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ORIGINAL ARTICLE

Experimental investigation on performance of different tool movement strategies in EDM process for boring operation

Sudhanshu Kumar[1] · **Harshit K. Dave**[1] · **Keyur P. Desai**[1]

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Abstract In the present paper, experimental study on boring operation in electro-discharge machining (EDM) has been carried out. Boring operation is used to enlarge internal diameter of a circular cavity. The internal diameter of a predrilled circular cavity has been enlarged using three different tool movement strategies, namely, die-sinking, helical, and radial in EDM process. The effect of all three strategies of EDM process for boring operation has been compared with respect to wear ratio (W_r), overcut (O_c), surface roughness (R_a), and circularity error (E_c). It has been observed that radial orbital strategy of EDM process is best suitable for boring operation in comparison with the other two strategies, as it produced lowest wear ratio with minimum overcut and circularity error.

Keywords EDM · Boring · Die-sinking · Helical · Radial · Orbital-EDM · Wear ratio · Overcut

1 Introduction

Electro-discharge machining (EDM) is a thermoelectric process during which heat energy of spark produced between the electrodes is used to erode materials from electrodes. Material removal in EDM process occurs by a series of sparks between the electrodes submerged in dielectric medium. This dielectric is fed to the working gap under pressure. It cools the tool and washes away eroded particles from workpiece [1]. Being a non-contact type of thermo-erosion process, EDM is not constrained by any mechanical property or complex geometry [2]. The application of EDM process is best suited for machining of hard materials that would be either difficult or ineffective with conventional machining methods. The most common application of EDM process is generating replica of tool shape on workpiece. However, the phenomenon of material removal of EDM process was utilized for other machining operations like drilling [3], milling [4], grinding [5], turning [6], slot generating [7], etc. These operations were performed by introduction of relative movement between tool electrode and workpiece while maintaining spark distance between electrodes. Relative movements between electrodes could be attained either after some modification or after having attachment on die-sinking EDM. If motion of tool electrode is guided and controlled on a specified trajectory, then its movement is termed as orbital tool movement. Rajurkar and Royo [8] studied the effect of orbital tool movement along with RF control in EDM. Authors observed the improvement in surface roughness at lower discharge current. Planetary/orbital movement avoids higher contamination of dielectric fluid in working gap, resulting in uniform distribution of spark and better surface finish. Sanchez et al. [9] used the multi-stage planetary tool movement to optimize the dimensional accuracy and surface roughness of a square cavity in EDM. Linear movement of tool electrode was used to remove the roughness peaks in workpiece. Orbital radius was varied by measuring the roughness peaks after machining. Thus, in multi-stage machining, dimensional target was achieved. Orbital motion of tool electrode was used to remove spikes that remained during drilling of blind hole with a hollow tool [10]. Bamberg and Sumet [11] applied the tool orbiting technique for improvement of surface quality of micro-holes and found that micro-holes by orbital technique produced the better surface quality compared with the non-orbited hole. Bamberg

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✉ Sudhanshu Kumar
sudhanshuk27@gmail.com

[1] Department of Mechanical Engineering, S.V. National Institute of Technology, Surat 395007, India

and Sumet [12] identified different possible tool orbiting strategies, namely, z-slicing, cylindrical slicing, and z-spiral in EDM process. Authors applied z-slicing orbital strategy for experimentations, and it was observed that surface quality and axial tool wear improve in orbiting technique. El Taweel and Hewidy [13] investigated the effect of different modes of orbital strategies, viz., spiral and helical on output, and observed that helical mode of orbiting yielded 43 % more material removal rate as compared with spiral mode. Dave et al. [14] experimentally observed and recommended that machining with helical mode of tool orbiting is effective for machining of Inconel 718. Dave et al. [15] investigated on the effect of orbital parameters on response characteristics using helical mode of tool orbiting while drilling a 10-mm blind hole by EDM process. Authors found that material removal rate was decreasing with increase in orbit radius while orbit radius has negligible effect on tool wear rate. Further, Dave et al. [16] developed a semi-empirical model for predicting material removal rate during orbiting machining in EDM process. The prediction of the model was close with experimental observation, but the developed model was limited for only Inconel 718 material.

In literature, it has been found that there is a possibility to control the tool movement on radial path in EDM process like other orbital path, i.e., z-slicing, cylindrical slicing, z-spiral, helical, etc. Various researchers have used the orbital path such as z-slicing, z-spiral, helical, etc., for several applications such as better feature quality of micro-holes, better dimensional accuracy, removal of spike during machining with tubular tool, and drilling of blind holes, but tool orbiting on radial path has not been applied in EDM process to the best of the authors' knowledge. Hence, an attempt to actuate the tool electrode on radial path in EDM process has been reported in the present work. In addition to controlling the tool movement on radial path, its application has been identified as boring operation in EDM process. Further, the response characteristics of radial tool movement have been compared with other possible methods of boring in EDM process.

To the best of the authors' knowledge, lesser work has been reported on the application of EDM process for boring operation. Boring, also known as internal turning, is used to increase the internal diameter of a hole. Initial hole is made with drill or may be cored during casting process. In conventional machining process, boring is done by milling, drilling, or turning operation. However, the boring operation is limited by the workpiece hole diameter and length. Smaller size of hole reduces the space for radial movement of boring tool and chip evacuation, resulting in poor surface finish and accuracy. Larger length of hole requires longer boring bar which may cause overhanging of boring tool. Extra overhanging of tool significantly reduces the metal removal rate in boring operation. Boring tool in conventional machining process should be harder (than workpiece) and rigid enough to withstand the cutting forces.

Electro-discharge machining process can be used for boring operation of hard materials, as this process is not affected by hardness of material. The dimensional error like overcut or taper, due to vibration and tool rigidity, is one of the major

