The state of the art of electrical discharge drilling: a review

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Received: 13 January 2022 / Accepted: 15 June 2022 / Published online: 2 July 2022
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Abstract
Electrical discharge machining (EDM) is one of the most widely used non-conventional methods to machine electrically conductive materials in the manufacturing industry because of its strong capability in machining difficult-to-cut materials irrespective of their strength and hardness. Electrical discharge drilling (EDD) is an important variant of EDM. Due to the limitation of conventional drilling processes, special holes, particular those with high aspect ratios on hard-to-cut materials, can only be drilled by EDD. Extensive research has been carried out to improve the efficiency and quality of the EDD process by using different approaches, such as assisted EDD and powder-mixed EDM drilling aiming to improve the material removal rate (MRR), tool wear rate (TWR), surface quality and accuracy. This paper provides a comprehensive review of the EDD process. Different methods were compared; the advantages and disadvantages of each process were summarised; state-of-the-art technologies and the latest development were introduced, and research trends and new directions were presented.

Keywords EDM · Electrical discharge drilling · EDD · Hole making · Electrode · Drilling

1 Introduction

Electrical discharge machining (EDM) is one of the most widely used non-conventional machining methods which has been extensively applied in the industry to the machine hard and electrically conductive difficult-to-cut materials since its invention in the 1940s [1]. In the EDM process, workpiece materials are removed by the heat generated by a large number of recurring electrical sparks occurring at high frequency in the small gap between the tool electrode and the workpiece [2–4]. Since EDM is a thermal machining process in which the tool electrode and workpiece have no physical contact with each other, chatter, vibration and mechanical stress, which are the common challenges encountered in conventional computer numerical control (CNC) machining processes, are thoroughly eliminated [5]. EDM can be used to machine any conductive materials irrespective of their mechanical properties such as strength and hardness [6, 7]. These advantages are particularly important for the manufacturing, aerospace and biomechanic industries due to the high demand for cutting tools, turbine blades, implants and artificial joints, which are made of hard-to-cut materials such as polycrystalline diamond, nickel-based and titanium alloys to withstand the high temperature and stress during their operation under harsh working conditions [8–10].

Drilling is an important fundamental machining process in the manufacturing industry. In conventional machining processes, different types of holes are made through drilling by using rotating drill bits of different shapes. Drilling high-quality holes on hard-to-cut materials, particularly deep holes, is a difficult task due to the high strength of the material, low rigidity of the drill bits, poor cooling effects of the process and the difficulties in expelling chips. In addition, drilling micro-holes and the holes with a large aspect ratio is even more difficult because of the risk of bending or the breakage of the drill bit. Hence, EDM technology, or electrical discharge drilling (EDD), is applied by using cylindrical electrodes to make hole features, especially those with small diameters and large aspect ratio holes on hard-to-cut materials. It can also be used to make holes in complex geometries with non-circular cross-sections by changing the shape of
the electrode, in which case is called electrical discharge hole making because the movement of the electrode is different from that in a drilling process [11]. For example, the square holes and curved holes can be machined by using specially designed facilities based on an EDM machine [12–14]. However, although EDD has dramatic advantages over conventional approaches, some inherent problems exist. For example, its machining efficiency is lower than that of the CNC method in drilling holes on workpiece made of conventional materials, and the holes made by EDD may be accompanied by thermal defects such as the recast layer, high residual stress and geometric errors, including overcut (OC) and taper. These problems result in poor hole quality and increased manufacturing costs [15–17].

Many investigations have been conducted in this area to improve the machining efficiency and the quality of holes made by EDD. However, there is a lack of in-depth understanding of the problems, and the inherent mechanisms behind the issues have not been systematically analysed. This paper aims to encapsulate the research outcomes in EDD processes and provide an overview of the state of the research work in this field. It begins with a brief introduction to EDM drilling and its applications, followed by the presentation of different methods and the latest technologies. New approaches recently developed to improve the EDD process focusing on the investigation of powder-mixed EDM drilling with 2D structure materials such as graphene are also introduced. At the end of the paper, research directions and development trends are presented.

2 Electrical discharge drilling principles and parameters

During the EDM drilling process, the temperature in the plasma channel between the anode and cathode can be up to 8000 to 12,000 °C [18–23]. The thermal energy produced by the impact of electrons and positive ions on the poles can melt and vaporise the electrode materials. The melted and vapourised materials are flushed away by dielectric fluid in the form of debris and result in craters on both the tool electrode and the workpiece [24–26].

A servo system is required to control the movement of the tool electrode at an appropriate speed and maintain a constant sparking gap between the electrode and the workpiece by comparing the gap voltage with standard reference values. [27–30]. Dielectric fluid is used to maintain insulation between the electrode and workpiece and to remove debris from the discharging gap [31]. The requirements for dielectric fluid are high dielectric breakdown strength and quick recovery ability after the breakdown [32]. The flushing of dielectric fluid could enhance debris removal and electrode cooling capability, positively affecting the machining efficiency [33]. A better flushing effect can be achieved by electrode rotation, workpiece rotation, increased flushing pressure and the application of specially designed electrodes.

The electrical parameters including discharge voltage (V), peak current (I), pulse duration (T_{on}) and pulse interval (T_{off}) have dominant impacts on the stability of the machining process [34]. The machining efficiency (performance) of an EDM drilling process can be evaluated by many factors, including material removal rate (MRR), tool wear rate (TWR) and surface integrity.

Surface roughness (SR) is relevant to the number and size of craters formed by the electrical sparks on the workpiece surface. The diameter and depth of the crater, which are affected by discharge voltage and peak current, determine the SR [35]. A white layer (recast layer) is formed on the workpiece by the resolidified metallic debris after the EDM drilling process; its thickness is depended on the pulse energy and the characteristics of the dielectric. A heat-affected zone is an area below the recast layer. In this area, the temperature is high enough to cause residual stress and temper the material, but it is not high enough to melt the material.

In an EDD process, taper and overcut are two common types of defects. They have a huge impact on the accuracy of the machined holes. These defects are mainly caused by electrode wear and secondary discharges [36, 37].

