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Developments in electrochemical discharge machining: A review on electrochemical discharge machining, process variants and their hybrid method

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Abstract

Electrochemical Discharge Machining (ECDM) is a hybrid non-conventional machining process used for machining both electrically conductive and non-conductive materials. It is particularly favoured for fabricating micro-scale features such as micro-holes, micro-channels, micro-grooves, and intricate 3D shapes across various materials. To enhance the efficiency of the ECDM process, several technical modifications have been integrated into its basic configuration, leading to the development of different ECDM process variants. Furthermore, researchers have introduced ECDM-based triplex hybrid methods to further optimize and enrich the process. This review article provides a comprehensive overview of recent advancements in the ECDM process, its variants, and triplex hybrid techniques. Additionally, future research opportunities and potential directions are explored.

1. Introduction

The rapid advancement of micro-level products has garnered significant attention due to their vast applications in fields such as micro-electromechanical systems (MEMS), microfluidics, and biomedical testing systems [1-3]. The manufacturing of these products has placed immense pressure on industries to develop efficient and cost-effective solutions. To meet industrial demands, researchers have explored both non-conventional and lithography-based micromachining techniques [4]. For small production volumes, non-conventional machining methods are more economical compared to lithographic techniques. Non-conventional machining processes utilize thermal, mechanical, or chemical energy—or a combination of these—for material removal. Thermal energy-based methods include laser beam machining (LBM) and electric discharge machining (EDM). LBM is effective in machining ceramics, polymers, and metals but involves high equipment costs and maintenance. Additionally, the presence of a heat-affected zone (HAZ) limits its industrial applications [5]. Thermal energy is

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also utilized in micro electric discharge machining (μ-EDM) [6] and wire-cut electric discharge machining (W-EDM)[7].But these techniques are restricted to conductive materials. Mechanical energy-based methods such as micro ultrasonic machining (USM) and abrasive jet machining (AJM) enable the creation of intricate micro-features on hard and brittle materials, regardless of their electrical conductivity [8,9]. However, their inability to process ductile materials limits their applications. On the other hand, chemical energy-based machining techniques offer the advantage of producing complex micro-profiles with a smooth surface finish on various materials [10]. Despite this, they suffer from drawbacks such as slow processing speeds, low dimensional accuracy, and limited aspect ratio structures. There was a growing need for a machining process capable of handling a wide range of materials, regardless of hardness, strength, or conductivity. To address this, electrochemical discharge machining (ECDM) was introduced by Kura Fuji in the 1968s [11].

Electrochemical discharge machining (ECDM) is an advanced micromachining technique that integrates two non-conventional machining processes: electrochemical machining (ECM) and electric discharge machining (EDM) [12]. Its simple setup and compact size make ECDM an attractive option for micro fabrication. In the literature, ECDM has been referred to by various names, including spark-assisted chemical engraving [13], electrochemical spark machining [14], micro electrochemical discharge machining [15], electrochemical arc machining [16], discharge machining of non-conductors [17], and electro-erosion dissolution machining [18]. One of the key advantages of ECDM over other machining techniques is its ability to process both conductive and non-conductive materials, as well as hard, brittle, and ductile materials. Initially, this method was used for drilling glass substrates [19], but it was later applied to machining ceramics, composites, and stainless steel. To enhance the capabilities of ECDM, researchers have manipulated electrochemical discharge energy, leading to the development of various ECDM process variants. These advancements have enabled operations such as fabricating intricate micro-profiles [20], producing micro-dies, deep drilling [21], machining cylindrical components [22], dressing micro-grinding tools [23], and slicing glass rods [24]. Overall, ECDM variants have demonstrated significant potential in microfabrication. However, ECDM also has limitations, including low aspect ratio structures and limited accuracy. To address these challenges, researchers have introduced external energy sources, resulting in the development of several ECDM process variants. More recently, the

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simultaneous integration of multiple external energy sources with ECDM has given rise to new triplex hybrid methods, which have significantly improved process performance. Despite these advancements, research is ongoing to further optimize the technique.

This paper aims to present recent developments in ECDM process variants and triplex hybrid methods, highlighting key findings and exploring future research opportunities.

1.1 Electrochemical discharge machining (ECDM)

Electrochemical Discharge Machining (ECDM) is a widely recognized hybrid micro-machining technique used for fabricating miniature components on both electrically conductive [25]and non-conductive materials [26]. The ECDM setup consists of two electrodes immersed in an electrolyte solution: the tool electrode (cathode) and the auxiliary electrode (anode). The workpiece is positioned beneath the tool electrode, as illustrated in Figure 1.

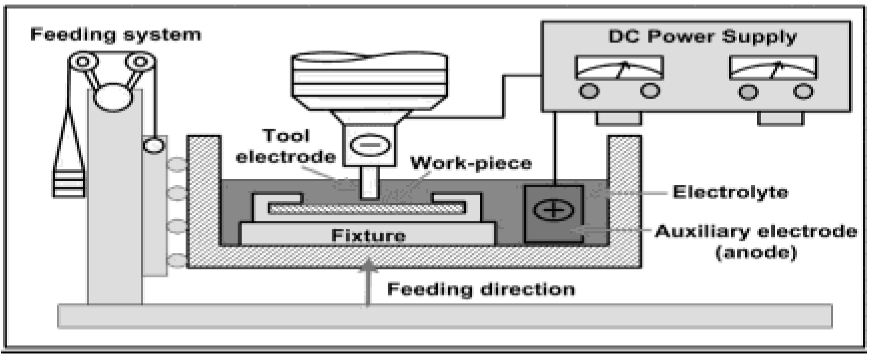

Fig. 1. ECDM Schematic

A DC power source supplies voltage across the electrodes, forming an electrochemical cell (ECC). Within the ECC, electrolysis occurs due to the potential difference between the electrodes, generating hydrogen gas bubbles at the tool electrode [27] and oxygen gas bubbles at the auxiliary electrode. Once the voltage surpasses a critical level, the rate of hydrogen bubble formation near the tool electrode exceeds the rate at which the bubbles disperse, leading to the accumulation of hydrogen gas around the tool [28]. These individual bubbles merge, forming a single large gas bubble, which eventually turns into a hydrogen gas film surrounding the tool electrode. This hydrogen gas film acts as an insulating layer, significantly reducing current flow [29] and creating a high electric field (around 10 V/mm) across the film, ultimately leading to arc discharge. High current densities at the sharp edges of the tool trigger spark

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initiation, and as the discharge progresses, it spreads across the tool's surface [30]. During this process, electrons bombard the nearby workpiece, generating intense heat that melts and removes material from the workpiece surface.

