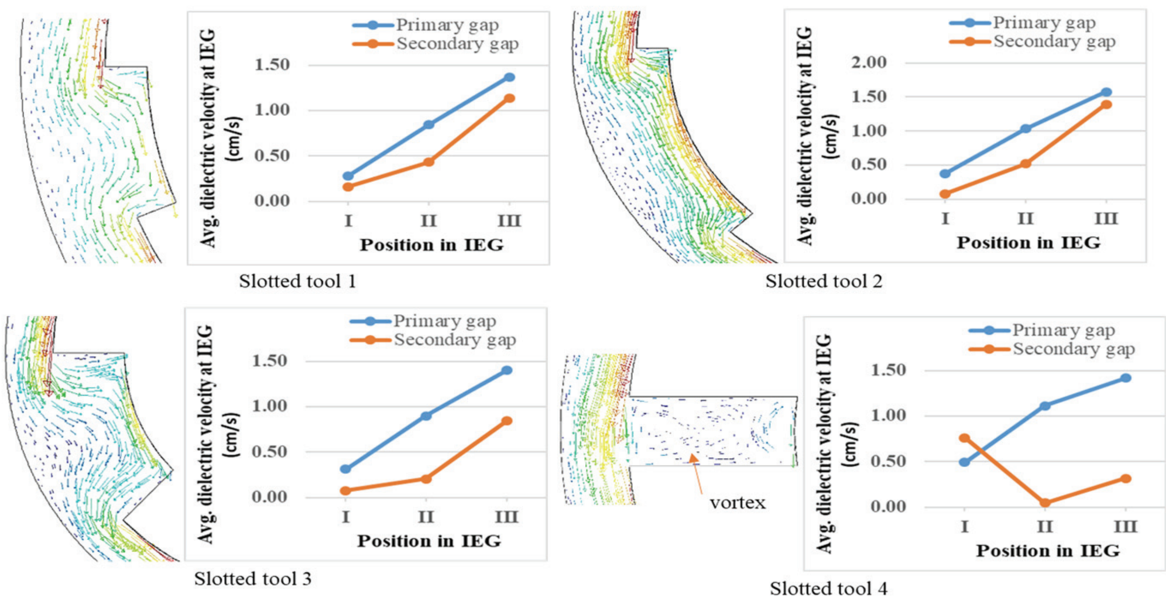


Fig. 5. Vector plot showing dielectric velocity in the slots of various slotted tools.

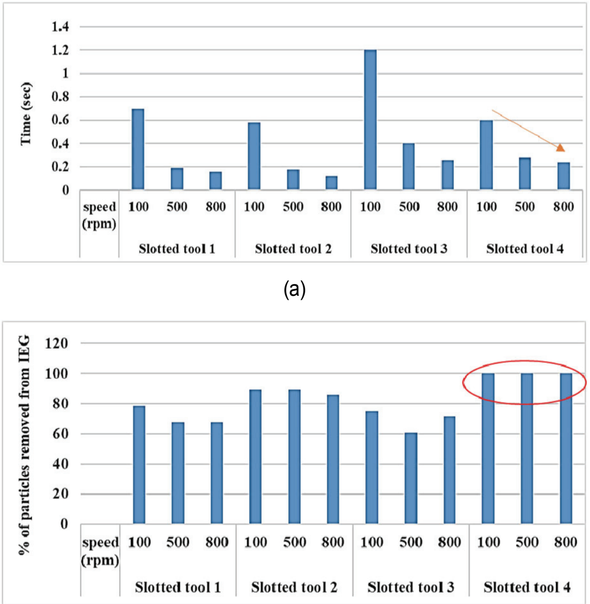


Fig. 6. Plot showing: (a) Time taken by the particles to move out of the gap; (b) percentage of particles removed from the gap for different slotted tools.