Machining parameters in EDD have a significant impact on its performance. A proper set of parameters could ensure the stability of the process and result in high machining efficiency and high surface integrity [38–40]. The empirical, Taguchi and grey rational analysis are the commonly used statistical methods for optimising electrical parameters [41, 42] and investigating their influence on MRR, TWR and surface integrity. In an EDD process, MRR can be increased by increasing discharge current because the pulse energy is increased, which in turn results in larger craters and more materials being removed. When the pulse-on time (T_{on}) is constant, the larger craters can cause an increase in both MRR and TWR at the cost of poor surface integrity [43]. MRR can also be influenced by pulse duration. In one duty cycle, when the pulse-on time is longer and the pulse-off time is shorter, the larger energy in the pulse results in a larger crater and more material being removed in a unit of time [44]. However, in the EDD process, it may not necessarily be the case because of the poor debris expelling capability. The larger discharge energy means more debris is generated. If the newly generated debris is more than those being expelled from the discharge gap, they will be accumulated at the bottom of the hole and cause abnormal discharges and, as a result, lead to lower MRR and the formation of tapered holes [45, 46]. Therefore, it is particularly important to set up proper parameters in EDD processes to balance the removal of workpiece material and debris.
Similar to the current, discharge voltage also impacts MRR. MRR increases with the increase of discharge voltage due to the increase in discharge energy [47, 48]. In an EDD process, a higher discharge voltage increases the sparking gap, which may enhance the flushing effect and stabilise the machining process [49–51].

3 Additional movement-assisted EDD processes

3.1 Vibration and rotation-assisted EDD

In the EDD process, it is important to swiftly remove the debris from the discharging gap because the flushing effect is very poor before the hole is drilled through in drilling both blind and through holes [52–54]. With the increase in drilling depth, the flushing effect becomes even worth, and more and more debris is accumulated; as a result, the probability of abnormal discharge is increased, and the frequency of normal discharges is decreased. Thus, the machining efficiency is decreased [55, 56]. The debris, which is accumulated in the side gap between the wall of the hole and the electrode, also contributes to the increase of the chance of secondary discharge and can result in the increase of the OC and hole taper [57, 58]. To overcome these problems, various additional movement-assisted EDD technologies have been developed in recent years to improve the machining efficiency, machining accuracy and surface finish by enhancing the debris evacuation. This approach usually utilises additional electrode motions (translational motion and rotational motion) during the EDM drilling process to enhance the debris removal effect, resulting in a higher MRR. Ultrasonic vibration (UV) and rotation (Figs. 1 and 2) are the two most widely used auxiliary means in the assisted EDD process [59–61]. These means can be applied not only to the electrode but also to the workpiece and dielectric fluid to expel the debris, which significantly influence the EDD efficiency on hole fabrication process, especially for deep blind hole fabrication [62–64].

Generally, the rotation motion is applied on the tool electrode, whereas the vibration and UV can be applied on either the tool electrode or workpiece electrode and dielectric fluid. The pumping effect generated by the relative vibration between the electrode and the workpiece makes it easier for the fresh dielectric fluid to enter the discharging gap and expel the debris out of the machine zone [65]. It has been found that when low-frequency vibration was applied to the workpiece, the MRR and SR could be significantly increased by 34.94% and 26.36%, respectively, whereas the TWR could be decreased by 16% because the vibration improved the capability of debris removal [67]. The rotation of the electrode can also increase fluid speed and generate the velocity gradient along the axle direction, which pushes the debris out from the gap. The mixed effect of vibration and rotation combines the advantages of both. These relative motions can enhance the flushing effect and increase debris evacuation in an EDD process and, as a result, improve MRR and reduce the OC and taper. The experiment results achieved by Yeo and Tan [68] in studying the UV-assisted micro-EDD (UV-M-EDD) based on fluidization engineering and ultrasonic degassing theories show that the machining stability (Fig. 3) and aspect ratio of machined micro-hole were 132% and 64% higher because the bubbles which were enlarged by UV-improved debris evacuation. However, although EDD efficiency can be improved and the electrode wear can be reduced by increasing the amplitude of ultrasound vibration, the large amplitude has negative effects on the dimension accuracy of the workpiece, as validated by Huang et al. [69] who studied the effect of UV-M-EDD in Nitinol.

The ultrasonic vibrator or the piezoelectric transducer can be mounted between the X–Y stage (table) and the work tank (or workpiece) to realise the vibration. The vibration of the dielectric can also be achieved by using a vibration horn in the vertical direction, with one side of the horn connected with the ultrasonic oscillator and the other side sunk into the dielectric [70–72]. For instance, by applying the UV on the dielectric fluid instead of the workpiece or electrode, Kim et al. and Ichikawa et al. [70, 71] attained a 1-µm diameter difference between the entry and exit of the hole. Gao and Liu [72] employed the UV on the workpiece and found that the MRR increased with an increase in UV amplitude due to the larger pressure difference in the machining zone caused by the higher amplitude, which enhanced the flushing effect.
Similar results were also found by Xing et al. [73] (Fig. 4). The flushing effect can be further enhanced significantly by combining inclined feed with the assistance of vibration which increased the machining depth of the holes by 75% [74]. The downwards inclination with vibration-assisted EDD is preferred because it is difficult for the vibrated electrode to pump the dielectric fluid to the machine zone when an upward inclined angle is applied. By combining EDD with ultrasonic machining (USM), it is able to result in the thinnest recast layer but the worst surface finish because the melted materials can be completely removed from the machined surface, which creates deeper craters [75] compared with conventional EDD and UV-EDD.

Theoretically, increasing the rotation speed of the spindle can increase the MRR and decrease the TWR, particularly in machining deeper holes. However, it was found by Kumar and Yadav [66] that the MRR remained constant after the spindle speed reached a threshold value in drilling titanium
Similar trend was found by Feng et al. [76] and Yahagi et al. [77] as well. In high-speed-rotation EDD, the higher rotation speed can reduce the taper of the micro-holes because at low rotating speed, the surface temperature is higher and debris can re-solidify on the machine surface. In addition, the TWR was reduced due to the more even spark distribution around the electrode.

The rotating tube electrode may lead to better machining performance than the rotating solid electrode due to the centrifugal force coupled with forced internal flushing which enhances the debris removal effect [78]. Similarly, introducing a planetary motion of the electrode can reduce tool wear and machining time and improve surface finish because the gap between the electrode and machined hole can be increased by the planetary motion, which improves the flushing of debris and keeps the electrode at a lower temperature [79, 80]. The actual hole depth becomes more accurate due to the reduction of electrode wear. Because the secondary discharges are reduced, the planetary movement of the electrode can reduce the deviation between the entry and exit (DVEE) as well. Li and Bai [81] found that with the translational motion of the workpiece, an improvement of 89.3% in machining depth and a reduction of 38% in machining time can be achieved. When the machining depth reached the threshold value of 1000 µm, the difference in MRR became significant. In addition, enlarging the eccentric radius also improves the MRR and aspect ratio of the machined holes.