Figure 2 Illustrates the discharge mechanism, which involves the following stages:

1. Electrolysis
2. Generation and accumulation of hydrogen bubbles
3. Bubble coalescence and gas film formation
4. Sparking and material removal

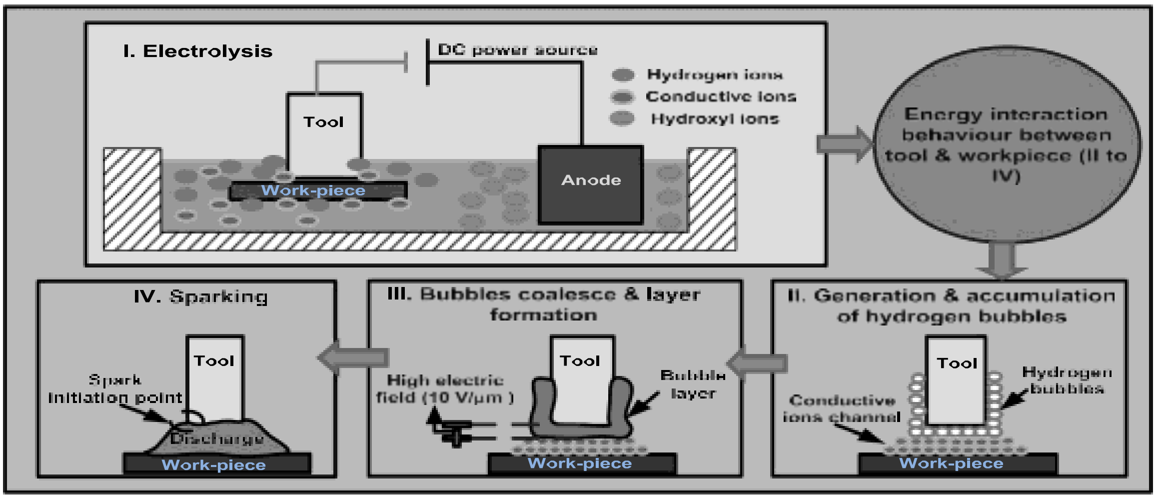

Fig. 2. ECDM Processes

Researchers have proposed different explanations for this discharge mechanism. Basak and Ghosh suggested that small conductive bridges exist within the densely packed gas film [31]. The high current densities in these bridges cause localized boiling, leading to arc discharge. Jain et al. viewed each gas bubble as a valve that breaks down under high electric fields, creating identical arc discharges. Meanwhile, Behrouz et al. captured simultaneous images of current signals and the patterns left on the workpiece, revealing that the arc discharge [32] takes on a cylindrical shape, reflected in the circular signatures on the machined surface.

The continuous discharge process also raises the electrolyte temperature, promoting chemical etching, which enhances surface finish. The combination of discharge melting and chemical etching makes the material removal mechanism highly complex [33]. While research is ongoing to quantify the contribution of each mechanism, experimental studies have confirmed that multiple process parameters directly influence ECDM performance. These parameters are broadly categorized into six groups, as illustrated in Figure 3:

1. Tool electrode
2. Workpiece
3. Electrolyte
4. Auxiliary electrode
5. Power source
6. Gaps between the electrodes and tool-workpiece

The cause-and-effect diagram in Figure 3 highlights the key factors governing ECDM process performance. Further research continues to refine our understanding of these interactions to enhance machining efficiency and precision.

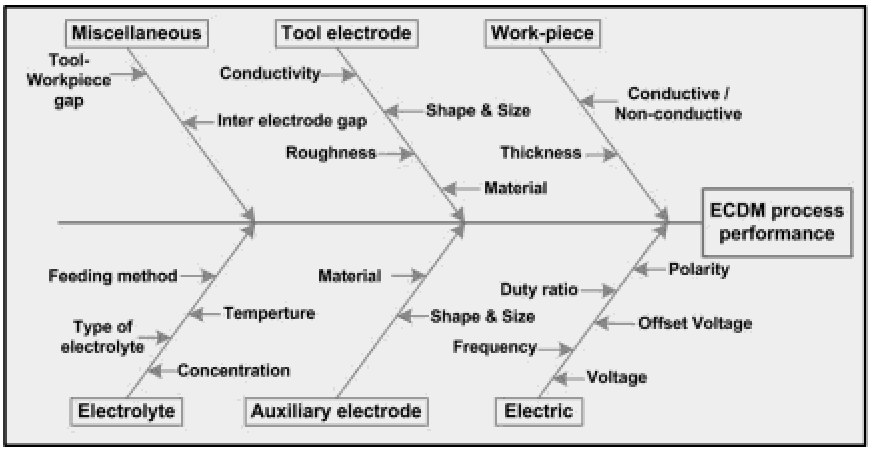

Fig. 3. ECDM Parameters

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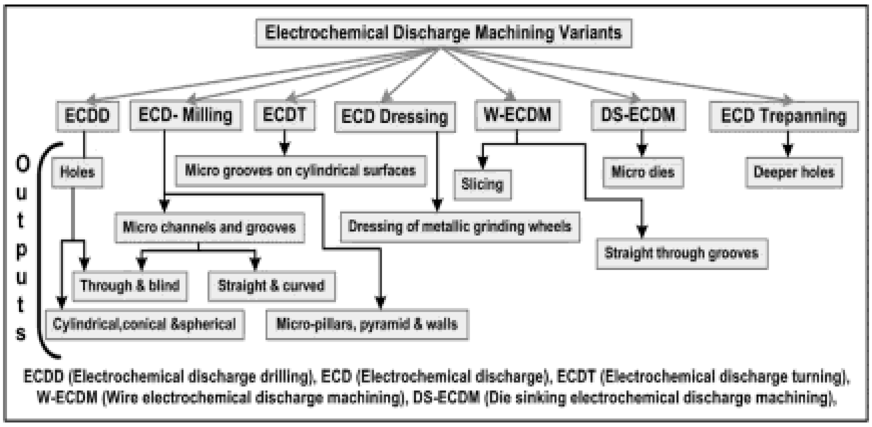

Fig. 4. Process Variants

2. ECDM Process Variants

Electrochemical Discharge Machining (ECDM) is a hybrid machining process that combines the principles of Electrochemical Machining (ECM) and Electrical Discharge Machining (EDM). This process is particularly useful for machining hard and brittle materials such as glass, ceramics, and composites, even if they are non-conductive. Different operations can be performed using the ECDM principle, includes:

Drilling – Used to create small, precise holes in non-conductive materials.

Milling – Enables the machining of complex shapes and surface textures.

Cutting – Suitable for slicing brittle materials without excessive tool wear.

Die-Sinking – Helps in creating intricate cavities and patterns.

Dressing – Used for modifying and sharpening abrasive grinding wheels.

Turning – Allows controlled removal of material for rotationally symmetric components.

These operations leverage the unique combination of electrochemical and electro-discharge effects, enabling material removal with minimal mechanical stress, making them ideal for delicate and intricate applications.

2.1 ECDM drilling

Electrochemical Discharge Drilling (ECDD) has gained significant attention due to the increasing demand for high-aspect-ratio, precise holes in both thick and thin substrates. This

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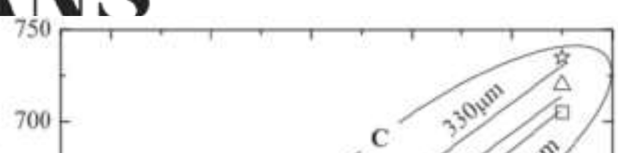
process plays a crucial role in microfabrication, with researchers successfully drilling both through and blind micromoles using the ECDD technique.

Initially, ECDD was primarily used for machining conductive materials such as cobalt, low-alloy steels, chrome, titanium, and neonic alloys. The machined surfaces of these materials exhibit a smooth finish, comparable to those achieved through electrochemical machining. However, beyond conductive materials, ECDD has also been effectively utilized for drilling non-conductive and brittle materials, including silicon nitride ceramics, steels, borosilicate glass, Pyrex wafers, soda lime glass, other glass wafers, silicon wafers, and e-glass-fibre-epoxy composites. The ECDD process is carried out by controlling the progressive movement of the tool electrode along the z-axis. The interaction between the tool electrode's movement and the discharge energy makes the process highly complex. Various parameters, including those related to the electrolyte, tool electrode, and power supply, play a critical role in regulating discharge energy and influencing machining performance. The next section explores significant research findings on key process parameters affecting ECDD.

In Electrochemical Discharge Machining (ECDM), machining voltage and drilling depth are crucial parameters that directly influence the discharge energy in the machining zone. As a result, the accuracy of machined microholes is determined by these factors, as illustrated in Fig. 5 [40]. Based on different combinations of machining voltage and drilling depth, the resultant mean diameter of the holes can be categorized into three distinct zones: A, B, and C.