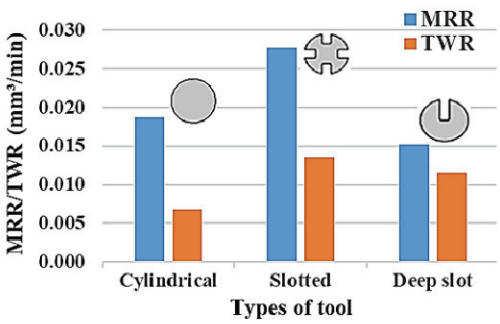


Fig. 7. Effect of the tool shape on MRR and TWR.

Fig. 7. The slotted tool reduced the total cross-sectional area by 25 % that of a cylindrical tool and the deep slot tool reduced the tool cross-sectional area by 15 % that of a cylindrical tool. The MRR and TWR were calculated by the conventional weighing method. The weight differences (in grams) of workpiece and tool before and after the machining were measured using a precision balance. It was observed that the slotted tool overperformed the cylindrical and deep slot tool. The radial slots on the periphery of the tool provide space for the debris to accumulate and eventually flush away due to tool rotation. This enhances the flushing of debris from the gap and improves the MRR. Due to effective flushing, the frequency of spark increases in the gap which led to an increase in the TWR. Also, due to the presence of slots the total area reduced increasing the TWR.

4.4 Effect of number of slots and tool speed

The machining performance was enhanced with the slotted tool and hence further investigation was done to study the effect of the number of radial slots on the MRR and TWR. Fig. 8 compares the MRR and TWR for a various number of radial slots on the periphery of the tool. It was observed that the tool with four slots had maximum MRR as compared to other tools. The MRR for all other tools having one, two and three slots was almost similar but has large variation in TWR. The tool wears with a faster rate for the tools with odd number of slots as compared to MRR. The MRR was higher than the TWR for the tools with even number of slots. An investigation was also carried out to study the effect of tool rotation speed on the machining performance. The slotted tool with four slots which is the best option among all tools was selected with a tool speed of 500 and 800 rpm. The MRR and TWR are given in Fig. 9 and it is observed that with the increase in the tool speed the MRR and TWR increases. This is due to effective flushing of debris from the gap due to higher dielectric velocity in the gap.

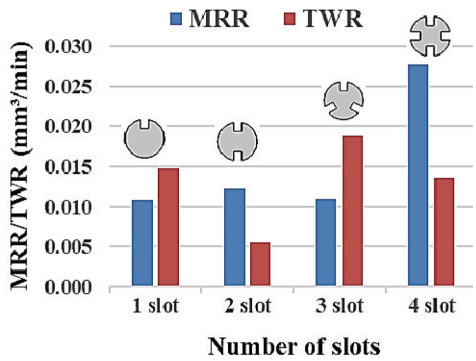


Fig. 8. Effect of number of slots on MRR and TWR.

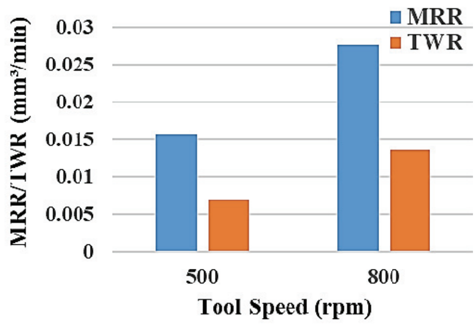


Fig. 9. Effect of tool speed on MRR and TWR using slotted tool.

4.5 Effect of slot width and height

The effect of slot width and height on the MRR and TWR was analyzed by varying the slot width keeping slot height constant and vice-versa. In both the cases, the cross-sectional area of slot (width × height) was constant and was 0.2, 0.3 and 0.4 mm^2, respectively. The effect of slot width and height on the MRR and TWR is represented in Fig. 10. It is observed that the effect of a change in the width of the slot is considerable as

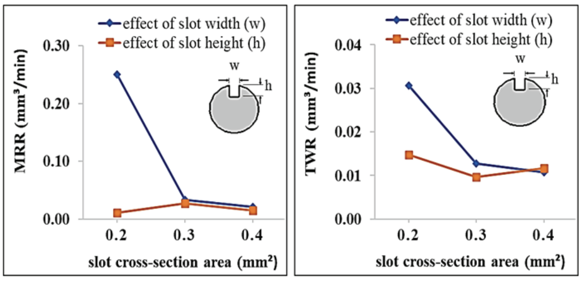


Fig. 10. Effect of slot width and height on MRR and TWR.