Since the drilling efficiency can be increased by employing vibration and rotational motions, some research was carried out to study the combining motions of vibration and rotation. Ghoreishi et al. [82] compared the effects of high/low-frequency axial vibration of electrodes, rotation of electrodes and the vibro-rotary method with respect to MRR, TWR and surface quality in die-sink EDD with flat end electrodes. It was found that the high-frequency vibration can significantly improve the MRR because the hydrostatic pressure variation can be increased by alternating pressure variation, which was produced by UV. As a result, the debris can be removed from the machining zone more efficiently. When combining UV with rotation, two velocity vectors were added together; the debris velocity was therefore increased. By combining the vibration with rotation motions, the MRR can be increased by 35% and 100% compared with using vibration and rotation of electrodes. Yu et al. [83] found that the machining performance can

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**Fig. 4** Effect of ultrasonic amplitude. a Effect of ultrasonic amplitude on MRR. b Effect of ultrasonic amplitude on relative TWR. c Effect of ultrasonic amplitude on taper angle θ. d Effect of ultrasonic amplitude on OC [73]
be significantly improved by employing UV and planetary motion because the width of the side gap was changing when the electrode had planetary motions, which prevented the block of the dielectric. The wetting effect caused by UV took a more significant role than the unevenly distributed gap, which was caused by planetary motion. Li et al. [84] developed the ultrasonic circular vibration (UCV) system for the EDM drilling process which provided a planetary motion of electrode at ultrasonic frequency and retained the advantage of the conventional planetary motion system. When planetary motion is at the ultrasonic frequency, the dielectric velocity can be increased significantly, which enhanced the capability of expelling debris. It was found that by using this system, the DVEE can be significantly reduced by 22% due to the reduction of abnormal discharge and debris resolified.

### 3.2 Magnetic-assisted EDD

The prompt evacuation of debris takes a vital role in EDD processes. To develop new methods with which debris can be removed more efficiently, research on magnetic-assisted EDM drilling has been carried out to investigate how to use the magnetic force to push the debris away from the machining zone so as to enhance the debris removal efficiency in the EDD process [85].

The magnetic system can be mounted at the bottom of the dielectric tank of the die-sink EDM machine. The magnetics can be fixed on a rotating disk driven by a motor (Figs. 5 and 6). The Lorentz force which is generated by the magnetic field and electric field is able to take the debris to the top of the workpiece, and thus, the chance of abnormal discharges is reduced [86]. By employing a magnetic force-assisted device, the machining process becomes stabler because the magnetic force pushes the debris away from the machining zone, which reduces the accumulation of debris in the inter-electrode gap; as a result, less materials are re-melted on the surface, abnormal discharges are reduced [87], and the probability of normal discharges is increased. The experimental results showed that the MRR in magnetic-assisted EDM drilling was about three times higher than that of the conventional EDM drilling, the relative TWR improved from 1.03 to 0.33% and the surface finish was reduced from 3.15 to 3.04 µm due to the higher debris removal capability [88]. By combining a magnetic field with ultrasonic vibration, even the taper of the hole can be improved [86].

### 3.3 Cryogenic-assisted EDD

The thermal conductivity and electrical conductivity of electrode and workpiece materials have significant impacts on EDD performance. The workpiece materials which has lower thermal and electrical conductivities tend to have lower MRR in the EDM drilling process. Recent research has also shown that cryogenic-assisted EDD can generate higher machining efficiency and surface quality [89]. The application of the cryogenic treatment on the workpiece leads to a change in the thermo-electrical conductivity of the workpiece, thereby increasing MRR. By applying deep cryogenic treatment (DCT) on the Ti-6246 workpiece before the EDD process, Gill and Singh [90] found that the MRR was 8.57% higher than machining the non-treated one in 180-min drilling time because the thermo and electrical conductivities of the workpiece increased. The TWR was decreased by applying DCT on the workpiece due to the fact that the drilling time was shorter for the DCT-treated workpiece, which also reduced the OC.

### 4 Tool electrode and dielectric fluids

#### 4.1 The effects of tool electrodes

The electrode configuration has a huge impact on EDD performance, especially in the EDD process. The poor flushing effect is one of the major problems which cause debris clogging in the machining zone and leads to short circuits [91–93]. The flushing efficiency can be improved by using electrodes of different shapes. Modifying electrode shape (external shape and internal shape) can change the dielectric flow behaviour in the machining zone and
thus improve the flushing efficiency. The shaped electrode, such as the helical electrode, side cut electrode, notch electrode and stepped electrode, can be combined with electrode rotation and vibration to significantly change the flow behaviour of the dielectric and provide the channel for debris evacuation. Thus, it is possible to achieve higher machining efficiency by optimising the electrode shape. Furthermore, using a shaped electrode with assisted EDD can significantly improve the surface integrity and reduce TWR, overcut and taper of the machined hole.

A hollow electrode is one type of commonly used electrode in the EDD process. The dielectric can be delivered to the machining zone through the internal hole of the electrode, which helps the removal of debris [94]. Gao [95] found that the length of the hollow electrode may affect the EDM drilling performance because the pressure loss in internal flushing increases with the length, which results in a weaker flushing effect. In addition, the flushing pressure can be decreased by increasing the diameter of the internal through hole, which also weakens the flushing [78]. Yilmaz and Okka [96] studied the effect of single and multi-channel electrodes and concluded that using a single channel electrode led to higher MRR and lowered TWR when machining Inconel 718, whereas the multi-channel could provide a better “cooling” effect, resulting in less removal of melted material [97]. Wang and Wang [98] found that by using a rotary electrode with eccentric through holes (Fig. 7), both MRR and TWR were increased. MRR was reduced by using an electrode with more through holes compared with that with fewer through holes due to the smaller discharge energy area.

![Schematic diagram of the debris driven by the magnetic force in the machining gap [87]](image1)

![Schematic drawing of an electrode with an eccentric through hole [98]](image2)
gap, and during this process, secondary discharges could occur, which may reduce the machining efficiency and increase the OC. To overcome this problem, Kumagai [99] developed a new strategy for machining narrow and deep holes by applying a composite electrode which had a rod electrode encased in a polytetrafluoroethylene (PTFE) pipe jacket to prevent the secondary discharge in the side gap.