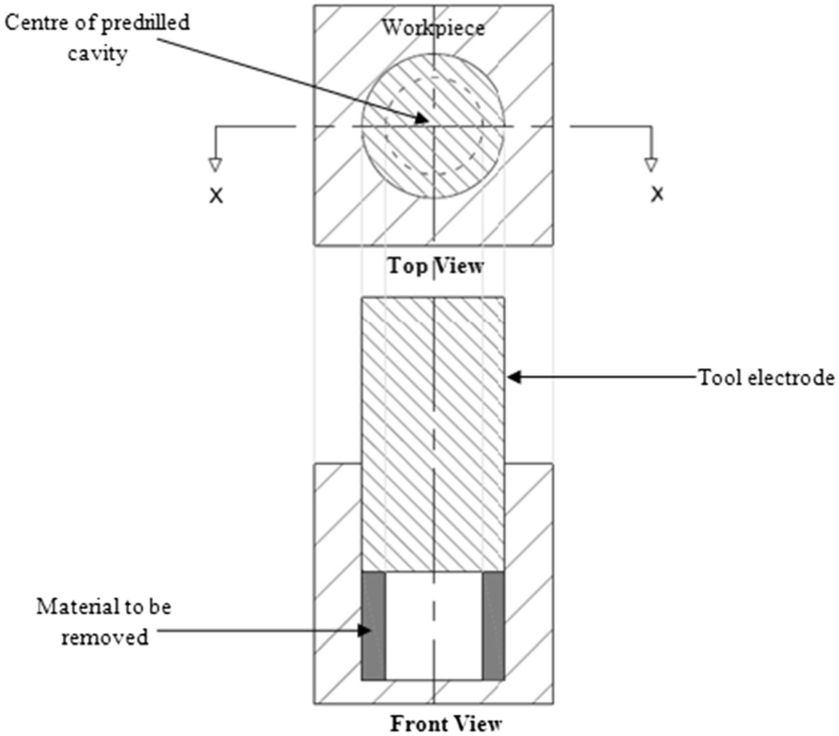


Fig. 1 Schematic diagram of die-sinking tool movement strategy in EDM process

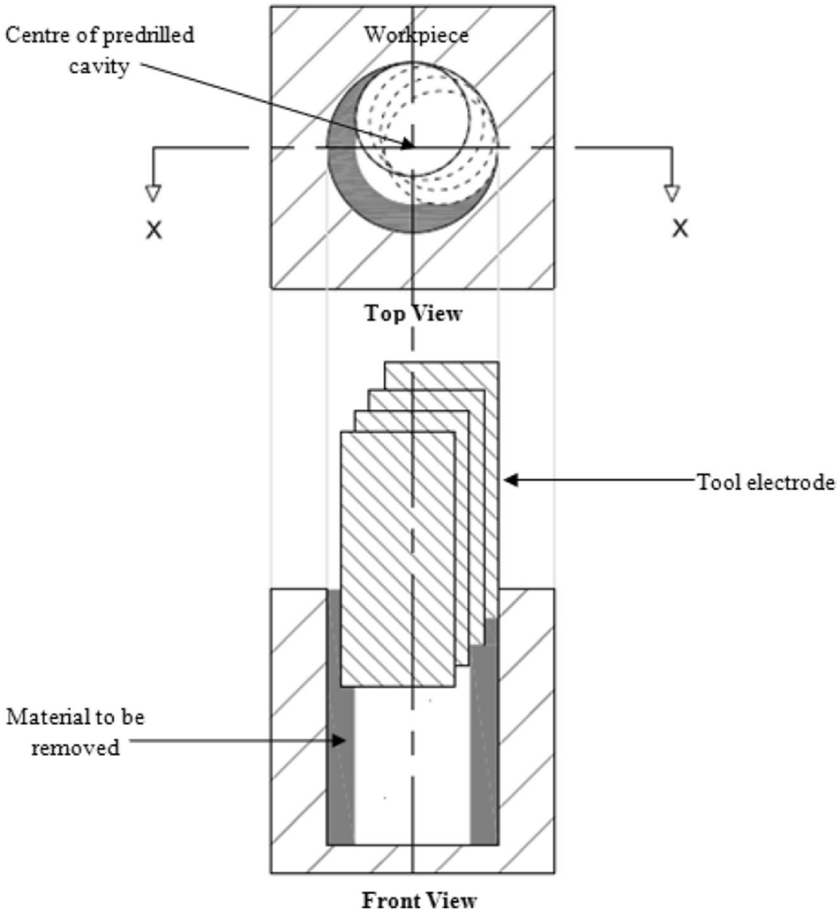


Fig. 2 Schematic diagram of helical orbital strategy in EDM process

problems associated with conventional boring operation and could be reduced within an acceptable range by using EDM process. The non-contact machining nature of EDM eliminates the possibilities of vibrations during machining, and therefore better dimensional accuracy of cavity can be achieved using EDM process. EDM process for boring operation can be applied for any size of cavity with respective size of tool as this machining process is free from force generated during machining.

In the present investigation, boring operation has been performed using EDM process on predrilled blind circular cavities 8.1 mm in diameter and 18 mm deep. Predrilled cavities (8.1 mm) have been enlarged to four different sizes, i.e., 9, 10, 11, and 12 mm in diameter, using three different tool movement strategies in EDM process, namely, die-sinking, helical, and radial. A comparative study has been carried out for the enlargement of drilled hole with respect to wear ratio, surface roughness, overcut, and circularity error.

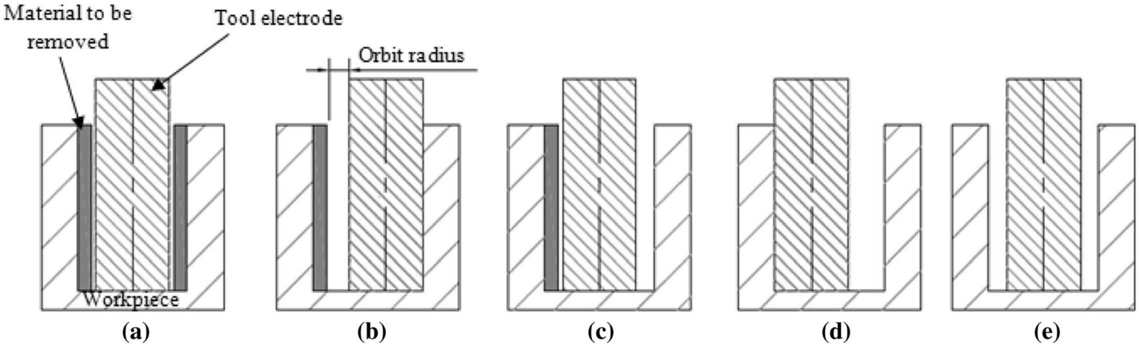


Fig. 3 Front view of the radial orbital strategy: **a** tool electrode at the center of cavity; **b** tool electrode position at the end of the first cut; **c** tool electrode position at 90° with first cut; **d** tool electrode position at 180° from the first cut; **e** tool electrode position at the centre after finishing the cut

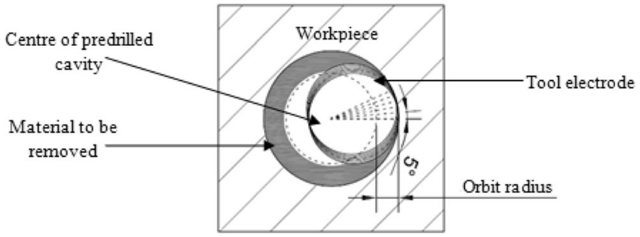


Fig. 4 Top view of the radial orbital strategy in EDM process

2 Tool movement strategies in EDM process for boring operation

In machining, boring is the process of enlarging the hole that has already been drilled by another means. In EDM process, size of circular hole can be enlarged with the help of spark produced between the electrodes. Hole size enlargement or boring operation can be achieved in EDM with three tool movement strategies, i.e., die-sinking, helical tool orbiting, and radial tool orbiting.

In die-sinking tool movement strategy of EDM process, tool electrode is attached with servo mechanism head that helps to maintain a small gap between tool and workpiece. Generally, tool electrode is given only jumping (reciprocating) motion to flush away the eroded particles. In this strategy, cavity is generated with matched tool electrode (as shown in Fig. 1). In the present study, predrilled cavities (8.1 mm) were enlarged to 9, 10, 11, and 12 mm using tool electrodes matched with respective cavity size.