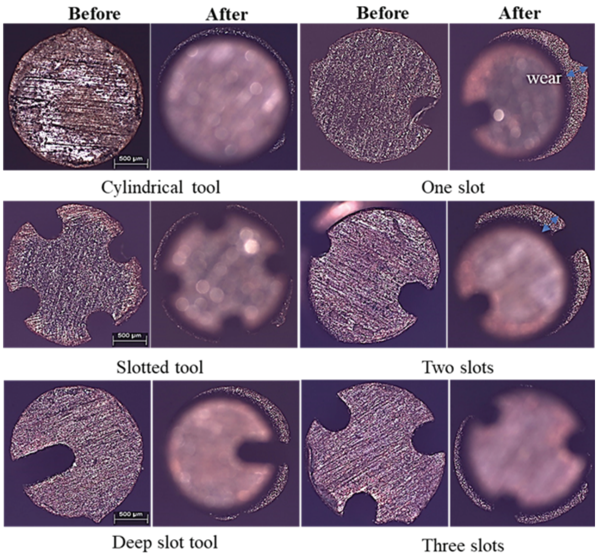


Fig. 11. Microscopic images of the tool cross-section showing the tool wear.

compared to the height on the MRR and TWR. The change in the width of the slot decreases the active peripheral surface facing the workpiece, which generates a spark and removes material. The optimum cross-sectional area of the slot is 0.2 mm^2 with slot width of 0.5 mm and height of 0.4 mm.

4.6 Microscopic study

The images of the cross-section of the tool before and after machining were taken using a metallurgical microscope. The maximum magnification capacity of the microscope is 1000×, but the images were taken at 40× magnification to cover the entire cross-sectional area of the tool. Fig. 11 shows the microscopic images of different tools before and after machining. It is observed that tool wear is uniform along the circumferential surface in case of cylindrical and slotted tool with four slots. While in case of tools with one, two and three slots the wear is not uniform along the circumference. The observation of the tool after machining revealed that the tool wears maximum near the slots. The tool with odd number of slots wore out at a faster rate as compared to the material removed.

Fig. 12 shows the SEM micrograph of the shape and surface topography of the tool surface after machining. The tool wear is

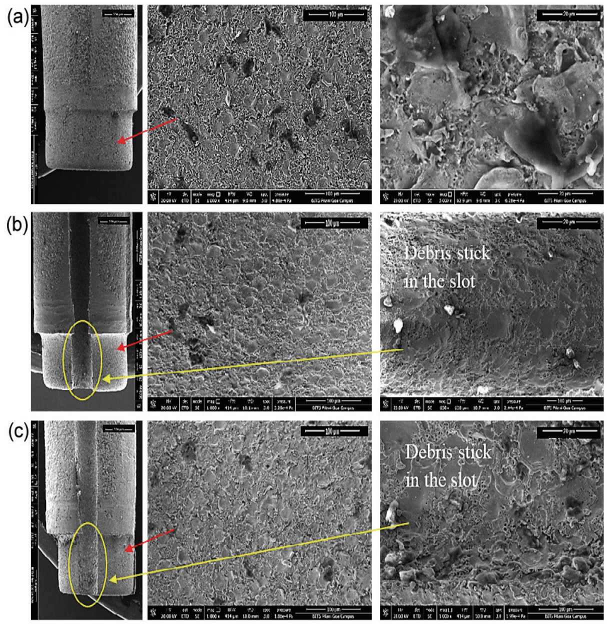


Fig. 12. SEM micrograph morphology of various tools: (a) Cylindrical; (b) deep slot; (c) slotted tool.