- **Zone A:** Micro holes in this zone are drilled at a voltage range of 28–37 V with a drilling depth of 100 µm. In this range, the mean diameter of the machined hole remains unaffected by machining voltage. Drilling occurs exclusively in the discharge regime, resulting in well-defined cylindrical contours with a smooth surface finish.
- **Zone B:** This zone includes micro holes with jagged outline contours, drilled at 30 V with depths of 200 µm and 300 µm. Drilling takes place in a transition phase between the discharge and hydrodynamic regimes, leading to irregular hole geometries.
- **Zone C:** Holes in this zone are drilled at voltages above 30 V with depths exceeding 100 µm. These holes are characterized by the presence of a heat-affected zone around their periphery. As drilling depth increases, it becomes increasingly challenging to maintain a continuous electrolyte supply at the tool tip. Consequently, the machining



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speed is no longer controlled by the number of discharges in the machining zone. Instead, it depends solely on drilling depth and becomes independent of machining voltage [40].

Fig. 5. Effect of machining voltage and drilling depth on the average diameter of the micro hole [40]

In the Electrochemical Discharge Drilling (ECDD) process, reducing gas film thickness is essential for achieving better repeatability [43]. To address this, research suggests adding surfactants, such as liquid soap, to the electrolytic bath. The presence of a surfactant helps to thin the gas film, leading to more uniform discharge energy distribution. As a result, the ECDD process delivers more consistent machining outcomes [44].

Apart from electrolyte modifications, tool electrode parameters also play a significant role in the ECDD process. The thermal conductivity of the tool electrode material directly influences the machining rate. Electrodes with high thermal conductivity facilitate higher material removal rates in the discharge regime but result in lower machining rates in the hydrodynamic regime. In the discharge regime, material removal occurs due to the concentration of heat energy on the tool surface. However, in the hydrodynamic regime, the machining process depends on how much heat energy reaches the machining zone. Since highly thermally conductive electrodes dissipate heat more efficiently towards the tool surface rather than the machining zone, they enhance machining rates in the discharge regime but reduce efficiency in the hydrodynamic regime [45].

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Another critical factor affecting machining performance in ECDD is the surface roughness of the tool electrode. The roughness determines the electrode's wettability, which influences gas film formation and process stability. Specifically, coarser tool electrode surfaces improve the material removal rate (MRR) by enhancing gas film coalescence and maintaining stable hole diameters during machining [46]. Therefore, using a rougher tool electrode surface is recommended for achieving higher MRR in ECDM [46].

A tool electrode with a spherical tip offers higher machining rates and improved accuracy compared to a conventional cylindrical electrode. The curved surface of the spherical electrode reduces the contact area between the tool and the workpiece, enhancing electrolyte flow at the tool's end [47]. This improved electrolyte circulation facilitates the rapid formation of the gas film, which in turn increases discharge frequency and material removal rate (MRR). As a result, machining efficiency significantly improves. Compared to a conventional cylindrical electrode, a spherical-tip electrode achieves an 83% reduction in machining time and a 65% reduction in hole diameter when fabricating 500 mm deep holes [47].

Tool wear is another critical factor affecting machining accuracy in the Electrochemical Discharge Drilling (ECDD) process. To maintain precision, Behroozfar et al. [48] studied tool wear behavior for different electrode materials under various voltage levels. Their findings indicate that steel and tungsten carbide (WC) tools deliver better performance and durability than brass electrodes [48].Beyond high-aspect-ratio holes, ECDD can also be used to drill holes with conical or spherical cross-sections by adjusting the polarity of the tool electrode. The tool electrode can be connected to either the negative (cathodic) or positive (anodic) terminal of the power supply, influencing the electrochemical action. This polarity adjustment alters the chemical etching process, particularly through the behaviour of hydroxyl (OH^-) radicals near the machining zone.

- **Cathodic Polarity:** The concentration of hydroxyl radicals decreases along the hole depth, leading to the formation of conical cross-section holes.
- **Anodic Polarity:** The Hickling-Ingram mechanism ensures a uniform distribution of hydroxyl radicals along the hole depth, resulting in holes with a spherical cross-section.

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Interestingly, chemical etching during the ECDD process smooths the spark-discharge-machined surface, yielding a refined surface finish [36]. A representative image of these cross-section variations is shown in Fig. 6 [36].

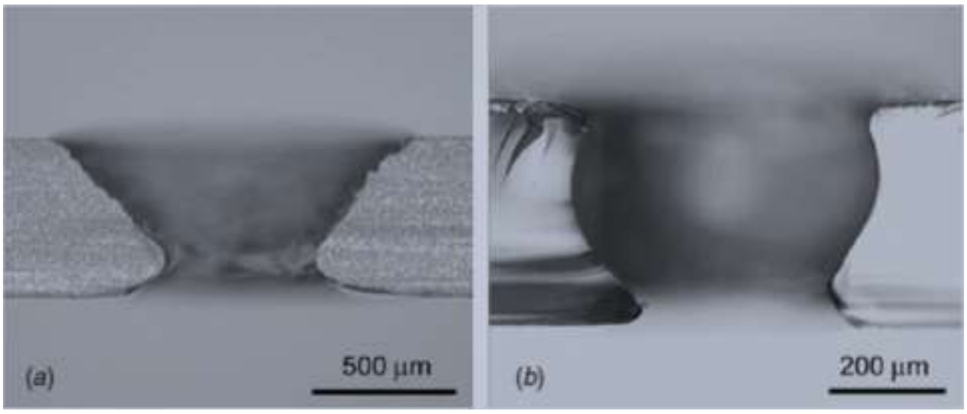

Fig. 6. ECDD developed micro holes

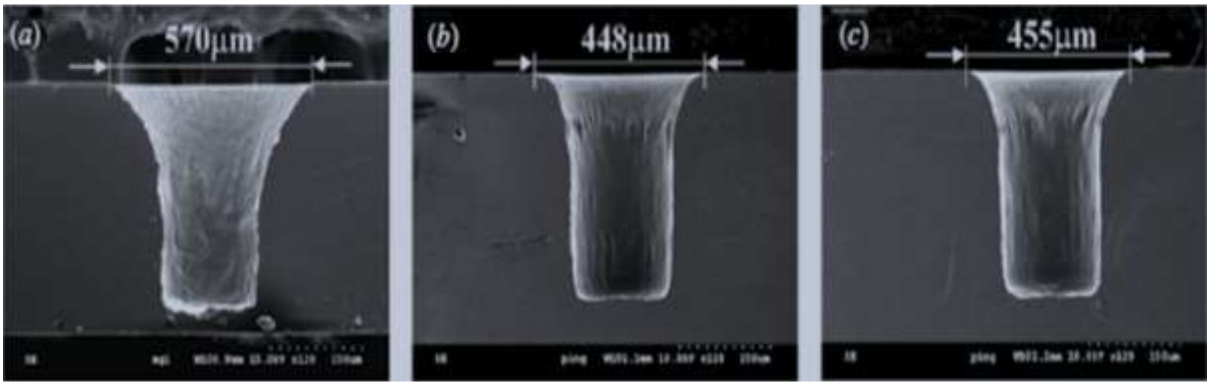

Fig. 7. Micro holes developed by using (a) DC voltage (b) pulse voltage, and (c) offset pulse voltage [50].

Electrochemical Discharge Drilling (ECDD) is a highly versatile process that has been successfully utilized for the rapid prototyping of fused silica microdevices. This technique enables the fabrication of high-aspect-ratio structures with micro-crack-free surfaces and a near-polished finish [49]. Reports indicate that conical holes with a diameter of 300 µm and a depth of 450 µm can be drilled in just 30 seconds [49].