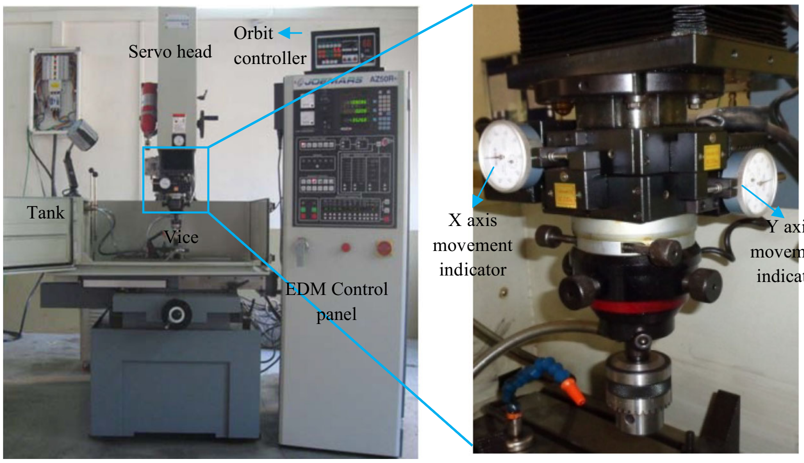
In helical orbital strategy of EDM process, tool electrode is actuating on a circular path with continuously varying depth while moving parallel to the *z*-axis. The helical orbital strategy has been shown in Fig. 2. This movement continues till the required depth is achieved. A single tool electrode with a specified size can generate different size of cavity. The maximum diameter of a circular cavity generated in helical tool path is limited to twice the diameter of the tool electrode used for machining. Boring operation was performed with helical tool movement using a single-diameter (8 mm) tool electrode by increasing the radius of tool movement in cavity. Hence, predrilled circular cavities of 8.1 mm in diameter were enlarged to 9, 10, 11, and 12 mm by setting the orbit radius to 0.5, 1.0, 1.5, and 2.0 mm, respectively.

Tool movement in radial orbital strategy is constrained in one plane only, and its motion in the vertical z direction is restricted. The various stages of machining with radial orbital strategy in EDM process is shown in Fig. 3. Initially, tool electrode is plunged to the bottom of the cavity (Fig. 3a) and then it is allowed to travel in the X-Y plane on a linear path. Tool electrode moves from the center of the cavity toward the wall of the cavity, as shown in Fig. 3b). Tool electrode returns to its initial position after achieving a specified dimension of cut. Next, movement of tool electrode is defined at a 5° increment in anti-clockwise direction with the preceding tool path. On repeating this movement, a complete circle is traced in 72 movements of the tool in a cavity as described in Fig. 4. Tool movement is guided by two-stepped motors (axis are perpendicular to each other) attached with the tool holder, and these motors are controlled with an orbit controller where dimension of cut and speed of tool movement can be selected.

3 Experimental details

Boring operation has been performed on Joemars AZ50R EDM machine (as shown in Fig. 5) with orbit cut attachment that guides the tool electrode on the helical and radial path during machining. The workpiece material used for experiments was austenitic stainless steel AISI 304 steel with dimension of 20 mm × 10 mm × 20 mm. To study the machined surface of cavity, split workpiece was used. Two workpieces were clamped together, and the initial hole of 8.1 mm in diameter was drilled at the parting line of the clamped work pieces as shown in Fig. 6. Further, these drilled holes were used for

Fig. 5 Experimental setup



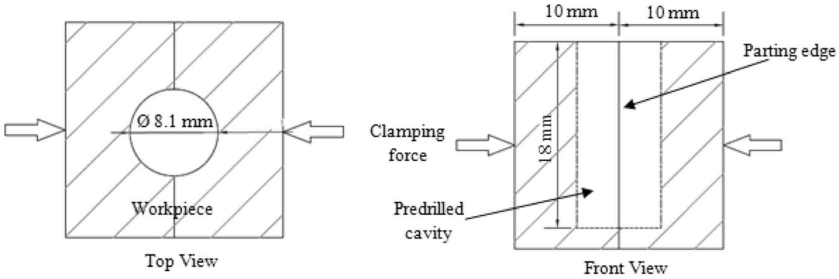


Fig. 6 Schematic diagram of workpiece arrangement

boring operations. Electrolytic copper material was taken for tool electrode preparation; copper rod turned into 8, 9, 10, 11, and 12 mm in diameter. Tool electrode of 8 mm was used in helical and radial orbital EDM process for generating different diameter sizes of holes whereas tools having 9, 10, 11, and 12 mm diameters were used in die-sinking EDM process for generating respective matched size of hole. Positive polarity of tool electrode has been employed for machining, as literature suggests that positive polarity yields higher removal rate [17].

Input parameters were selected through literature [18] and user manual of Joemars AZ50R EDM machine. Table 1 represents the values of parameters selected in present experiments. Each experiment was repeated twice under the same condition, and average value of each experiment was taken.

During EDM process, the important response parameters were wear ratio (W_r), surface roughness (R_a), overcut (O_c), and circularity error (E_c).

Material removal from workpiece and tool was expressed in wear ratio (W_r). It is the ratio of volume of material removed from tool electrode in unit time to the volume of material removed from workpiece in unit time. Mathematically, it is expressed as given in Eq. 1:

$$W_r = \frac{(W_{t_b} - W_{t_a}) \times \rho_w}{(W_{p_b} - W_{p_a}) \times \rho_t}$$

$$\begin{aligned} \text{where,}\ W_{p_b} &= \text{weight of workpiece before machining} \\ W_{p_a} &= \text{weight of workpiece after machining} \\ W_{t_b} &= \text{weight of tool before machining} \\ W_{t_a} &= \text{weight of tool after machining} \\ \rho_t &= \text{density of tool material} \\ \rho_w &= \text{density of workpiece material} \end{aligned} \tag{1}$$

Surface roughness was measured using Mitutoyo SJ-400 surface roughness tester (as shown in Fig. 7a). It is quantified by the vertical deviations of a real surface from its ideal form. The arithmetic mean of the deviations of surface (R_a) was used to evaluate the surface roughness. Each R_a value was obtained by averaging six measurements at different locations in the cavity.

Overcut in boring operation is defined as the gap between machined cavity and targeted bore radius, as shown in Fig. 8. It is mathematically expressed as shown in Eq. 2:

$$\begin{aligned} \text{Overcut } (O_c) &= \frac{D_a - D_t}{2} \\ \text{where, } D_t &= (2 \times S_r) + t \\ D_a &= \text{Actual cavity diameter}, \quad D_t = \text{Targeted bore diameter} \\ S_r &= \text{Orbit radius}, \quad t = \text{Tool diameter} \end{aligned} \tag{2}$$

In the case of die-sinking EDM process, orbit radius (S_r) became zero.

Circularity is defined as a condition which states that all data points lying on a plane perpendicular to the axis should be equidistant from the axis [19]. The data points were obtained from actual measurement of the hole (cylinder) using vision measuring system (VMS) of 3 μm accuracy (as shown in Fig. 7b). Using the least squares circle (LSC) method, a circle was fitted to the profile. The center of that circle was used to fit the smallest circumscribed and the largest inscribed circles to the profile. The radial difference between these two circles was used as a measure of circularity error (E_c) as shown in Fig. 9.

