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Evaluation of Material Removal Mechanism and Strategic Solutions to Improve Performance in the ECDM Process

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ABSTRACT: *First introduced in 1968, Electrochemical Discharge Machining (ECDM), also known as Electrochemical Spark Machining (ECSM), opened a new direction in the field of non-traditional machining. This method is primarily applied to process non-conductive materials such as quartz, glass, ceramics, and similar substances. Although numerous studies have been published, the material removal mechanism in the ECDM process has not yet been fully clarified. Moreover, to date, this technology remains mainly a subject of academic research and has not been widely applied in the industrial sector. Therefore, in-depth research is essential to improve machining efficiency and expand the practical application potential of ECDM. This paper presents an overview of the material removal mechanism in ECDM, and proposes research directions and potential solutions to enhance the removal rate and overall efficiency of the machining process in the future.*

Keywords— *ECDM, Material removal mechanism, Biodegradable dielectric fluid, Discharge voltage, Fuzzy-logic, Artificial neural network.*

NOMENCLATURE

Symbol	**Description**	**Unit**
Vcrit	Critical Voltage	*V*
Icrit	Critical Current	*A*
V	Voltage	*V*
I	Current	*A*
T	Temperature	*℃*
Espark	Spark Energy	*J*
V_f	Feed Rate	*mm/s or mm/min*
MRR	Material Removal Rate	mm^3/min or mm^3/s
SR	Surface Roughness	*µm*
SEC	Specific Energy Consumption	J/mm^3
Cp	Concentration	*g/ml*
EWR	Electrode Wear Rate	% or mm^3/min
rpm	Rotations per minute	*rpm*
mS/cm	MilliSiemens per cm	*mS/cm*
E	Eccentricity	*mm*
d	Tool diameter	*mm*
D	Diameter of hole drill	*mm*

Greek letter

η	Efficiency	

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I. INTRODUCTION

Electrochemical Discharge Machining (ECDM) is an advanced micromachining technique, particularly effective for processing non-conductive materials such as glass and ceramics. This machining process is a combination of two phenomena: electrolysis and electrical discharge. When a direct current (DC) or pulsed voltage is applied between the tool electrode (typically the cathode) and the counter electrode (typically the anode), electrolysis occurs in an alkaline electrolyte solution (such as NaOH or KOH), generating hydrogen and oxygen gas bubbles. Once the voltage exceeds a certain threshold, the gas bubbles accumulate and coalesce to form an insulating gas film around the tool electrode. This gas film acts as a dielectric medium, enabling electrical discharges to take place. The heat generated from these discharge pulses, combined with the chemical etching effect of the electrolyte, causes melting, vaporization, and subsequent removal of material from the workpiece surface. Thanks to this unique mechanism, ECDM is capable of precisely fabricating microstructures such as holes, grooves, microchannels, and 3D pillars on non-conductive substrates. The machining performance in ECDM is influenced by various technological parameters, including the electrode material and geometry, feed rate, type of electrolyte, applied voltage and current, as well as the inter-electrode gap. Its outstanding precision and design flexibility have made ECDM widely applicable in the fabrication of complex microscale features. This method is demonstrating significant potential in high-tech fields such as microelectromechanical systems (MEMS), biomedical engineering, and microfluidics.

II. MECHANISM OF MATERIAL REMOVAL

2.1. The gas film formation

In the ECDM (Electrochemical Discharge Machining) process, material removal efficiency primarily depends on the formation of a gas film around the electrode (Fig. 1). The gas film is generated through bubble coalescence due to electrochemical reactions or localized vaporization caused by the Joule heating effect (Fig. 1(a, b)), or a combination of both. As the current density increases, the number and size of bubbles also increase.

This bubble layer consists of three distinct zones: the adhesion zone (attached to the electrode), the diffusion zone, and the saturated solution zone, where bubble growth ceases [1].

When the applied voltage exceeds the critical threshold, bubbles coalesce to form a continuous gas film (Fig. 1(c)). At elevated electrolyte temperatures, the gas film becomes thinner, more uniform, and exhibits slight oscillations. Discharge initiates at a localized point and propagates along the gas film–electrolyte interface (Fig. 1(d)), inducing material removal through melting, vaporization, and electrochemical dissolution due to the low electrical conductivity of the electrolyte.