For achieving nearly straight holes, the use of a DC pulsed power supply is recommended. Additionally, research has shown that applying an offset voltage of 10 V can reduce machining

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time by approximately 60% while maintaining similar hole accuracy, as illustrated in Fig. 7 [50].

2.2 ECDM Milling

The Electrochemical Discharge Milling (ECDM) process has emerged as a promising technique for fabricating complex 3D microstructures on glass and quartz materials. Researchers have successfully used this method for surface texturing of microchannels [54], as well as for the fabrication of microchannels [20,51,52] and microgrooves [53].

In ECDM, a rotating cylindrical wheel serves as the cutting tool (cathode electrode) and follows a predefined machining path. Among the key process parameters, tool rotation rate and tool travel rate play a crucial role in determining machining outcomes. A higher tool rotation rate helps eliminate electrolyte replenishment issues, leading to microgrooves with reduced width and sharper edges. However, groove depth remains independent of the tool rotation rate. The individual effects of tool rotation rate on groove width and depth are illustrated in Fig. 8 [55].

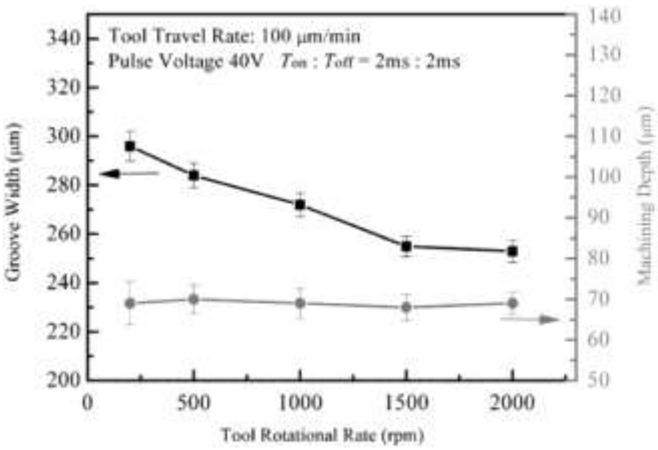

Fig. 8. Effect of tool rotational rate on groove width and depth [55]

Additionally, a higher tool travel rate results in shallower microgrooves with increased width, as shown in Fig. 9 [55]. To achieve deeper microgrooves, a layer-by-layer material removal approach with a small depth of cut is employed in ECDM. This approach enhances electrolyte flushing in narrow and deep machining zones, allowing for the fabrication of deeper microgrooves with a smooth surface finish.

For achieving precise microgroove shapes on glass substrates, Zheng et al. recommended the following machining parameters:

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- **Voltage:** 40 V DC
- **Pulse on/off duration:** 2 ms: 2 ms
- **Tool rotation rate:** 1500 rpm
- **Tool travel rate:** 1000 mm/min [55]

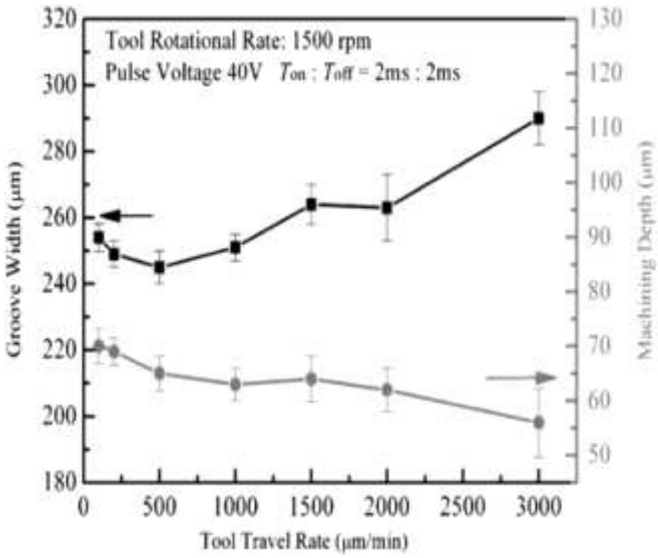

Fig. 9. Effect of tool travel rate on groove width and depth [55].

The potential of the ECDM process in machining intricate microstructures, such as micro-grooves, micro-pillars, and micro-pyramids, is demonstrated in Fig. 10. The ability to fabricate such precise structures highlights the versatility and effectiveness of the ECDM process [56].

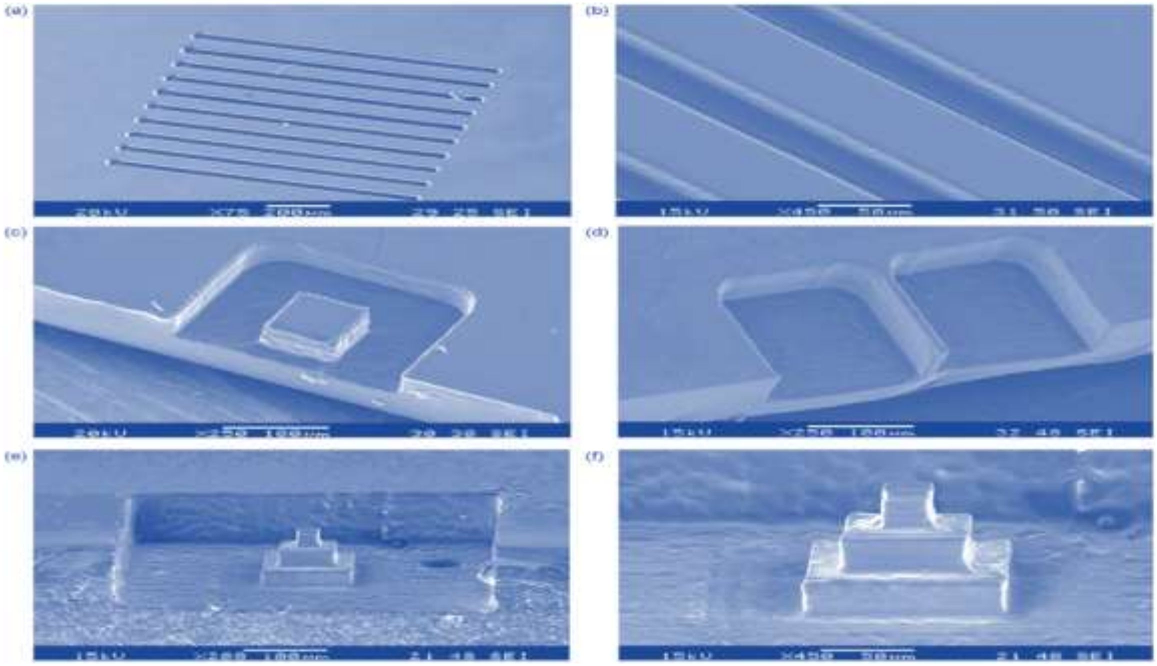

Fig. 10. a) Micro-grooves, (b) enlarged figure of micro-grooves, (c) micro-pillar, (d) micro-wall, and (e,f) micro-pyramid machined on glass [56].

2.3 ECDM turning

Electrochemical Discharge Machining (ECDM) with continuous rotation of the workpiece is an advanced technique used for machining cylindrical components. A schematic representation of this process, known as Electrochemical Discharge Turning (ECDT), is illustrated in Fig. 11. In this setup, the rotating workpiece is submerged in an electrolytic bath. During machining, the rotational motion enhances the supply of fresh electrolyte into the narrow gap between the tool and the workpiece.