Table 1 Experimental condition for boring operation

Parameters	Description
Workpiece material	AISI304
Tool electrode material	Copper
Tool polarity	Positive
Open circuit voltage	170 V
Peak current	13 A
Pulse on time	195 μs
Pulse off time	85 μs
Spark gap	62 V
Orbital speed	0.13 mm/s
Flushing time	0.267 s
Machining time	0.667 s
Machining depth	18 mm

Fig. 7 Measuring equipments. **a** Surface roughness tester. **b** Vision measurement system

(a) **(b)**

4 Results and discussion

4.1 Wear ratio (W_r)

The effect on wear ratio (W_r) with variation of bore diameter under different tool movement strategies in EDM process is shown in Fig. 10. The bar diagram is plotted between wear ratio (W_r) on the vertical axis and bore diameters on the horizontal axis. From Fig. 10, it can be observed that minimum wear ratio (W_r) was obtained with radial orbital strategy whereas maximum wear ratio (W_r) was observed with helical orbital strategy in EDM process. In case of the die-sinking tool movement strategy, wear ratio (W_r) was observed as maximum at lower bore diameter and decreases with increase in bore diameter of cavity for die-sinking EDM process. Similar results have been reported (in die-sinking strategy) by Kiyak et al. [20] in terms of material removal rate and percentage tool wear rate. Material removal rate was reported increasing with increase in tool diameter, and percentage tool wear rate was decreasing with increase in tool diameter.

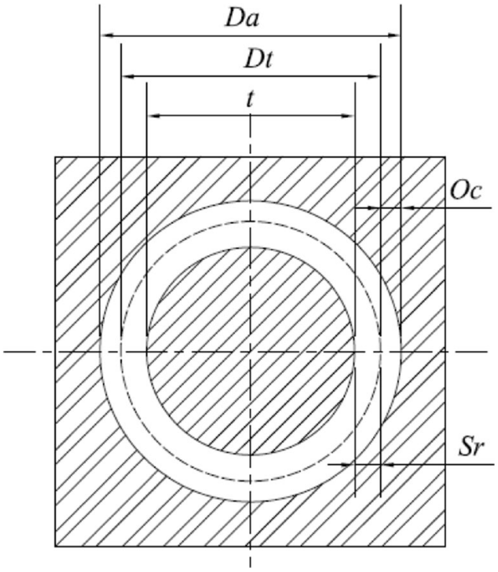


Fig. 8 Top view of a bored cavity with related geometric dimensions

Material removal in EDM process takes place due to intense heat produced by a series of sparks between the electrodes. High temperature leads to melting and vaporization of material from workpiece as well as from the tool electrode. Radial orbital strategy in EDM process produced lower wear ratio (W_r) than the other two strategies. Wear ratio (W_r) for smallest bore diameter with die sinking and helical orbital strategy was 95 and 94 %, respectively, more than that with radial orbital strategies in EDM process. This indicates that volume of material removed from workpiece is much higher than that from tool electrode during radial orbital strategy. Lower tool wear for removal of the same volume of workpiece may be responsible for the lower wear ratio for radial orbital strategy in EDM process. Radial orbital strategy in EDM process involved tool movement in only the X-Y plane; i.e., its movement in the vertical direction was restricted. Therefore, machining occurred due to horizontal movement of tool electrode and major portion of workpiece was cut due to the sparking at the cylindrical surface of tool electrode. This prevents the sharp edge of tool electrode from excessive wear. On the contrary, in the case of die-sinking and helical orbital strategy, wear at the edge of tool electrode was greater than that in radial orbital strategy, which increases the wear ratio (W_r). Figure 11 clearly shows that wear along the edge of tool

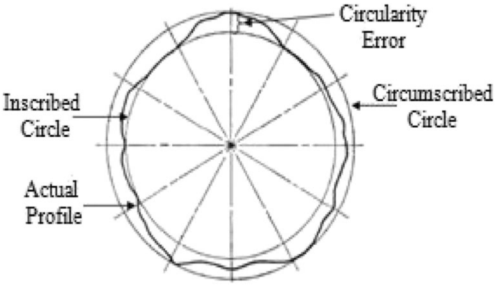


Fig. 9 Theoretical sketch for circularity error

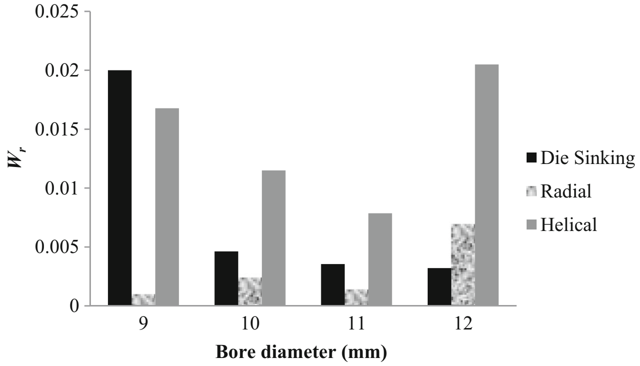


Fig. 10 Wear ratio versus bore diameter for different tool movement strategies in EDM process

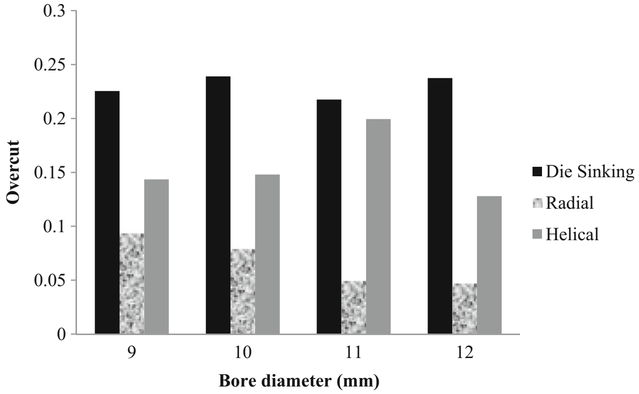


Fig. 12 Overcut versus bore diameters for different tool movement strategies in EDM process

electrode is higher for helical and die-sinking strategies than that for radial orbital strategy in EDM process.

Wear ratio (W_r) was observed higher at higher bore diameter (12 mm) under radial orbital strategy than that of die-sinking strategy in EDM process. At higher bore diameter, tool electrode (8 mm diameter) has to remove larger volume of material, by increasing orbit radius, which increased the tool wear in radial orbital strategy and in turn increased the wear ratio. Die sinking strategy in EDM process used matched size of tool electrode with cavity size. Therefore, for larger cavity size, die-sinking strategy required larger tool electrode. Larger cross-sectional area of tool electrode bears lesser tool wear due to a reduction in the ratio of edge wear to the surface wear obtained [21].