When internal flushing is applied, the recirculation zone is formed at the bottom end of the electrode. The formation of the recirculation zone may lead to the accumulation of debris and, as a result, increase the chance of secondary discharge [100]. New electrodes with an orifice at the bottom end of the electrode were developed to reduce the accumulation of debris in the recirculation zone [101]. With such a design, debris accumulation is avoided and a better surface finish and higher machining depth could be achieved.

Instead of using the electrode with a circular cross-sectional area, side-cutted electrodes such as slotted electrodes have been developed in the EDD process as well. By using a slotted electrode, a pathway is provided for the expanded bubbles to be evacuated from the machining zone. The additional pathway would facilitate the removal of debris, reduce side sparks and reduce the taper [102, 103]. These effects also can be achieved by using single-notch electrodes. For slotted electrodes, the slot height plays a more significant role than slot width because the ingress and egress of the dielectric fluid are aligned with the height of the slot [104]. In addition, with the same frontal area, a single deep slot provides better performance than multiple shallow slots because of the high-pressure gradient and the large sweep zone, which enhance the debris evacuation at the centre of the electrode. Based on side-cutted slots, further changes have been made by machining micro-slots at the bottom end of the cylindrical electrode (Fig. 8) [105]. The single eccentric slotted electrode provides the 11.27% higher MRR and 54.24% less DVEE, and blind holes with a higher aspect ratio can be machined. This is because the slotted electrode gives more space for bubbles and debris to escape from the machining gap. On the contrary, the double-slotted tools provide lower MRR compared with single slotted electrode due to smaller sparking area.

Although the side-cutted electrode provides some advantages in the EDD process, the rotation of the electrode has to be employed to make the circular hole, which increases the complexity of the machine setup. To achieve better flushing effects without the rotation of the electrode, stepped electrodes were developed [106]. It has been found that before the machining depth reached the height of the body electrode of 2 mm, the machining speed of all types of electrodes was identical. When the machining depth exceeded 2 mm, the stepped electrodes provided higher MRR. In addition, the maximum effective cutting depth can be increased by up to 132.184%. This is because by using the stepped electrode, the debris can be easily removed from the machining zone. In addition, the stepped electrode increased the width of the annular gap; as a result, the debris clogged at the side gap had no influence on the discharging process, and the chance of abnormal discharge and secondary discharge was reduced. Similar experiments were also conducted by Jamkamon and Janmanee [107]. The SR of the side wall of the machined hole was higher when using the stepped electrode because the secondary discharge on the side area had been reduced. To achieve higher MRR and better surface finish, hybrid processes were developed by combining the EDD process with the gridding process and adding particles into the dielectric as abrasive [108]. The rotating electrode not only functioned as a typical electrode for EDM drilling but also functioned as a grinder to polish the machined surface of the hole. By using this method, the hole taper, DVEE and SR can be reduced significantly. The vibration motion of the electrode can be employed in this hybrid process to improve the quality of the machined hole further. It has been found by Wang et al.

Fig. 8  Electrodes: a schematics of slotted electrode, b single slotted, and c double slotted [105]
that when using micro-ultrasonic vibration lapping (MUVL) with the stepped electrode, the DVEE decreased. The roundness and surface roughness of the machined holes were improved by employing MUVL and stepped electrodes. Subsequent experiments have been conducted by Liu et al. [109] by using high-frequency dither grinding (HFDG) with stepped electrodes (Fig. 9). The SR can be improved by employing the HFDG with both cylindrical electrode and stepped electrode. However, the stepped electrode provides a better surface finish compared with the cylindrical electrode due to the fact that the side gap for the cylindrical electrode is larger than that of the stepped electrode; hence, the abrasive particles moved freely in the gap, which decreased the grinding efficiency.

Besides the stepped electrode, helical electrodes can also be used to improve the performance of the EDD process. The helical grooves provide channels for debris evacuation and can reduce debris clogging at the bottom and, as a result, enhance the debris removal capability to reduce the relative tool wear rate (RTWR). The geometrical effects of the helical electrode in the EDM drilling process have been studied by Plaza et al. [110]. It has been found that a lower pitch angle provides better machining effects compared with a higher pitch angle because debris would travel a longer distance to be evacuated from the hole when using the electrode of a higher pitch angle. By using the helical electrode with a bigger flute depth, the MRR was significantly increased compared with a lower flute depth. In the near-dry EDD process, the helical tubular electrode resulted in the highest MRR and best surface finish, followed by the slot tubular electrode and purely tubular electrode [111]. This is because the slot tubular electrode can cause re-deposition of debris, whereas this phenomenon had not been observed when using a helical electrode (Fig. 10).

When combining a helical electrode with a rotating motion, the mobility of the fluid can be increased and the debris can be driven upward by the helical grooves, which enhances the debris evacuation. Hence, the protective layer of the debris on the workpiece was weakened and, as a result, increased the MRR. Also, the MRR increases with an increase in the rotating speed of the helical electrode [112].

When using the helical electrode in UV-assisted processes, the OC, taper and machining time can be reduced and the reduction becomes more significant when the machining depth increases. This is because the helical electrode with UV causes a strong cleaning effect in the machining zone, and the groove of the helical electrode results in the reduction of clogging debris in the side gap, which reduces the secondary discharge. Hung et al. [113] employed the helical electrode micro-ultrasonic vibration finishing (HE-MUVF) process by using a stepped helical electrode (Fig. 11) with an abrasive slurry. It was observed that overall, the IVEE (improvement of variation between entrance and exit) was improved by introducing HE-MUVF and the surface roughness can be reduced from 1.345 to 0.58 µm. A similar strategy has been used by using a stepped helical electrode [114]. Subsequent experiments were conducted by Hsue and Chang [115] by using a tapered helical tool in a hybrid-EDM process.
drilling process. Because the added abrasive diamond reduced the side wall discharges, and the tapered helical tool had advantages on electrode penetration and expelling debris at the beginning phase of the drilling process, better surface roughness was achieved by using hybrid-EDM drilling.