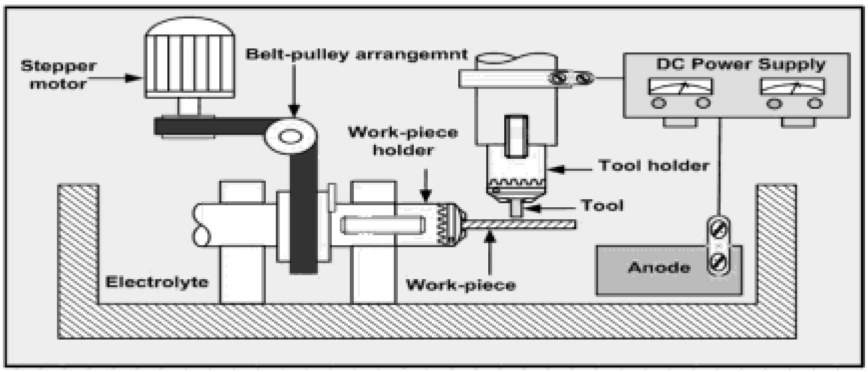

Fig. 11.

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The rotation speed of the workpiece plays a crucial role in determining process performance. At an optimal rotation rate, deep, narrow grooves with sharp edges can be effectively machined. However, excessively high rotation speeds hinder film formation, leading to a reduction in material removal rate (MRR). Thus, maintaining an appropriate rotation speed is essential for achieving efficient machining outcomes [22].

2.4 ECDM dressing

The dressing of worn micro-grinding tools using the principles of Electrochemical Discharge Machining (ECDM) has led to the development of an innovative process variant known as Electrochemical Discharge Dressing (ECDD) [23]. This process involves immersing the worn grinding tool (cathode) in an electrolyte, along with an auxiliary electrode (anode). During ECDD, spark energy facilitates the removal of metallic bonds and workpiece debris from the surface of the worn micro-grinding tool. This results in the protrusion of fresh abrasive grains along the tool's periphery, effectively restoring its cutting ability. The electrolyte in this process serves multiple functions, acting as a dresser, dielectric medium, cooling agent, and flushing agent to prevent burr formation in the machining area. The performance of ECDD is assessed based on the surface morphology of the grinding tools, the forces exerted during grinding, and the surface roughness of the machined components. This method has been found to produce protruded grains that are free from damage. Additionally, the use of ECDD-treated grinding tools has demonstrated a 50% reduction in normal grinding forces, leading to improved surface quality with lower roughness [57].

2.5 Wire ECDM

Many researchers have integrated the principles of Wire Electric Discharge Machining (WEDM) with Electrochemical Discharge Machining (ECDM) to develop Wire Electrochemical Discharge Machining (WECDM), an effective process for slicing and cutting hard and brittle materials [62]. In WECDM, a traveling wire immersed in an electrolyte serves as the cutting tool (cathode), as illustrated in Fig. 12 [24,58].

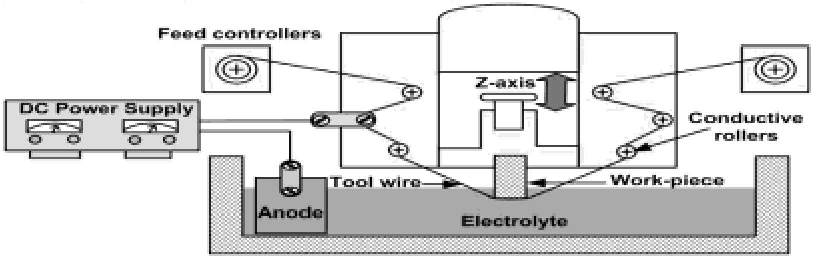

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Fig. 12.

To maintain consistent contact between the workpiece and the tool wire, Yang et al. proposed two workpiece feed mechanisms: the weight-loading mechanism and the reciprocating mechanism. Among these, the reciprocating mechanism demonstrated superior surface quality and accuracy in machining micro-grooves, as shown in Fig. 13 [59]. In contrast, the weight-loading mechanism relies on mechanical force to keep the wire and workpiece close together, which hinders effective debris flushing. The accumulation of unflushed debris leads to secondary discharges, resulting in poor surface quality and imprecise micro-groove profiles. The reciprocating (to-and-fro) motion of the workpiece across the tool wire improves debris removal, enhancing machining performance.

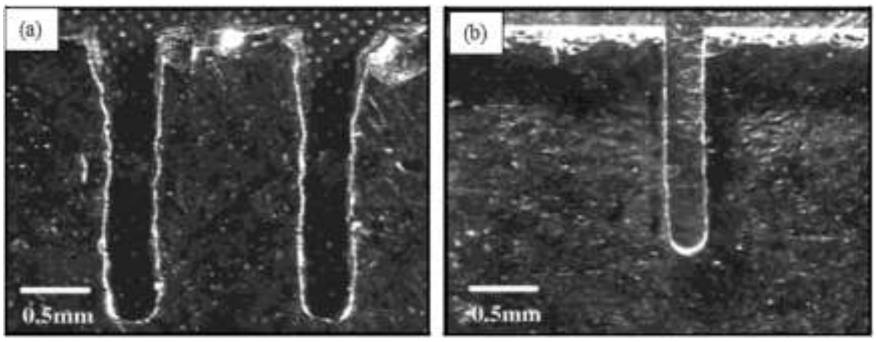

Fig. 13.

To further improve machining rates and the geometric accuracy of micro-grooves, SiC abrasive particles are introduced into the electrolytic bath (Yang et al.). These abrasives disrupt the formation of the insulating layer around the tool wire, increasing the critical voltage and promoting efficient material removal. Additionally, SiC abrasives act as finishing agents by eliminating micro-cracks and melted zones from the machined surfaces [59].

During micro-groove fabrication, the feed rate is a critical process parameter, significantly influencing the slit depth, as shown in Fig. 14 [60]. The maximum recorded slit depth is 2000 μm at a feed rate of 350 μm/min. However, increasing the feed rate beyond this point disrupts the gas film around the tool, reducing slit depth. Interestingly, the mean slit width remains unaffected by feed rate variations [60].

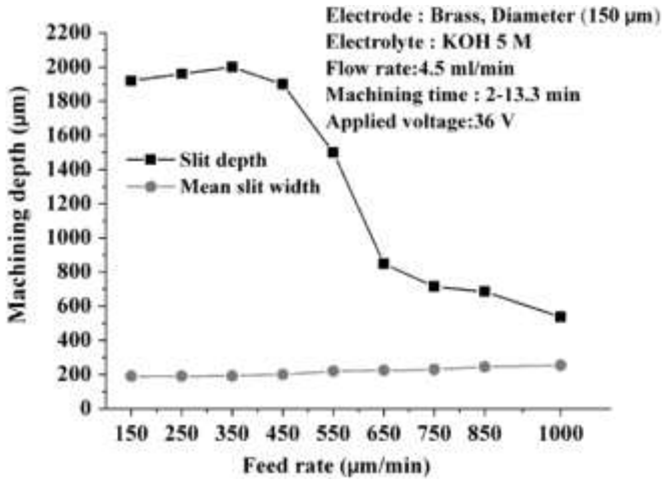

Fig. 14.

In Wire Electrochemical Discharge Machining (WECDM), the occurrence of electric discharges within the electrolytic bath generates toxic fumes, leading to environmental pollution, particularly around the machining chamber. To mitigate this issue, Chand et al. developed the titrated electrolyte flow method, which involves supplying the electrolyte in the form of droplets. This approach reduces the amount of electrolyte available at the machining zone, thereby minimizing environmental pollution [60].

An interesting aspect of this method is the comparison of material removal rates with the conventional setup—whether it is higher, lower, or similar remains an area of investigation. The optimal wire breakage conditions have been identified at an electrolyte concentration of 10% and a voltage below 60 V. Additionally, WECDM is a cost-effective machining process [61].