A thorough investigation of the gas film's structure, formation mechanism, and discharge behavior is essential. Geometric parameters (e.g., thickness, dimensions) can be captured using high-speed imaging, though challenges arise due to process instability. The gas film thickness is influenced by electrode geometry, electrolyte type/concentration, temperature, and surface wettability. The film's physical composition can be analyzed using spectroscopic techniques.

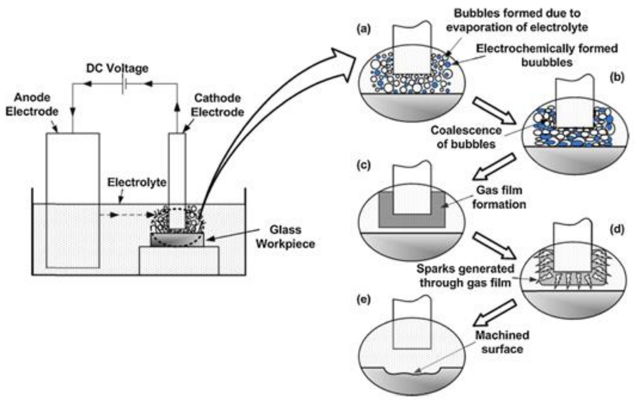

Fig. 1. Schematic diagram of ECDM illustrating formation of gas film and associated machining; (a) electrolyte evaporation and bubble formation, (b) Coalescence of bubbles, (c) gas film formation, (d) discharging/sparking through gas film, and (e) thermally eroded/machined surface of workpiece

In electrochemical discharge machining (ECDM), the average gas film formation time represents a critical kinetic parameter that determines discharge initiation and varies with machining parameters. The discharge process is characterized by five distinct regions in the current-voltage characteristic curve (Fig. 2[2]): (i) OA region - no electrolysis occurs due to insufficient voltage, (ii) AB region - linear current increase with bubble accumulation around the electrode, (iii) BC region - current reaches critical limit (Icrit) with bubble coalescence, (iv) CD region - rapid current decrease as the gas film forms, and (v) DE region - complete electrode insulation occurs with spark generation initiating material removal. The film formation time depends on inter-electrode resistance during power application.

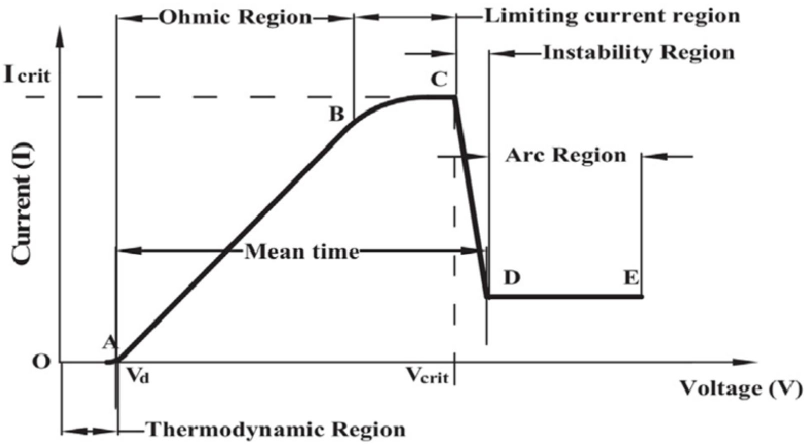

Fig. 2. Current–voltage characteristic of film formation and discharge in ECDM (adapted from [2]).

Experimental observations (Fig. 3) demonstrate that current gradually increases over time due to electrolyte heating and consequent resistance reduction, enhancing conductivity; when current exceeds the threshold, bubble formation occurs leading to gas film development [3]. The gas film serves as a dielectric layer for the discharge process, with its quality directly affecting machining efficiency. Influencing factors include: buoyancy force, surface tension, capillary thermal flow, electrostatic force between bubbles and electrode, surface wettability, current density, resistivity, as well as tool dimensions and immersion depth (Fig. 4).