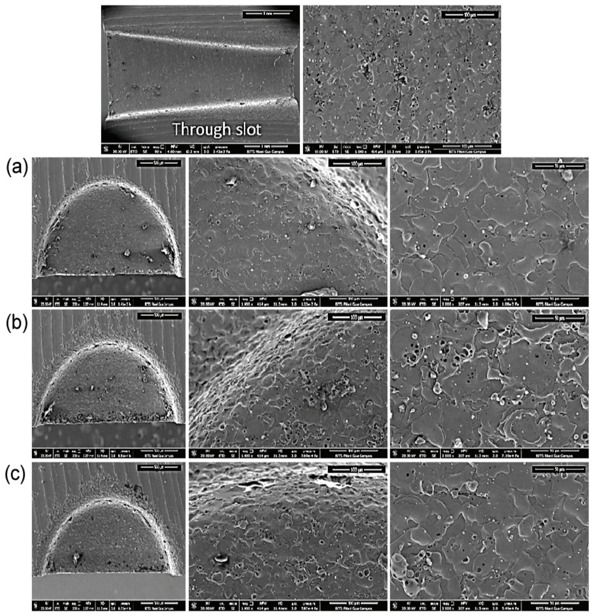


Fig. 13. SEM micrograph morphology of channel surface machined using: (a) Cylindrical; (b) deep slot; (c) slotted tool.

clearly seen after machining the channel in one pass. It is observed that the surface of the cylindrical tool is comparatively rough and many black spots are observed. This black spot may be due to the carbon emitted during machining and gets deposited on the tool surface. The surface of the deep slot and slotted tool is relatively smooth as compared to the cylindrical tool. Very few black spots are visible on the surface of the slotted tool and are smoother than the other two tool surface. This shows that the material removal rate is good using the slotted tool. The slot provided on the surface of the tool drags the debris from the IEG and improves the flushing efficiency. The temperature of the debris is very high and it does not cool rapidly. If these debris are unable to move out of the slot, then it gets stick to the slot surface, which is clearly seen in Fig. 12.

The surface topography of the machined channel using various tools is shown in Fig. 13. Through channel is machined using single slot tool and it is visible in the figure that the channel is tapered. This is due to the wear of tool while machining the channel. It took nearly 2 hours to machine the channel and hence to reduce the time of machining the other channels are machined by traveling a distance of 1 mm in the workpiece. The edges and the surface of the channel machined by slotted tool contain fewer unwanted particles as compared to the surface machined by cylindrical and deep slot tool. At a higher magnification scale, uniformly distributed particles are observed on the machined surface using the cylindrical and slotted tool. Also, the surface is smooth with only a few small pores visible. But the surface machined using deep slot tool shows pores with large size and a greater number of pores. These pores may lead to the generation of cracks. The surface is relatively rough and contains uneven size particles.

5. Conclusion

This study explored the suitability of using slotted tools in comparison to the cylindrical tools towards enhancing the MRR in the ED milling of channels. The following conclusions are drawn:

(1) The CFD analyses of the flow-field gave useful insights into the dielectric and debris movement in the IEG and helped in optimizing the tool geometries. The dielectric velocity in the IEG is the major factor that affects the debris flushing.

(2) The flushing efficiency of slotted tools with four slots was found most effective and was verified experimentally. The reduction of tool cross-sectional area by 25 %, increased the MRR by 150 % as compared to the cylindrical tool. The effect of slot width as compared to slot height was more on the MRR and TWR.

(3) The surface topography of the cylindrical tool shows black spots and relatively rough surface as compared to a slotted tool which shows the inability of the tool to remove the by-products of the machining. The machined channel using slotted tool shows a smooth surface with uniformly distributed particles. These advantages of the slotted tool make it appropriate for ED milling.

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