One of the key advantages of WECDM is its ability to process both conductive and non-conductive materials. It has been successfully applied to machine a wide range of materials, including glass [58], ceramics [63], quartz [60], glass-epoxy, Kevlar-epoxy [64], and metal matrix composites [65].

2.6 Die-sinking ECDM

The die-sinking variant of the Electrochemical Discharge Machining (ECDM) process is widely used for fabricating small and shallow dies on both conductive [18] and non-conductive materials [66]. Research on Die-Sinking ECDM (DS-ECDM) has shown that it achieves a

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higher material removal rate (MRR) compared to standalone Electrochemical Machining (ECM) and Electrical Discharge Machining (EDM) processes [18]. In terms of precision, the dimensional tolerances of machined parts in DS-ECDM are comparable to those in EDM and even better than those in ECM. However, the surface integrity of machined parts is influenced by the combined effects of ECM and EDM. High sinking rates can be achieved using a hollow bronze tool, with a feed rate ranging from 3 to 18 mm/min, a pulsed DC voltage of 20–30 V, and an electrolyte solution containing 120 g/l $NaClO_3$ [18]. In this setup, the tool electrode is a bronze pipe with an inner diameter of 3.7 mm and an outer diameter of 9.4 mm, ensuring efficient machining performance.

2.7 Electro chemical discharge trepanning

The Electrochemical Discharge Trepanning (ECDT) method has been successfully used to fabricate deep holes in hard and brittle materials. In this process, the tool electrode is given an orbital motion by offsetting its axis from the spindle axis. ECDT has proven to be an efficient and cost-effective technique for deep-hole machining. Jain et al. extended the depth limitations of the ECDM process by fabricating through-holes with depths of 1.35 mm in alumina and 2.35 mm in quartz [21]. To further enhance surface quality and hole depth, Chak et al. replaced the conventional gravity-fed tool with a spring-fed tool embedded with abrasive particles. These abrasive particles facilitate high-frequency electrical discharges, while the rougher tool surface improves cutting action. As a result, the process achieves a higher material removal rate (MRR) and better-machined surface quality. Additionally, the use of an abrasive electrode significantly reduces the average taper value from 13.411 to 2.051. Experimental findings also indicate that using a pulsed DC power supply enhances process efficiency [67].

3. ECDM triplex hybrid methods

Electrochemical Discharge Machining (ECDM) is a hybrid machining process that combines the principles of electrochemical and electrical discharge machining. This unique combination of energies has been effectively used for various machining operations, including drilling, milling, and turning.

To further enhance the performance of ECDM-based processes, researchers have integrated additional energy sources, leading to the development of ECDM-based triplex hybrid methods. These processes involve a controlled and simultaneous interaction of three energy sources

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within the ECDM setup. Based on the nature of the third energy source or interaction, triplex hybrid processes are categorized into primary and secondary hybrid methods (Fig. 15).

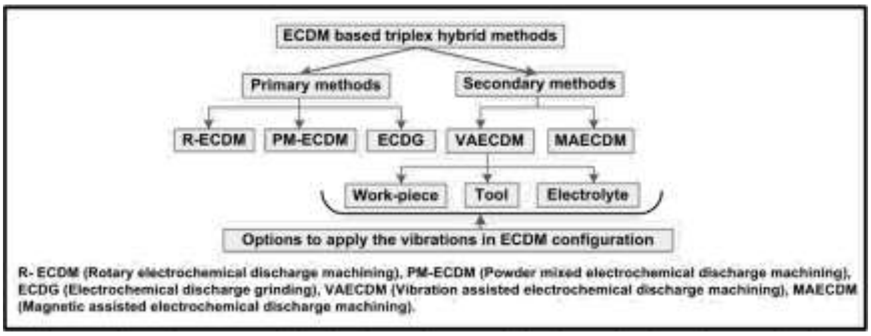

Fig. 15.

Primary hybridization occurs when a third energy source is introduced through tool rotation or by adding powders into the electrolyte. In contrast, secondary hybridization involves the use of mechanical or magnetic forces to assist material removal. However, in all these methods, electrochemical discharge remains the primary mechanism for material removal.

The following section of this paper provides a detailed discussion on various ECDM-based triplex hybrid methods

3.1 R- ECDM (Rotary- ECDM)

The introduction of tool electrode rotation in Electrochemical Discharge Machining (ECDM) has led to the development of a primary triplex hybrid method known as Rotary Electrochemical Discharge Machining (R-ECDM) [68–72]. This process offers the advantage of drilling straight holes with small entrance diameters due to the rotary motion of the tool electrode.Tool rotation helps distribute spark energy more uniformly across the machining region, rather than concentrating it at a single point. As a result, the drilled holes are straighter, smoother, and crack-free. However, excessively high tool rotation speeds can cause significant agitation in the electrolytic bath, destabilizing the discharge and reducing machining efficiency.During the machining of Pyrex glass using a cylindrical tool with a 200 µm diameter, the variation in hole entrance diameter with respect to tool rotation speed can be divided into two distinct regions. In **Region I** (500 to 1500 rpm), the entrance diameter of the hole progressively decreases as the tool rotation speed increases. In **Region II** (beyond 1500 rpm), lower sparking frequency and prolonged machining time lead to an increase in the hole

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entrance diameter.For better form and dimensional accuracy of the holes, the gap between the hole's periphery and the tool's sidewall is a crucial factor. To maintain form accuracy, Zheng et al. designed a tool with flat sidewalls and a flat front (Fig. 16). This design allows for adjusting the distance between the hole's periphery and the tool sidewall by modifying the tool thickness. Increasing this distance minimizes discharge effects on the hole's sidewalls while also ensuring electrolyte supply in the narrow gap. As a result, deep micro-holes with minimal taper can be achieved [68].Tungsten carbide-based rotary tools have been successfully used to create micro-holes in glass substrates with an impressive aspect ratio of 11:1 [69]. Additionally, J. Kozak et al. developed physical and mathematical models to predict the performance characteristics of R-ECDM, recommending shorter pulse on-times for improved surface quality. Their mathematical model has also been suggested for practical applications [70].R-ECDM has been widely used to fabricate micro-holes in various materials, including borosilicate glass [69], Pyrex glass [68], difficult-to-cut steel [71], and stainless steel [72].

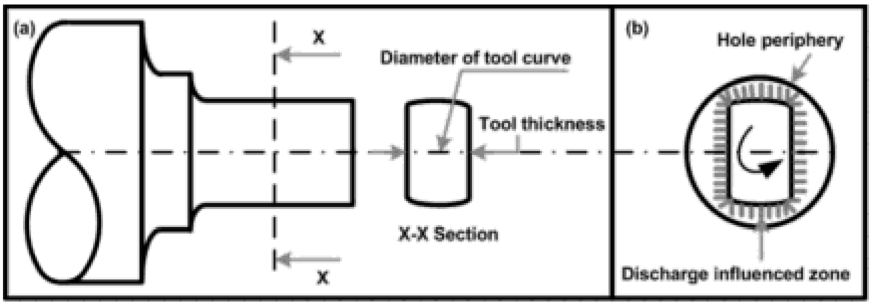

Fig. 16.

3.2 Powder mixed ECDM

The addition of abrasive particles to the electrolytic medium has led to the development of a triplex hybrid method in Electrochemical Discharge Machining (ECDM) known as Powder-Mixed Electrochemical Discharge Machining (PM-ECDM). This method enhances surface integrity and improves process repeatability.

The presence of abrasive particles, such as graphite, within the gas film helps reduce the direct impact of spark energy on the work surface, resulting in a smoother surface finish. The extent of spark energy reduction depends on how the conductive abrasive particles behave between the tool electrode and the work surface.