4.2 The effects of dielectric fluids and flow

The basic function of the dielectric fluid is to isolate the tool electrode and the workpiece, between which high current density can be generated in the plasma channel. The dielectric fluid is also used to cool down the high temperature of the electrodes and flush the debris away from the discharging gap to avoid the development of particle linkage, which can cause a short circuit and result in the disruption of the discharge process and damage the machined surface. The most commonly used dielectric is hydrocarbon compound fluid such as kerosine and deionised water [116]. During the EDD process, by-products can be produced and expelled in the form of smoke and fume, which can cause environmental and human health hazards. The type and content of the hazardous elements influence the extent of the negative impact of EDD by-products. The properties of the dielectric fluid used are very important when it comes to the potential threat to the environment and health [117]. Dry EDM drilling is a process that uses gas as the dielectric instead of liquid for environmental preservation and the consideration of human health. It can also avoid the fire hazard caused by the hydrocarbon dielectric fluids [118]. With the participation of oxygen, a higher MRR can be obtained in machining high-strength material. High-pressure gas feeding through a hollow pipe is also used to remove the debris efficiently [119–122]. Kunieda and Yoshida [123] developed gaseous dielectric discharge machining as new technology to reduce the environmental and health hazard, since the EDD process was achieved in a gaseous medium rather than in kerosine or mineral oil. With the absence of the dielectric fluid, arcing and unstable machining can frequently occur, which increases the machining time and SR. Kao et al. [124] found that the machining time to drill a 1.27-mm hole on Al6061 in dry EDD condition (air) was 428 s, whereas in near dry (air and deionised water) and wet conditions (deionised water), it was 11 s and 13 s, respectively. To achieve better machining performance, Xu et al. [125] applied the UV when using gas as a medium of EDD. The experimental results showed that when UV was introduced in gas EDD, the MRR could be significantly increased, and less micro-cavity was found on the machined surface. Singh et al. [126] studied the effect of gas-assisted EDD by using multi-hole rotary electrodes on EDM drilling of Ti6Al-4 V. Unlike the dry EDD which uses gas as dielectric, the electrode and workpiece were still submerged in the
dielectric fluid, but gas was used as a secondary medium. It has been found that under the same condition of machining, the MRR can be 75% higher, whereas TWR can be 30% lower when using the multi-hole rotary tool assisted with argon gas. This is because the rotation of multi-hole electrode enhanced the flushing effect, and the heat at the tip of the electrode could be dissipated by the argon gas, which facilitated the development of smaller craters on the tool surface. However, in the industry application, the multi-hole rotary electrodes are hard to manufacture and the cost to fabricate such electrodes has significantly impacted their application. Bunched electrodes, as another type of electrode, can be used instead to reduce the cost and machining preparation time [111]. Similar research also has been conducted by Zhang et al. [127] by using nitrogen for gas-assisted EDD. However, in their research, the gas was being applied not only for cooling but also for reaction with Ti-6Al-4 V. It was found that the gas-assisted EDD yielded a better surface finish (up to 28% reduction on SR), less pores were observed on the machined surface, and the SR was significantly lower because, with the participant of nitrogen gas, the discharge energy density was reduced and the discharge gap was increased; thus, the discharge energy was more evenly distributed on the surface. In addition, the machining performance of Ti-6Al-4 V has been improved due to the formation of TiN on the machined surface.

The flushing method of the dielectric has impacts on MRR, TWR and surface integrity. The MRR can be significantly improved by optimising the flushing of the dielectric. In an EDD process, the flushing of dielectric plays a more important role compared with EDM milling or wire-EDM because an enclosed cavity is formed during the drilling process before the electrode breaks through. The side gap between the electrode and the wall of the hole is too small for debris evacuation. Moreover, with the increase in machining depth, the debris needs to travel a longer distance to be evacuated, and this may lead to a decrease in drilling efficiency [128, 129]. To optimise the method of flushing, it is important to investigate the movement of the debris and bubbles. For this purpose, high-speed cameras and transparent materials were used during the EDM to capture the movement of the debris and bubble in various flushing methods; e.g., Wang et al. [130] found the expansion of the bubbles was the main factor which brought the debris out of the inter-electrode gap during the period electrode moving down, and with the continuity of the machining process, the cleaning effect of the bubble decreased and caused the accumulation of debris. Ekmekci and Sayar [131] studied the debris and its effects and found that the debris accumulated at the tip of the electrode formed a conical and behaved as a tool electrode. The parabolic shape formed on the tool electrode was mainly due to the vortex of the dielectric fluid being produced in the inter-electrode gap. The concavity at the tip of the electrode was reduced as the discharge voltage and energy increased due to the finer debris generated at low discharge voltage and smaller energy, which resulted in better flushing at the corner of the tip.

With the development of computational technology in recent decades, computational fluid dynamics (CFD) has become one of the most commonly used tools in investigating debris and bubble movement in EDD. By using CFD simulation, the flow of dielectric, debris and bubble movement can be visualised, and the velocity of the dielectric can be calculated, which helps to optimise the movement and the shape of the electrode to improve machining efficiency as the performance of the EDD process can be significantly influenced by these factors. The effects of the assisted EDM in the drilling process have also been investigated by using the CFD simulation. By conducting the CFD simulation, Li and Bai [81] found that the linear velocity of the dielectric fluid could be increased by increasing the eccentric radius of the translational motion, which enhanced the debris removal. In addition, the debris was more likely to accumulate at the side gap of the hole instead of the bottom gap. Therefore, the discharge sparks were less likely to concentrate at a fixed location, which improved the machining performance. Results of the CFD simulation conducted by Feng et al. [76] showed that the fluid velocity increased with the rotating speed of the electrode; therefore, more debris could be removed from the bottom gap to the side gap due to the velocity gradient generated along the radial and axial direction. Mastud et al. [132] studied the debris motion in vibration-assisted Revers-EDM. Based on the CFD simulation result, it was found that the debris velocity was increased by employing the vibration of the tool electrode plate.

The main mode of bubble evacuation was the bubble expansion movement, and the majority of the debris were removed from the machine zone by following the movement of the bubble [133]. The movement mode of debris and bubbles was similar under the different EDD conditions. However, bubble expansion is more brutal when pulse-on time and discharge current increase. Cetin et al. [134] studied debris distribution in relation to jump height in EDD deep-hole machining. The simulation results showed that the alignment of vortices was different at different jump heights (low and high). The maximum dielectric velocities were similar for two different jump heights since the jump speed was the same. Because the vortex was generated at the lower part of the side gap, more debris could be found between the lower and centre part of the side gap.