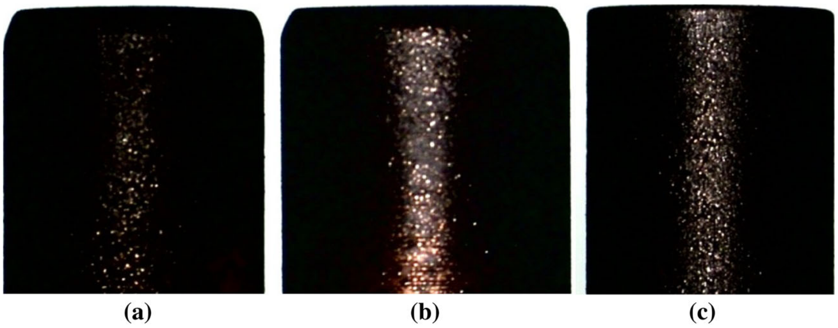
Wear ratio in the case of helical orbital strategy remained higher in comparison to other two tool movement strategies in EDM process. This was possibly due to excessive wear at the edge of tool electrode. Owing to the nature of tool movement in helical EDM process, mainly bottom side edge of tool involves during machining that leads to concentrate wear at edge of tool electrode. The results observed in the present investigation are slightly different from those reported by Dave et al. [15] who observed a decreasing trend of MRR with negligible change in TWR during drilling of the 10-mm blind hole with helical tool orbiting or in other words increasing wear ratios with orbit radius. This could be probably be due to the difference in the geometry of the workpiece used. In the present work, the workpiece with a predrilled hole is used, whereas Dave et al. [15] have used a solid workpiece.

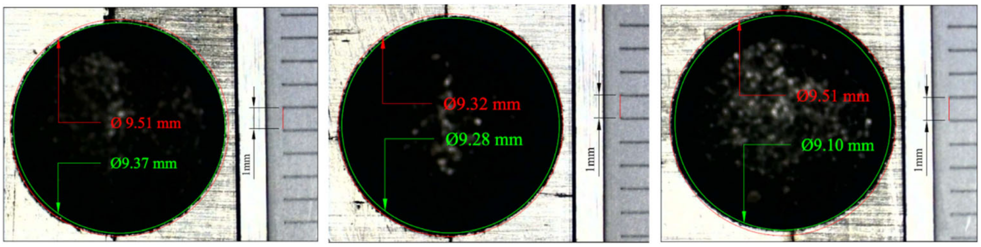
4.2 Overcut (O_c)

Figure 12 represents the effect of bore diameters on overcut of the cavities generated using different tool movement strategies in EDM process. It is clear that cavities that were enlarged using radial orbital strategy in EDM process have resulted lowest overcut for all bore diameters. Overcut measured at 9 mm bore diameter, and radial orbital strategy resulted 58 and 35 % lower in comparison with that of die-sinking and helical orbital strategies in EDM process, respectively. Maximum overcut was observed for lower bore diameter (smaller gap between tool and workpiece), and further increase in bore diameter decreased the overcut of the cavity. At 12 mm bore diameter, radial orbital strategy in EDM process produced minimum overcut.

Generally, overcut occurs due to the secondary sparks generated due to the presence of impurities or debris in the gap between tool electrode and workpiece while it is being flushed out by the dielectric fluid. As the debris is flushed out, it generates secondary sparks between itself and the side wall of the cavity being machined. A similar observation has been reported by Yu et al. [22]. During die-sinking EDM, a minimum gap is maintained between the entire tool periphery and

Fig. 11 Edge wear of tool electrode for 9 mm bore diameter in **a** helical orbital; **b** die-sinking; and **c** radial orbital strategy in EDM





(a) **(b)** **(c)**

Fig. 13 Circumscribed and inscribed circles on cavity generated using **a** die-sinking; **b** radial orbital strategy; and **c** helical orbital strategy in EDM

the cavity surface throughout the process. As a result, when deep holes are drilled, the overcut increases all across the cavity surface. However, when tool is moved on a helical path, the minimum distance between tool periphery and cavity surface is not maintained continuously just as in die-sinking process. Tool electrode removes material while moving on the helical path. The point of minimum distance keeps on changing continuously and hence the scope of generation of secondary sparks also reduces. During radial orbital strategy, tool electrode moves radially outwards and material removal takes place till the final position is achieved. The tool electrode retracts back to initial position, and then the forward movement is initiated at an increment of 5° from the previous movement. Thus, the scope of sparking at previously machined surface is highly reduced. Moreover, during helical and radial tool movement, the tool kinematics results into better flushing due to more space available. Thus, overcut observed under radial orbital strategy was least followed by helical orbital strategy.

4.3 Circularity error (E_c)

Circularity error represents the maximum deviation of a circular profile from a perfect circle. Figure 13 shows the circumscribed and inscribed circle for a typical sample. Figure 14 shows the variation of circularity error with the bore diameters for the machined cavities generated with different tool movement strategies in EDM process. Circularity error decreased with increase in bore diameter with radial orbital strategy. Initially, maximum circularity error was found with helical strategy and starts reducing with increase in bore diameter up to 11 mm. In the case of the die-sinking machining strategy, initially circularity error is found at minimum and starts increasing with increase in bore diameter up to 11 mm. Among all three machining strategies, radial orbital strategy yielded minimum circularity.

Dimensional accuracy of any cavity generated by EDM process depends on effective flushing, stable machining, or debris ejaculation. Effective flushing plays an important role in maintaining stable sparking during machining by avoiding accumulation of debris in electrode gap. Presence of debris in electrode gap changes the radial gap because of secondary sparking [23], and this leads to the dimensional error in machined cavity. The contamination of working gap with eroded particles also leads to the unstable machining in EDM process [24]. The presence of debris in spark gap intensifies the discharge phenomenon because some abnormal material removal happened, and this increased the circularity error. It is worth noting that circularity error seems to be improving with the use of orbital strategies. Similar observation has been reported by researchers El-Taweel and Hewidy [13].

4.4 Surface roughness (R_a)

Surface produced in EDM process is a result of randomly distributed pattern of craters and its boundaries, cracks, and re-solidified layers. Figure 15 shows the average roughness value R_a measured at the machined cavities produced under

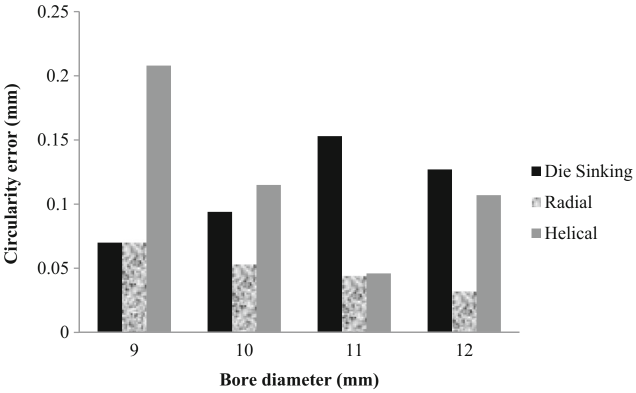


Fig. 14 Circularity errors versus bore diameters for different tool movement strategies in EDM process