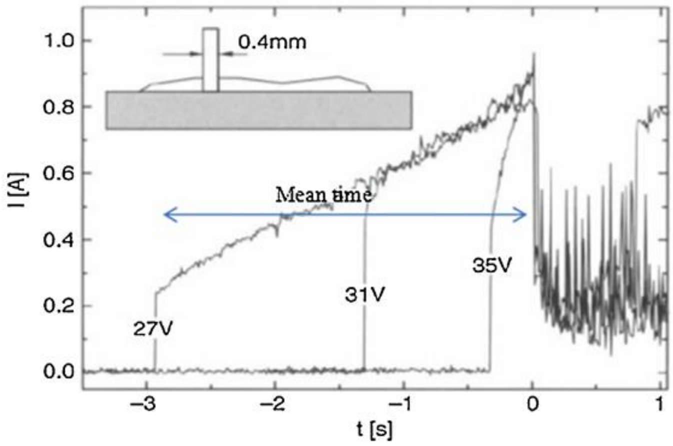

Fig. 3. Voltage step input for various voltages in the case of a high inter-electrode resistance (adapted from [3]).

The gas film forms through combined effects of hydrogen bubbles (from electrochemical reactions at the cathode) and electrolyte vapor, according to the reactions: Cathode: $2H_2O + 2e^- \rightarrow 2(OH)^- + H\uparrow$; Anode: $4(OH)^- \rightarrow 2H_2O + O\uparrow + 4e^-$.

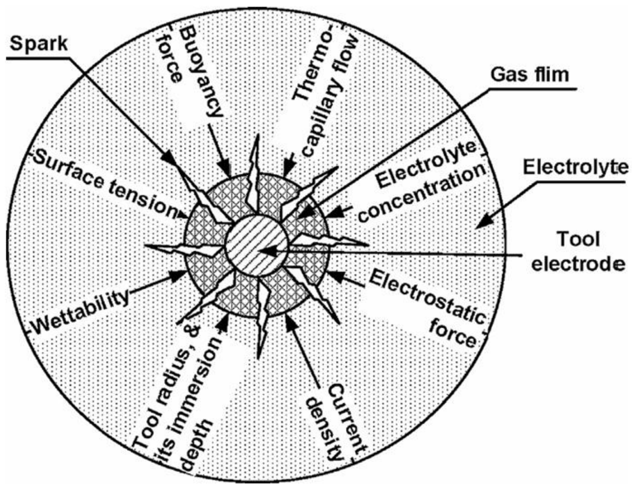

Fig. 4. Parameters affecting the gas film.

Current density directly influences bubble formation rate. Bubbles detach from the surface through the interaction between buoyancy force and surface tension. When voltage exceeds the critical threshold, bubbles coalesce to form a gas film. Bubble wettability is affected by electrolyte viscosity and temperature. The gas film demonstrates greater stability in static environments but becomes unstable under electrolyte agitation. Bubble layer thickness depends on multiple factors including: electrolyte resistance, electrode surface area, tool radius, and immersion depth.

According to Han et al. [4], when tool radius increases from 50 to 300 μm and immersion depth rises from 8 to 303 μm, the minimum gas film thickness increases from 3 to 45 μm. Guelcher et al. [5] further demonstrated that capillary thermal flow, induced by temperature gradients at the electrode surface, promotes bubble migration and coalescence, facilitating gas film formation.