The effects of machining depth and electrode diameter have also been investigated by conducting CFD simulations. The increase of electrode diameters has benefits for debris removal because a larger diameter of electrodes reduces the resistance of the dielectric fluid. Whereas an increase
The dielectric fluid is critical in the EDM drilling process. Using different types of dielectric fluid could cause different results in terms of MRR, TWR and surface integrity. The relative electrode wear can be significantly decreased by using a water-based dielectric. The salts added to the dielectric change material removal mechanism; hence, the eroding process becomes a combination of EDD and electro-chemical machining (ECM), and as a result, the wear of the electrode can be reduced [136]. The viscosity of the dielectric fluid has an influence on the machining time. Higher viscosity dielectric is more likely to result in short circuit and vibration [137]. The effects of dielectric in EDM drilling of Inconel 718 have been studied by Li et al. [137]. They found that the diameter of the machined hole increased with the conductivity of the dielectric fluid except for the kerosene. However, the holes machined by kerosene have the thinnest recast layer due to the lower conductivity and solid compress effect for the discharge channel. When machining Inconel 718 by EDD, the super dielectric can be used to achieve higher MRR; however, the TWR also increased. This is because the fluid with high dielectric constant provides advantage in plasma formation, which stores high energy in the electric field. In addition, few discharges can be generated during the pulse-off time due to the high capacitive effect [138].

Changing flushing parameters such as dielectric flow pressure could have significant effects on EDD performance and surface texture in the EDD process. Since it will influence the efficiency of debris removal, which could have a huge impact on MRR in the EDD process, it is important to optimise the flushing parameters. The dielectric flow rate of internal flushing plays an important role in determining the crack density and the thickness of the recast layer. The debris which is more easily accumulated at the inter-electrode gap causes the concentration of discharge which may lead to heat concentration. The heat concentration coupled with a lower flow rate increases the chance of surface cracking, and the crack density is related to the thickness of the recast layer [139]. When machining through holes, the breakthrough stage is one of the major concerns because the taper is formed during the breakthrough stage due to electrode wear. In addition, the flushing effect is significantly lower when the electrode penetrates the workpiece because the internal flushing dielectric directly flows out through the hole. Wang et al. [140] studied the effect of dielectric flushing pressure in EDM fast hole drilling and concluded that in the blind hole stage, the internal flushing pressure has a major effect on debris removal. However, in the breakthrough stage, the external flushing has a significant effect on the flushing of debris. The surface quality can be improved due to the effective debris removal in the breakthrough stage. To improve the machining efficiency and accuracy, Zhang et al. [141] developed a new method, which can detect the finishing process by analysing the normal discharge ratio, short circuit ratio and open circuit ratio. It was found that the overall efficiency was improved, and the machining time was reduced in the breakthrough stage.

Powder-mixed-EDM (PM-EDM) is one of the more recent innovations in EDM drilling holes. Powders with specific materials are added to the dielectric fluid to improve its breakdown characteristic. The series discharges caused by the powders enlarge the sparking gap, which can facilitate the removal of the debris and stable machining process [142–144]. The added powder would be energised and move in a zigzag fashion during the pulse-on time. The charged particles could be accelerated under the action of the electric field and act as a conductor to promote the breakdown of the dielectric. In powder-mixed EDM drilling, the dielectric circulation system is different from that in conventional EDD because the particles added into the dielectric need to be blended homogeneously. The powder concentration may affect machining performance. Too many powders may lead to particles clogging at the discharge gap and reduce the machining efficiency [75]. Wang et al. [108] and Paswan et al. [145] studied the effect of graphene powder in deionised water on EDM drilling of titanium alloy and Inconel 718, respectively. By adding graphene oxide nano-particle into deionised water, a significant increase in MRR and decrease in SR were found in both processes. In Wang’s experiments, the SR was decreased by 40% when nano-particles were added, and in Paswan’s experiments, while the MRR increased from 0.0323 to 0.0258 g/mm3 because of the formation of the graphene bubbles which increased the spark gap, influenced the dielectric breakdown and expansion of the plasma channel and, as a result, reduced the abnormal discharge and improved the machine stability.

When machining square holes by EDD, one major concern is that unstable sparks were produced by using non-circular electrodes [146, 147] which could affect the squareness of the machined holes. To overcome this problem, Kumar et al. [148] added SiC powder into the kerosene in machining carbon fibre reinforced polymers (CFRPs). It has been found that the SiC-kerosene mixed fluid has a huge impact on squareness, hole depth, SR and electrode wear because the SiC powder increases the dielectric strength, and more thermal energy is generated in the machining zone. SiC powder also can reduce the insulation strength of the dielectric, which causes the increase in the discharge gap. As a result, the high-energy plasma channel can be generated, and MRR thus increased. Salecha et al. [149] also used SiC powder to improve the machining performance on Inconel 718. It has been found that overall, the nano-size SiC powder provides better MRR compared with micro-sized SiC powder. Increasing the
concentration of the SiC powder can increase the MRR as smaller sparks can be generated by adding SiC powder. However, if the concentration is overly high, short circuit will occur and smaller MRR will be caused.

5 Application and capability of EDD and EDM hole making

5.1 Micro-EDM

Micro-EDM (M-EDD) is defined as the manufacturing of products with features that have a size under 999 µm [150]. The drilling of micro-holes in micron-size is highly demanded in the aerospace industry, but it is difficult by using conventional drilling method because the fabrication of the drill bit of ultra-small diameter is hard to achieve, and the drill bit is prone to bending or breakage when drilling high aspect ratio holes [151]. In an M-EDM drilling process, the electrode and workpiece have no physical contact with each other; therefore, M-EDD has become more and more popular in drilling small diameter holes with large aspect ratios. The major differences between conventional EDD and M-EDD are the size of the electrode, discharge current, voltage, machine resolution and high accuracy of the servo system [152]. Since the size of the M-EDD is significantly smaller than the conventional EDD, the high level of discharge energy is not preferred as it can significantly influence the accuracy of the machined micro-holes and could cause the welding of the electrode with the workpiece [153], and the poor flushing condition in M-EDD can aggravate this phenomenon [154]. Therefore, in M-EDD, lower peak current and short pulse duration are preferred at the cost of lower volumetric removal for each discharge. Meanwhile, the lack of fresh fluid in the machining zone is another problem for M-EDD. Internal flushing is not achievable for M-EDD, since fabricating internal through the hole on ultra-small diameter electrodes is impossible [155]. To improve the machining efficiency, employing relative motion is more widely used in M-EDD to pump fresh fluids into the machining zone and remove the debris [156].