Han et al. described two key behaviors of conductive particles in this process:

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1. Conductive particles attached to the tool electrode intensify the electric field at localized areas, leading to more stable discharges.
2. Electrostatic forces cause the abrasive particles to move dynamically, enabling continuous charge transfer between the tool electrode and the work surface.

In the machining of borosilicate glass, the introduction of graphite abrasive particles (10 mm in diameter) into a sodium hydroxide electrolyte solution significantly improved surface roughness, reducing it from 4.86 µm to 1.44 µm [73].

3.3 ECDM- Grinding

Electrochemical Discharge Grinding (ECDG) is a triplex hybrid machining process that integrates three distinct mechanisms: mechanical abrasive cutting, electrochemical dissolution, and electrical discharge erosion [74]. This combination enhances machining efficiency and allows for precise material removal.

In ECDG, a rotary tool embedded with abrasive particles acts as both a grinding wheel and a cathode. The periphery of the grinding wheel consists of abrasive particle layers held together by a metallic bonding system. The conductive metallic bond material facilitates spark generation, which melts and removes material from the work surface. Simultaneously, the abrasive cutting action contributes to material removal through mechanical abrasion [75].

The material removal mechanism in ECDG is illustrated in Fig. 17 [76]. For improved surface quality and higher material removal rates, experimental studies have shown that maintaining a minimal gap and maximizing the contact area between the abrasive tool and the work surface is essential. A thinner gas film with maximum cutting edges enhances machining performance. Additionally, tool feed rate is identified as a critical parameter to ensure proper contact between the abrasive particles and the workpiece.

ECDG has been effectively used for developing micro-holes and finishing cylindrical surfaces, particularly through the centerless grinding module of ECDM [23]. Researchers have recommended conical grinding wheels for machining borosilicate glass and cylindrical grinding wheels for alumina to optimize the process for different materials [76]. This method has also been successfully applied to machine metal matrix composites [77, 78], alumina, and glass [76].

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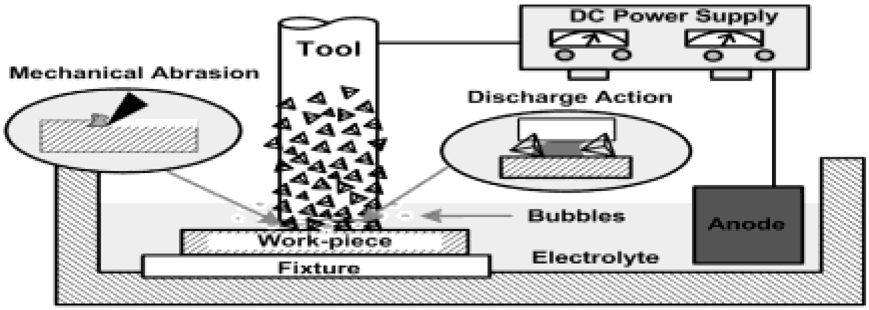

Fig. 17.

3.4 Magnetic field assisted electrochemical discharge machining (MAECDM)

Cheng et al. introduced a magnetic-field-assisted electrochemical discharge machining (MAECDM) method by incorporating a magnetic unit inside the tool chuck to enhance machining efficiency and improve micro-hole accuracy. The MAECDM system features a specialized magnetic tool chuck to hold the tool electrode, as illustrated in Fig. 18. The setup allows for the application of a magnetic field in both upward and downward directions.

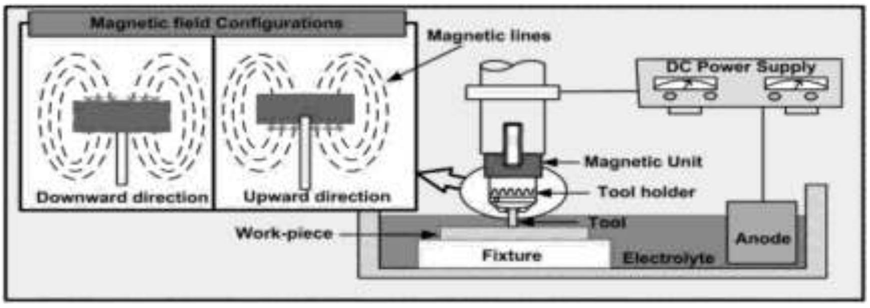

Fig. 18.

When the magnetic field is applied, magnetohydrodynamic (MHD) convection is induced in the electrolyte, enhancing electrolyte circulation within narrow gaps. This improved circulation facilitates the removal of hydrogen gas bubbles from the tool surface, necessitating a higher voltage to maintain a stable gas film over the tool electrode. The increased voltage contributes to greater machining efficiency. Additionally, efficient electrolyte circulation preserves gas film quality during deep-hole fabrication, ensuring stable discharges that enhance geometrical accuracy.

Studies indicate that applying an upward magnetic field leads to a 57.4% reduction in machining time and a 23.8% decrease in overcut, demonstrating significant process improvements [79].

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3.5 Vibration based ECDM

In electrochemical discharge machining (ECDM), an inadequate electrolyte supply between the tool tip and the workpiece surface presents a challenge in fabricating deep micro-holes. To address this issue, researchers have explored the use of vibrations applied to the tool electrode [80], electrolyte [81], or workpiece [82].

Notably, Wuthrich et al. successfully drilled 300 mm deep micro-holes within 10 seconds by applying low-frequency vibrations (0–30 Hz) to a tool electrode with a 0.4 mm diameter. These tool vibrations effectively doubled the material removal rate (MRR) [80]. Additionally, modifying the gas film geometry with ultrasonic vibrations (≥2 mm amplitude) led to consecutive pulse discharges, further increasing MRR compared to conventional ECDM without vibration. Sustained pulse discharges over longer durations enabled the fabrication of deeper holes.

Interestingly, increasing the vibration amplitude from 2 mm to 3.5 mm resulted in wider and denser pulse discharges. While this led to a lower MRR, it significantly improved surface integrity. According to percolation theory, these wide current pulses are associated with faradic currents, which arise due to electrolysis on the tool surface when gas bubble density is low [82].

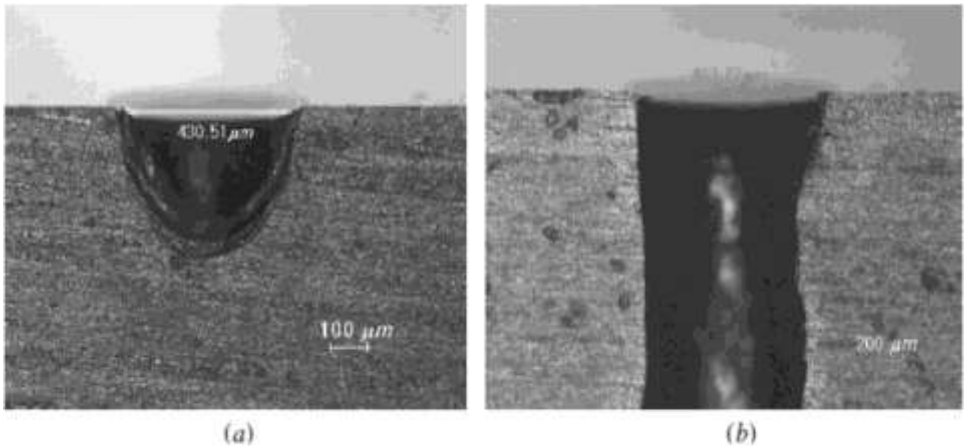

Fig. 19.

Furthermore, applying a 1.7 MHz frequency to the electrolyte solution generated uniform sparks around the tool's walls and bottom face. This uniform discharge enhanced hole depth

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while reducing taper, as shown in Fig. 19, increasing the hole depth from 320 µm to 550 µm [81]. The use of ultrasonic vibrations effectively improved electrolyte supply at the machining zone, with vibration amplitude being a critical process parameter.