2.2. Stability of the gas film

In electrochemical discharge machining (ECDM), the gas film typically exhibits instability and oscillations, adversely affecting micro-machining repeatability. Pulse voltage application has been shown to improve stability by enabling controlled formation and collapse of the gas film, thereby reducing fluctuations, enhancing precision, and lowering the required critical voltage [6]. Gas film thickness can be modulated through four primary approaches: (i) inducing hydrodynamic flow via electrode or workpiece rotation, (ii) improving electrode wettability through surfactants like SDS [7], (iii) increasing bubble nucleation site density, and (iv) employing pulse voltage to reduce heat accumulation and improve machining accuracy [8] ,[9]. Furthermore, elevated electrolyte concentration accelerates electrolysis, generating additional OH^- ions while reducing surface tension, which collectively thins the gas film and enhances machining precision [10]. Gautam and Jain [11] demonstrated that tool rotation (particularly orbital motion) significantly increases machining depth, while Wüthrich and Bleuler [12] developed a stochastic model of bubble growth dynamics that established critical voltage and current density thresholds. Fig. 5 [2] illustrates the ECDM material removal mechanism where discharge-induced high temperatures reduce glass viscosity, facilitating chemical etching through the formation of a softened glass zone containing electrolyte salts and water vapor, thereby accelerating the machining process.

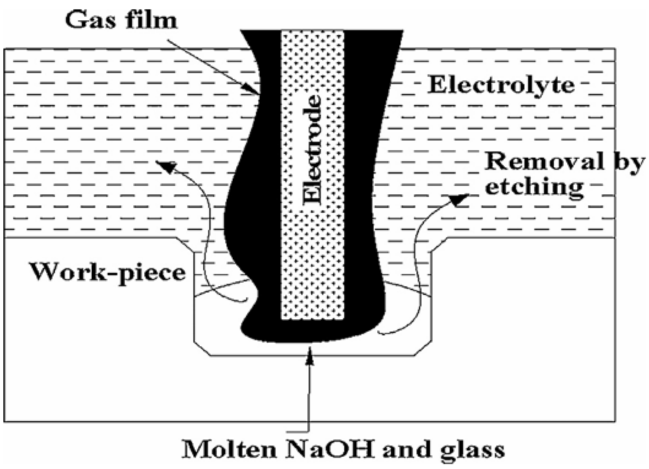

Fig. 5. Schematic of glass machining with ECDM (adapted from [1])

When NaOH is employed as the electrolyte, the material removal process occurs through the sodium silicate formation reaction: $2NaOH + SiO_2 \rightarrow Na_2SiO_3 + H_2O$, where the reaction products are subsequently flushed away by the electrolyte flow. Elevated electrolyte temperatures accelerate this reaction, thereby enhancing the machining rate [13]. At shallow depths, rapid material removal occurs when sufficient temperatures are achieved due to efficient heat transfer within the workpiece. Conversely, at greater depths, restricted electrolyte access to the tool tip reduces discharge activity, diminishes chemical etching, and hampers debris removal, consequently decreasing the machining rate - demonstrating the depth-dependent nature of material removal rate. Furthermore, the electrolyte's complex physicochemical properties significantly influence machining performance. The ECDM process is governed by multiple interrelated factors, as clearly illustrated in Fig. 6 through a fishbone diagram that systematically presents the cause-effect relationships governing the machining process.

III. ANALYSIS OF DISCHARGE MECHANISM

The working principle of ECDM has been extensively studied, yet the discharge mechanism remains incompletely understood. Liu et al. [14] described the process with the workpiece as anode and tool electrode as cathode, where electric double layers form on both electrode surfaces. When the cathode's double layer becomes fully charged, H_2 gas generation increases the interelectrode resistance, causing voltage to rise until breakdown occurs, initiating sparks and sustaining arc discharge. The discharge cycle consists of three phases: rapid voltage increase, spark generation, and arc maintenance voltage, followed by voltage drop to zero at pulse termination. Their model predicts breakdown voltages between 26-34 V, matching experimental results. Kulkarni et al. [15] investigated discharges on various materials at 155 V in 5% HCl solution, observing discrete current pulses at 30-93 Hz frequency, with discharges occurring above 25 V - resembling gas discharge phenomena under strong electrode fields. Skrabalak et al. [16] developed a hybrid model combining simultaneous electrochemical (ECD) and discharge (EDM) processes in the interelectrode gap, dependent on gap thickness: ECD dominates at gaps exceeding threshold, while both ECD and EDM occur at/below threshold. Machining rate and surface quality depend on this interaction, primarily governed by feed rate and current. They also developed a fuzzy-logic controller for real-time feed rate adjustment, improving machining quality through rapid response to voltage and current fluctuations.