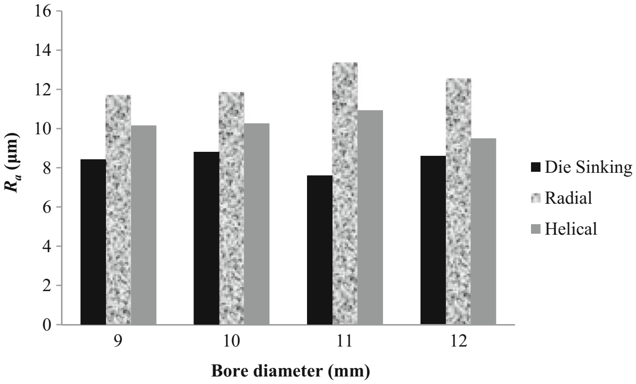


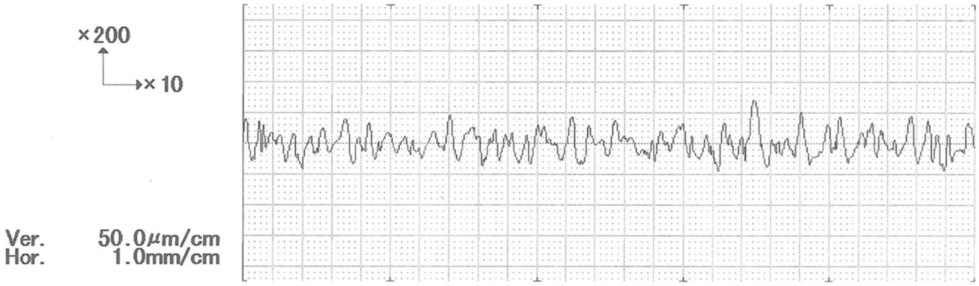
Fig. 15 Surface roughness versus bore diameters for different tool movement strategies in EDM process

different tool movement strategies in EDM process. It indicates that surface roughness value R_a is relatively lower for die-sinking strategy than that for helical and radial orbital strategies in EDM process. Machined surfaces generated from die-sinking strategy shows minimum R_a value, whereas maximum R_a value is observed on cavities generated by radial orbital strategy. In radial orbital strategy, surface roughness is found to be increasing with increase in bore diameter up to 11 mm and further increment in bore diameter decreased the surface roughness. Further, little variation in surface roughness with change in bore diameter was observed in helical orbital strategy. Similar results have been reported by Dave et al. [14].

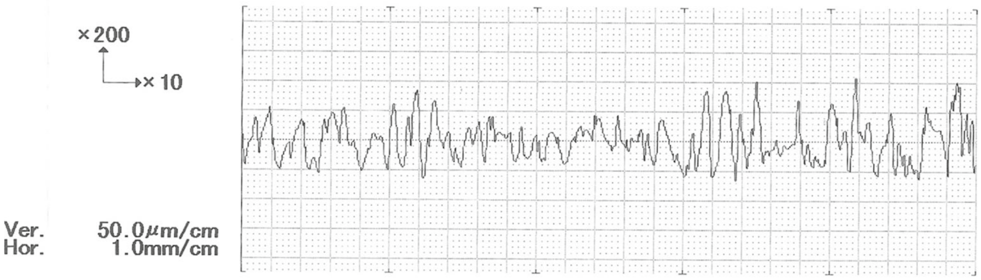
Typical surface roughness profiles are shown in Fig. 16.

The reason for lower surface roughness with die-sinking strategy in EDM process is generation of re-solidified layer over machined surface. Re-solidified layers were formed due to the deposition of molten particles that were not ejected after sparks. If molten material was not allowed to be removed quickly, it got deposited over the surface again. The effectiveness of flushing decides the removal of molten materials as well as formation of re-solidified layers [25]. Due to rapid heating and cooling of a recast layer, some micro-cracks were generated on the machined surface [26]. As shown in Fig. 17 a, random distribution of micro-cracks could be observed over the entire machined surface. This indicates that the recast layers deposited have been formed over the entire surface in die-sinking EDM process, and due to this, shallower craters were observed. These shallower craters are responsible for relatively lower surface roughness. The effect of flushing in radial and helical orbital strategies in EDM process was better than that in the die-sinking strategy because tool was continuously changing its position. This resulted to a faster removal of molten material from surface resulting into the formation of deeper craters. This could be clearly seen in Fig. 17b, c; it is also worth noting that the boundaries of the micro-craters formed on the surface which are generated under helical and radial orbital strategies are slightly projected upward resulting into the formation of ring-like structures. The unevenness caused by these structures may result into higher surface roughness.

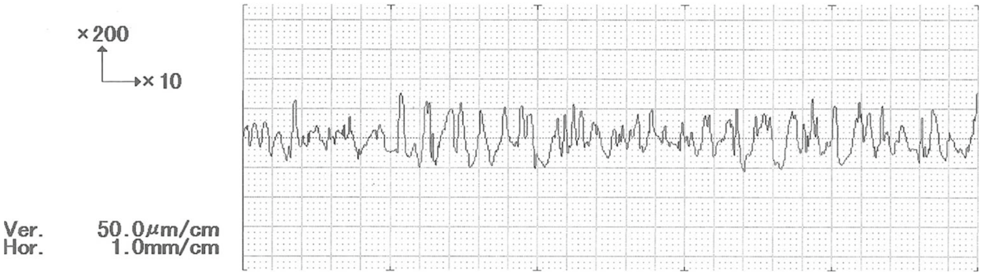
Fig. 16 Surface roughness plots observed on machined surface under 11 mm bore diameter



(a) Surface roughness plot of EDM machined surface generated using die-sinking strrategy



(b) Surface roughness plot of EDM machined surface generated using radial orbital strategy



(c) Surface roughness plot of EDM machined surface generated using helical orbital strategy