The fabrication of the tool electrode for M-EDD is another challenge because the ultra-small tool electrode is hard to be manufactured by using conventional machining methods. Electrical discharge grinding is the effective process for making the electrode for M-EDD. Typically, the stationary sacrificial block, rotation sacrificial disk and running wire (WEDG) methods were used to fabricate the micro-structure electrode (Fig. 12), and all these methods have their advantages and disadvantages in terms of accuracy and efficiency. The rotating sacrificial electrode methods (rotation disk and running wire) can produce the microstructure electrode more efficiently. The stationary method has been found that it causes significant taper and is inaccurate in dimension due to the wear of the sacrificial electrode. The rotating disk method can provide a better surface finish compared with the running wire method, which is influenced by wire diameter and feed rate [157]. In practice, the SX-100HPM and SX-200HPM from SARIX in Switzerland can be machined to an accuracy of +/- 0.002 mm. A 0.3-µm tungsten electrode has been fabricated by Egashira et al. [158] by using wire-electrical discharge grinding (WEDG) and ECM.

In M-EDD, the electrode wear is critical in machining accuracy since the size of the machined hole is very small, whereas the machining time has a huge effect on TWR. The percentage contribution of TWR showed that the machining time is the major aspect, followed by feed rate and
percentage of peak power for UV [159], and the equations to calculate electrode wear have been developed based on the volumetric wear of the electrode [160]. The machining time can be reduced by employing UV because less abnormal discharges occurred, which increased the electrode feed rate. Using the ultra-small energy in M-EDD can be realised by applying the UV to the dielectric fluid and the rotation of the electrode because without the UV and rotation, the debris cannot be removed efficiently due to the small energy and gap. Sundaram et al. [159] studied the processing parameters of ultrasonic-assisted M-EDD hole making and found that the capacitance and percentage of peak power for UV have a significant effect on MRR. Also, the percentage contribution of MRR showed that the percentage of peak power for UV has the most significant influence on MRR; by contrast, the feed rate has the least influence on MRR. In drilling micro-holes on PCB, the burr can be eliminated by combing the mechanical drilling process with the EDD process [161].

5.2 EDD on hard-to-cut materials

In micro-EDM drilling of deep holes, the electrode is prone to flex due to its extremely small diameter, which is easy to bend by a small amount of force acting on it, especially when high flushing pressure and rotational speed are applied. The deformation of the electrode can cause dimension error, particularly in drilling a deep hole with a large aspect ratio. To overcome this problem, Yu et al. [162] designed a special clamp and guiding device (Fig. 13), which minimises the deformation of the electrode under the high flushing pressure and rotating speed. By using this equipment, the aspect ratio of the micro-hole can be up to 44:1.

Fig. 13 Schematic diagram of the experimental device [162]
advantages of these materials also cause problems in their machining processes. They are hard to cut by using conventional machining methods such as drilling, turning and milling. The cutting forces generated by the tool in removing redundant materials may cause chatter, vibration and premature tool failure. Therefore, EDD is an ideal alternative because it can machine any conductive materials irrespective of their mechanical properties. However, even though EDD has such advantages in machining hard-to-cut materials, some problems still exist. For example, when machining Ti-6Al-4 V by EDD, the debris is easily adhered to the surface of the workpiece due to the strong alloying tendency of Ti-6Al-4 V. Also, the debris of Ti-6Al-4 V is heavier than other light materials like aluminium; thus, it is harder to remove it from the machining zone [163]. The parametric effects of Ti-6Al-4 V have been studied in much research [164]. Pulse-on time has the most significant effect on MRR, OC and taper. The TWR is majorly affected by the peak current and increases the peak current; as a result, increasing the white layer. The dielectric flushing pressure and duty factor have little effect on MRR and TWR. However, the flushing dominates the machining efficiency especially in machining small hole.

The parametric effect of the EDD process on Inconel 718 has been studied by Kuppan et al. [165]. The experimental results show that the plasma channel can be expanded by long pulse-on time, which reduces the energy density of the workpiece; hence, the MRR decreases. In terms of surface roughness, the total energy of the spark can be increased by increasing the pulse-on time, which expands the melting boundary (wider and deeper). As a result, the surface roughness is increased. The MRR can be influenced by the rotation speed of the electrode as well, especially at the lower current settings. This is because the concentration and size of the debris are lower at the lower current, and the effectiveness of debris removal can be improved by increasing the rotating speed of the electrode.

Akıncıoğlu [166] studied the parametric effect (pulse-on time, pulse-off time and discharge current) on titanium (Gr2) alloy. It can be found that SR increases with the discharge current. This is because as the current increases, deeper craters are formed on the surface. However, the TWR decreases with the increase of the discharge current because the high current allows the work surface to quickly reach the melting point of the material being processed. So, more material can be removed within the same pulse-on time. The best MRR can be achieved when the discharge current is 8 A, pulse-on time is 124 µs, and pulse-off time is 48 µs. The best surface roughness can be achieved when the discharge current is 8 A, pulse-on time is 120 µs and pulse-off time is 40 µs.

The physical properties of the hard-to-cut materials also have an impact on machining performance and results. The low thermal conductivity (and high ductility) may lead to a higher percentage of the short circuit because the lower thermal conductivity leads to poor heat dissipation and, as a result, worsens the state between the electrodes, which reduces machining stability and MRR. The pulse and discharge energy need to be controlled precisely in M-EDD. The transistor-type and RC-type controllers are two common controllers used in EDD. The control of the discharge energy of the RC-type pulse generator is much easier than the transistor-type pulse generator. Jahan et al. [167] studied the M-EDD of tungsten carbide by using both transistor-type and RC-type pulse generators. The results showed that the RC-type pulse generator resulted in better surface finish, dimension accuracy and circularity of the machined holes because the low discharge energy generated in each pulse by the RC-type pulse generator caused smaller craters. Liu et al. [168] studied the M-EDD by using a multi-step RC charging strategy and found that it could provide better controllability and consistency and achieve the low discharge energy of 125 nJ. Multi-step RC charging strategy gives more time intervals for the dielectric to recover its insulation strength, which may reduce the possibility of abnormal discharge [169, 170]. By comparing the machining feasibility of WC–Co and SUS 304 in deep hole M-EDD, Jahan et al. [36] found that WO-Co has less overcut, less expansion at the entrance of the micro-hole and better surface quality at the rim of the micro-hole because the WO-Co has higher thermal conductivity, higher yield strength and lower ductility. As a result, the material becomes less ductile at high temperature. Hence, the surface becomes smoother and surface quality is better when the machined surface cools down. The effectiveness of the magnesium content on EDM drilling of Al–Mg–Ti alloy has been studied by Eyercioglu and Gov [171]. It was found that the MRR is higher when the Al–Mg–Ti alloy has more magnesium because more materials melt and vapourised during the EDM drilling process. In addition, more debris was generated during the machining process when machining higher magnesium content Al–Mg–Ti alloy, which increased the possibility of secondary discharge and, as a result, increased the OC.