4. Research Potential

This review article provides an overview of research conducted in the field of electrochemical discharge machining (ECDM), including its process variants and triplex hybrid methods. The literature suggests that past research has primarily focused on developing micro-features on non-conductive materials. A summary of published studies on ECDM variants is presented in Fig. 20.

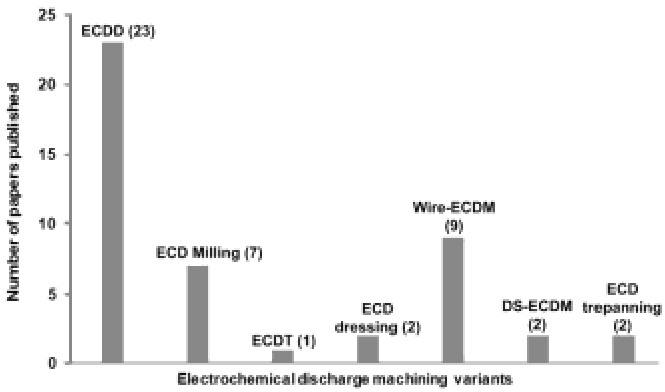

Fig. 20.

It is evident that electrochemical energy has been widely utilized in micro-hole drilling through the electrochemical discharge drilling (ECDD) process variant. ECDD has demonstrated the ability to drill micro-holes with conical or spherical profiles [36] and fabricate deep micro-holes with an aspect ratio of 11:1 [69]. Additionally, the electrochemical discharge milling variant has been used to engrave serpentine-shaped microchannels with a width of 30 µm, a depth of 70 µm, and a surface roughness of 0.099 µm [56]. The potential to generate surface textures on microchannel surfaces using electrochemical discharge milling [54] highlights emerging opportunities for microfluidic applications. Further research is required to achieve repeatable and well-defined surface textures through this process.

Moreover, various other process variants have been explored for performing diverse operations on different materials. The capabilities of these variants, along with potential research directions, are compiled in Table 1.

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Electrolytic media play a crucial role in ECDM, significantly influencing process performance. The search for environmentally friendly, cost-effective, and efficient electrolytes is ongoing, with water-based emulsions emerging as a promising alternative. In industrial applications, the primary objectives are to achieve high precision, superior surface integrity, and cost-effective processing. Every investigation into the ECDM process or its variants aims to fulfill these requirements. However, minor modifications to existing processes—without requiring significant changes—could enhance process efficiency. An example of such an advancement is the development of vibration-assisted ECDM [80], which integrates small process variations to improve machining performance.

Table 1 Research potential of ECDM

ECDM variants	Capabilities of the ECDM process variants		Research opportunities
	Geometrical features	Work materials	
Electrochemical discharge drilling	*Feature shapes:* conical, spherical [36] and cylindrical [40] hole forms. *Maximum aspect ratio* = 11:1 [69]	Cobalt, low-alloy steels, chrome, titanium, nimonic alloys [34], silicon nitride ceramics [19], cutting steel [35], borosilicate glass [36–38], e-glass–fiber–epoxy composites [42], soda lime glass [40], silicon wafers [25] and Pyrex wafer [39].	Improvement in process repeatability and accuracy can increase industrial applicability
Electrochemical discharge milling	*Feature shapes:* complex 3D micro-structures like micro grooves [53], micro channels (straight, U-shaped and serpentine), micro-pillars, micro-pyramids [56] and surface texturing of the micro channels [54]. *Dimensions:* width of 30 µm and depth of 70 µm with surface roughness of 0.099 µm [56].	Pyrex glass [53,55], borosilicate glass [54] and quartz [52].	Investigations can be conducted on electrochemical discharge milling for fabrication of complex micro features with high aspect ratios.
Electrochemical discharge turning	*Feature shapes:* micro grooves on cylindrical rods of diameter 5 mm [22]. *Dimensions:* Width .35 mm and depth .6 mm [22].	Soda lime glass [22].	Possibilities exist to machine other materials.
Electrochemical discharge dressing	Dressing of 850 µm grinding tool [57].	Applied only for metallic bonded diamond coated grinding wheels [23,57].	In depth parametric analysis can provide better results as well as wider scope.
Wire-electrochemical discharge machining	*Feature shapes:* micro-grooves, micro slots [61,59,60] and cutting of glass rods [62]. *Dimensions:* 8.8 mm long slots [61] and minimum width of the slots 160 µm [60].	Glass [58], ceramics [63], quartz [60] glass-epoxy, Kevlar-epoxy [64] and metal matrix composites [65].	Possibilities exist for addition of additional axes in manipulator for machining of complex 3D profiles.
Die-sinking electrochemical discharge machining	*Feature shapes:* cylindrical dies [19]. *Dimensions:* Depth of blind sink= 30 mm [19]. *Conicity in cylindrical die shape (die-shaping factor)* = 0.05–0.19 mm/mm [19].	316 Stainless steel alloy [19].	Research related to the processing of different materials and complex die shapes demands more investigation.
Electrochemical discharge trepanning	*Feature shapes:* cylindrical holes [21]. *Dimensions:* 2.35 mm depth of hole [21].	Alumina and quartz [21].	Modifications in tool design can further enhance the dimensional accuracy of the process.

The vibration-assisted ECDM process has demonstrated the capability to drill 300 µm holes in less than 10 seconds. However, a comprehensive study is essential to further enhance its potential applications.

The manufacturing industry is increasingly focusing on the development of micro-level products, particularly using high-strength advanced materials. To meet current market demands for micro-product fabrication, ECDM presents an opportunity to create multiple micro-features—such as holes, channels, and surface textures—on a single substrate. This capability opens new research avenues for various fields, including lab-on-a-chip technology and microelectromechanical systems (MEMS).

Composite materials, recognized for their high strength-to-weight ratio, corrosion resistance, chemical resistance, and durability, are gaining prominence as future materials [83]. However, limited research has been conducted on machining composite materials, including metal matrix and polymer matrix composites. There is significant potential for fabricating complex geometries on these materials using ECDM.

Ultimately, the true value of research in electrochemical discharge machining will be realized when these advancements are successfully integrated into industrial applications, enabling innovative manufacturing solutions.

5 Conclusions

After a comprehensive analysis of advancements in electrochemical discharge machining (ECDM) variants and its triplex hybrid methods, the following key conclusions can be drawn:

1. **Versatile Machining Process** – ECDM is a prominent non-conventional hybrid machining technique capable of processing both conductive and non-conductive materials.
2. **Enhanced Micro-Fabrication** – A significant advancement in ECDM variants is the ability to fabricate intricate microscale profiles on difficult-to-machine materials, achieving high surface quality and improved machining rates.
3. **Emerging Dressing Technique** – Electrochemical discharge dressing is a promising method for effectively restoring worn micro-grinding tools.
4. **Efficient Material Slicing** – Wire electrochemical discharge machining (W-ECDM) is a highly effective technique for slicing materials, regardless of their conductivity.
5. **Cylindrical Machining Capability** – Electrochemical discharge turning (ECDT) is an adaptable extension of ECDM, suitable for machining cylindrical components.

6. **Improved Drilling Performance** – Rotary ECDM (R-ECDM), vibration-assisted ECDM (VAECDM), and magnetic-field-assisted ECDM (MAECDM) enhance drilling efficiency by improving material removal rate, hole depth, and accuracy. Additionally, electrochemical discharge trepanning is particularly well-suited for drilling deep holes with large diameters.

7. **Effective Surface Finishing** – Electrochemical discharge grinding (ECDG) is a highly efficient method for finishing micro-holes and cylindrical surfaces on both conductive and non-conductive materials.

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