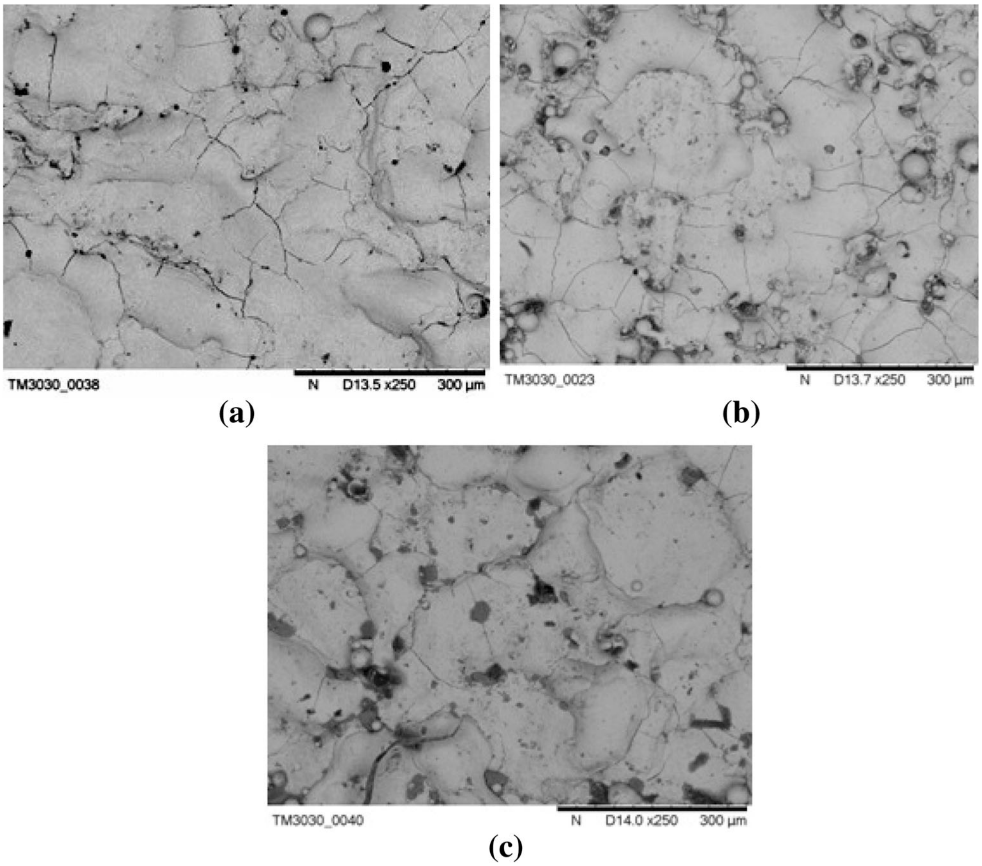


Fig. 17 SEM image of surface generated by **a** die-sinking; **b** helical orbital; and **c** radial orbital tool movement strategies in EDM Process

5 Influence of tool movement strategies in EDM process on machined cavities

The effect of different tool movement strategies in EDM process on quality of machined hole was studied using VMS at ×35 magnification. Ideally, blind cavity should have zero curvature of radius at the bottom surface as shown in Fig. 18a. In actual machining condition, there is presence of curvature between the vertical and horizontal surface which indicates that some materials were left uncut as shown in Fig. 18b.

Figure 19 shows the cross-sectional views of the machined cavities. Curvature at the bottom of the cavity was observed. Maximum corner radius (4.09 mm) was observed in cavity generated with helical orbital strategy in EDM process, and minimum corner radius was observed in the cavity generated with radial orbital strategy. The corner radii were observed as increasing with increase in bore diameter in helical orbital strategy. Curvature at the bottom surface of a cavity is due to the edge wear of tool electrode. The cavity generated in EDM process is the replica of tool shape, and the shape of tool electrode is degenerated in the course of machining which affects the shape of cavity. In the case of helical orbital strategy, tool movement follows the helical path in which machining is done mainly with the edge of tool electrode. Therefore, wear on the edge of tool occurred more than that in die-sinking and radial orbital strategies in EDM process. With the increase in bore diameter, tool wear became worse because more material has to be removed by the same tool electrode. Relatively smaller radius of curvature, varying between 0.39 to 0.70 mm, observed in cavities is generated with radial orbital strategy in EDM process. The result indicates that the edge wear on the tool electrode with radial orbital strategy in EDM process was relatively lower than that in die-sinking and helical orbital strategies in EDM process. This could be explained by the movement of tool electrode during radial orbital strategy in EDM process. In radial orbital strategy, tool electrode only actuates on the horizontal path and its motion in the vertical direction is restricted; therefore, mainly the cylindrical surface of tool is engaged in machining. So, this prevents the

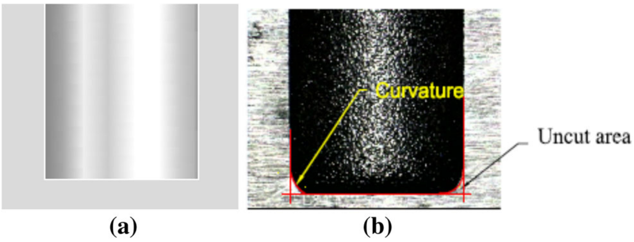


Fig. 18 Cross-sectional view of workpiece. **a** Ideal blind cavity. **b** Actual machined cavity with curvature

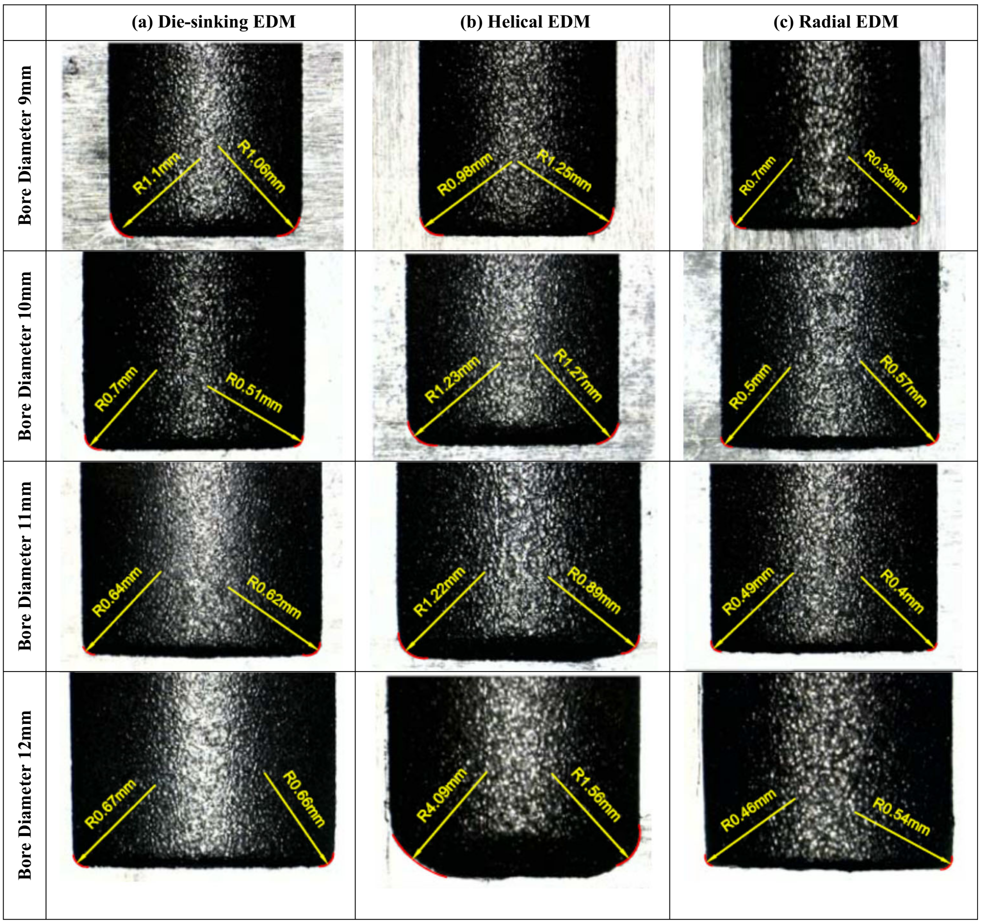


Fig. 19 Cross-sectional image of cavity generated by **a** die-sinking; **b** helical orbital; and **c** radial orbital tool movement strategies in EDM process

excessive wear on the tool's edge and resulted smaller curvature radius at the bottom of cavity.