5.3 EDM making of curved holes

The drilling of curved holes is an important task in manufacturing injection moulds. The reason for this is that the moulding system needs curved cooling channels to reduce the temperature of moulded parts and the cooling time has a great influence on the efficiency of the moulding process. Unlike conventional cooling channels, these conformal cooling channels are curved, which means they cannot be machined by conventional drilling or milling processes. To machine the curved holes, the mole EDM and a self-movable mechanism have been developed by Fukui et al. [172] and Ishida et al. [173], which include an automatic discharge gap controller and
shape memory alloy to complete the task. But the curvature is limited to two dimensions only. Improvements have been made to improve the EDD performance and machinability of the curved channel forming process (Fig. 14) [12]. The direction of the electrode was controlled by wires, and the spring was used to control the width of the gap. Curved holes with a length of 34 mm can be machined smoothly, and L-shape holes can also be easily machined by using this device; to elongate the machining length, a flexible structure and guide wheels were added on the slender body (Fig. 15) [13].

A string-ball structure which only feeds downwards and is controlled by gravity was developed to machine the...
curve hole in 2015 [14]. The direction of the curved hole was controlled by the rotation of the workpiece (Fig. 16), and the machining depth is limited by the EDD stability. To increase the maximum machining depth and dimensional accuracy, UV was added to the system [174]. However, the maximum machining depth and bent angle are still limited by the mechanism itself because the leading wire could have contact with the workpiece after the workpiece reached a certain tilt angle and depth, which may cause undesired discharge at the entrance of the channel. To further improve the practicability of this system, a foil supporting guide was developed so that the channel with a higher bending angle can be machined [175]. The new mechanism has been developed by Okada et al. [176] to form the internal space. A rotating rod is mounted on the Z-axis of the machine with a pivot point at the end of the rod. The ball-end electrode is fixed on the pivot point of the rod. The material can be swept off by the rotating electrode, and the shape of the internal space is controlled by the pivot angle of the ball-end electrode (Fig. 17). In order to dress the inner surface of the mould, a string-bead system was developed by Hsue et al. [177] (Fig. 18). The electrode was a string fixed on the wire between the guiding balls. An Ra of 5.9 µm on the internal hole has been achieved, while the original surface roughness was in the range of 15.4 to 26 µm.

6 Trends and conclusions

Various EDD technologies have been developed to meet the increasing demands of the industry. With the development of these technologies, the machining efficiency has been significantly improved and the machining time was deducted. This makes EDD more practical in industry applications. This paper presents a comprehensive review of the EDD process. The principle of EDD was briefly introduced, different types of EDD were discussed, and the current body of research has been thoroughly analysed. EDD parameters and electrode materials have a significant impact on the performance of EDD processes. The proper EDD parameters and electrode material need to be chosen to achieve higher machining efficiency and less electrode wear. Significant research has been done regarding the parametric effect. However, with the development of the new materials, the study of parametric effect is still required to find the optimised EDD parameters for new materials. The use of electrodes of different shapes and assisted EDD leads to an increase in EDD efficiency. The shaped electrodes (e.g., stepped, side-cutted, grooved, helicased) provide more space for debris evacuation, and short circuits and arcing can be avoided; as a result, better machining performance can be achieved. With the advance in CFD technology, the theories
behind improvement have also been discovered and studied by many researchers. However, a more detailed study is required to investigate the influence of sparks on dielectric flow. In addition, the simulation of the sparks and formation of plasma channels are still lacking at this stage. In-depth studies have been conducted on the influence of the dielectric, including the influence of different dielectrics and the different powder-mixed dielectrics on EDD. With the development of nano-technology, nano-particles have been used in EDD in recent years to improve EDD performance on different materials. The nano-particles added into the dielectric act like conductors to improve the breakdown characteristic of the dielectric fluid. However, further study is required to investigate the principle behind the phenomenon. As the demand for high-precision products increases, micro-hole machining becomes more challenging in the industry, especially for M-EDD. Studies have been conducted regarding micro-tool fabrication and micro-holes machining; ultra-small diameter with high aspect ratio holes can be achieved. However, achieving high machining accuracy and high surface quality of micro-holes by EDD is still a challenge, and it needs to be further improved. In addition, curved micro-hole machining is one of the research trends. Although the machining of curved holes (channel/tunnel) has been developed for years, it can only machine macro-holes with small bent angles, and the accuracy is also an issue due to the limitation of the servo mechanism. With the advance in control systems and precision machining technology, more suitable equipment can be developed to improve the machinability and accuracy of curved holes by EDD. With the wide application of hard-to-cut materials, comprehensive studies have been conducted on EDD of hard-to-cut materials; for instance, parametric studies and different methods such as vibration and rotation have been used to improve the machining efficiency of hard-to-cut materials. However, the machining speed and accuracy in machining these materials on EDD are still the concerns, and further study is required to improve the EDM drilling efficiency to make it more feasible for the industry. In addition, only a few research were focused on semi-conductive materials and composite. The machining performance of EDD can be significantly impacted by the EDD controller and movement control of the electrode, especially for M-EDD, due to the size of the machined holes. However, the development of controller and servosystem for M-EDD are still lacking. Also, the servo system can be combined with geometry prediction to improve the machining accuracy. The research on geometry prediction on EDD is one of the trends in recent years. Little research has been carried out to establish the models of the EDD hole making process to predict the geometry of machined holes. By predicting the wear of the electrode, the compensation can be applied to improve machining accuracy. However, the research on this region is still lacking.

Author contribution Not applicable: optional.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. This research was partially supported by the Australian Research Council (ARC) under the Discovery Projects scheme [Grant Number: DP180100762 and DP210103278]. As the Chief Investigator, Songlin Ding has received research support from the ARC.

Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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