6 Conclusions

In this experimental investigation, the suitability of three different tool movement strategies in EDM process, namely, die-sinking, helical, and radial orbital strategies, is assessed for boring operation with respect to wear ratio (W_r), overcut (O_c), circularity error (E_c), and surface roughness (R_a). The following conclusions can be made from obtained results:

1. Radial orbital strategy in EDM process proves its capability for boring operation in generating circular cavities with better feature tolerances with same tool electrode.
2. Wear ratio (W_r) obtained for all the three tool movement strategies in EDM process is lowest for radial orbital strategy and is 95 and 94 % less than that of die-sinking and helical orbital strategies in EDM process respectively for 9 mm bore diameter.
3. Negligible edge wear on tool electrode was observed in radial orbital strategy in EDM process whereas maximum edge wear was found in helical orbital strategy in EDM process.
4. Overcut is measured at 9 mm bore diameter, and radial orbital strategy has resulted 58 and 35 % lower than that of die-sinking and helical orbital strategies in EDM processes, respectively.
5. Radial orbital strategy in EDM process generated circular cavity with minimum circularity error.
6. Die-sinking strategy in EDM process generated cavities with lower surface roughness than radial and helical orbital strategies in EDM process.
7. The cavity generated with radial orbital strategy in EDM process has minimum radius of curvature at the bottom surface.

The research finding explores the possibilities of the application of different tool movement strategies in EDM process for boring operation. Radial orbital strategy in EDM process can be applied for enlargement of predrilled cavity with great tolerance. The remarkable benefits of using radial orbital strategy in EDM process for boring operation is reduction in tooling cost. Same tool electrode can be used for generation of large cavity. This process has tremendous potential on account of its applications, and it is expected that it will be successfully and commercially utilized in modern industries.

References

1. Jain VK (2012) Advance machining processes. Allied Publishers Pvt. Limited, New delhi
2. Kumar H, Davim JP (2011) Role of powder in the machining of Al-10% SiCp metal matrix composites by powder mixed electric discharge machining. J Composite Mater 45(2):133–151
3. Ferraris E, Castiglioni V, Ceyssens F, Annoni M, Lauwers B, Reynaerts D (2013) EDM drilling of ultra-high aspect ratio micro holes with insulated tools. CIRP Annals - Manuf Technol 62(1): 191–194. doi:10.1016/j.cirp.2013.03.115
4. Karthikeyan G, Ramkumar J, Dhamodaran S, Aravindan S (2010) Micro electric discharge milling process performance: an experimental investigation. Int J Mach Tools Manuf 50(8):718–727. doi:10.1016/j.ijmachtools.2010.04.007
5. Lee E-S, Ahn S-O (1999) Precision surface grinding of Mn–Zn ferrite with in-process electro-discharge dressing (IEDD). Int J Mach Tools Manuf 39(10):1655–1671. doi:10.1016/S0890-6955(99)00016-4
6. Song KY, Chung DK, Park MS, Chu CN (2013) EDM turning using a strip electrode. J Mater Process Technol 213(9):1495–1500. doi:10.1016/j.jmatprotec.2013.03.005
7. Ayesta I, Izquierdo B, Sánchez JA, Ramos JM, Plaza S, Pombo I, Ortega N, Bravo H, Fradejas R, Zamakona I (2013) Influence of EDM parameters on slot machining in C1023 aeronautical alloy. Procedia CIRP 6:129–134. doi:10.1016/j.procir.2013.03.059
8. Rajurkar K, Royo G (1989) Effect of RF control and orbital motion on surface integrity of EDM components. J Mech Working Technol 20:341–352
9. Sanchez JA, Lopez de Lacalle LN, Lamikiz A, Bravo U (2006) Study on gap variation in multi-stage planetary EDM. Int J Mach Tools Manuf 46(12–13):1598–1603. doi:10.1016/j.ijmachtools.2005.09.012
10. Gu L, Li L, Zhao W, Rajurkar KP (2012) Electrical discharge machining of Ti6Al4V with a bundled electrode. Int J Mach Tools Manuf 53(1):100–106. doi:10.1016/j.ijmachtools.2011.10.002
11. Bamberg E HS, Jorgensen JD Flexural micro-EDM head for increased productivity of micro-holes. In: ASPE Conference, Norfolk, 2005. pp 82–85
12. Bamberg E, Heamawatanachai S (2009) Orbital electrode actuation to improve efficiency of drilling micro-holes by micro-EDM. J Mater Process Technol 209(4):1826–1834. doi:10.1016/j.jmatprotec.2008.04.044
13. El-Taweel T, Hewidy M (2009) Enhancing the performance of electrical-discharge machining via various planetary modes. Int J Mach Mach Mater 5(2–3):308–320
14. Dave H, Desai K, Raval H (2012) Experimental investigations on orbital electro discharge machining of Inconel 718 using Taguchi technique. Int J of Mod Manuf Technol 4(1):53–58
15. Dave HK, Desai KP, Raval HK (2013) A Taguchi approach-based study on effect of process parameters in electro discharge machining using orbital tool movement. Int J Mach Mach Mater 13(1):52–66
16. Dave HK, Desai KP, Raval HK (2013) Development of semi empirical model for predicting material removal rate during orbital electro discharge machining of Inconel 718. Int J Mach Mach Mater 13(2–3):215–230
17. Torres A, Luis C, Puertas I (2015) Analysis of the influence of EDM parameters on surface finish, material removal rate, and electrode wear of an INCONEL 600 alloy. Int J Adv Manuf Technol:1–18
18. Dave HK DK, Raval HK (2011) Effect of the orbital tool movement on the material removal rate during electro discharge machining. In: Advances and Trends in Engineering Materials and their Applications, Montreal, Canada, 2011. Montreal, Canada, pp 365–370
19. Dimensioning and Tolerancing: ASME Y14.5M-1994 (1995). ASME,
20. Kiyak M, Aldemir B, Altan E (2015) Effects of discharge energy density on wear rate and surface roughness in EDM. Int J Adv Manuf Technol 79(1–4):513–518. doi:10.1007/s00170-015-6840-9
21. Sohani MS, Gaitonde VN, Siddeswarappa B, Deshpande AS (2009) Investigations into the effect of tool shapes with size factor consideration in sink electrical discharge machining (EDM) process. Int J Adv Manuf Technol 45(11–12):1131–1145. doi:10.1007/s00170-009-2044-5
22. Yu ZY, Rajurkar KP, Shen H (2002) High aspect ratio and complex shaped blind micro holes by micro EDM. CIRP Annals Manuf Technol 51(1):359–362. doi:10.1016/s0007-8506(07)61536-4
23. Jia Z, Zheng X, Wang F, Liu W (2011) Radial gap measurement and manufacturing error evaluation for small hole machined by micro-EDM. Int J Manuf Technol Manag 22(2):94–106
24. Valentincic J, Kuser D, Smrkolj S, Blatnik O, Junkar M (2007) Machining parameters selection for varying surface in EDM. Int J Mater Prod Technol 29(1–4):344–357
25. Lin Y-C, Lee H-S (2008) Optimization of machining parameters using magnetic-force-assisted EDM based on gray relational analysis. Int J Adv Manuf Technol 42(11–12):1052–1064. doi:10.1007/s00170-008-1662-7
26. Zhang Y, Liu Y, Ji R, Cai B (2011) Study of the recast layer of a surface machined by sinking electrical discharge machining using water-in-oil emulsion as dielectric. Appl Surf Sci 257(14):5989–5997. doi:10.1016/j.apsusc.2011.01.083