Mediliyegedara et al.[17] demonstrated that ECDM performance in terms of surface quality and material removal rate depends on complex interrelated factors that are difficult to model using conventional mathematical approaches. They proposed a pulse classification system comprising five distinct types: arc discharge, spark discharge, electrochemical discharge, pure electrochemical, and short-circuit pulses, utilizing artificial neural networks for accurate pulse identification. Jiang et al.[18] developed a model to estimate spark energy and analyze conical electrode effects. Their findings revealed that while sudden current surges upon voltage application indicate spark initiation, spark discharge may not occur immediately even when the threshold voltage is exceeded, primarily due to gas film instability. This phenomenon underscores the critical role of gas film stability in discharge initiation, where unstable gas films can delay or prevent spark generation despite sufficient voltage conditions.

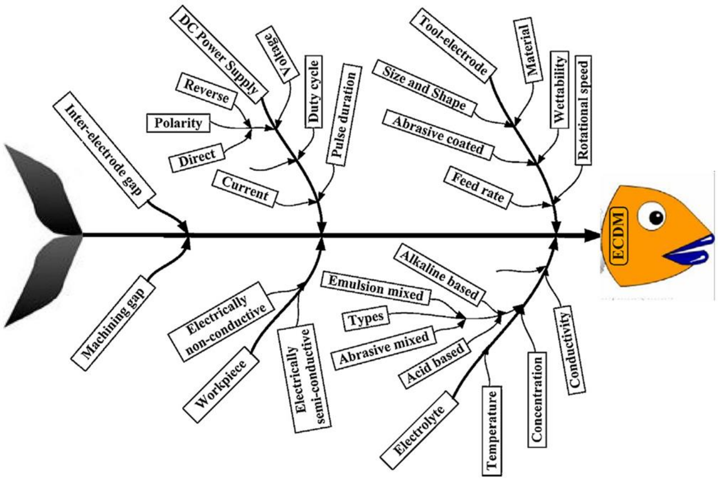

Fig. 6. Fish-bone diagram of various parameters involved in the ECDM process.

IV. ENHANCEMENT IN MATERIAL REMOVEAL

In the ECDM machining process, performance is typically evaluated based on factors such as material removal rate (MRR), surface quality, and machining accuracy. Among these, MRR is the most frequently emphasized aspect in the majority of studies [10, 11, 19-24]. The machining efficiency is influenced by several key operating parameters, and previous research has primarily focused on analyzing the effects of these parameters on MRR when processing materials like glass. Relevant advancements and some notable approaches proposed by various authors will be briefly outlined in the following section.

4.1. Enhancing chemical etching

Optimizing the flow of the electrolyte solution to the machining zone, especially during the drilling of deep holes, can enhance the efficiency of chemical erosion in the ECDM process. Maintaining a stable electrolyte flow can be improved by employing tool electrode movements such as rotation or vibration. Moreover, designing appropriate electrode shapes — such as ball-end, helical, rectangular, or cylindrical cross-sections — also significantly contributes to improving the circulation of the electrolyte solution to the machining area. [25-28]

4.2. Effect of tool-electrode shape

Compared to cylindrical electrodes, needle-shaped electrodes provide significantly faster drilling speed and higher efficiency, especially at low voltages, with an average drilling rate approximately ten times greater. Wüthrich et al.[29] xplained that in the discharge zone, needle-shaped electrodes concentrate the discharge sparks at the tool tip, thereby increasing the discharge density and resulting in a higher material removal rate—this effect is particularly pronounced in the discharge region. In addition, ball-end electrodes [25], which have a smaller contact area between the tool and the workpiece, have also been reported to enhance the flow of the electrolyte solution toward the tool tip. Furthermore, tool vibration, as observed by Wüthrich et al.[30] was also found to increase the drilling rate.

4.3. Effect of tool-electrode rotation

Rotating the electrode during drilling at a fixed feed rate helps improve the MRR, accuracy, and surface finish while limiting stray corrosion at the hole entrance and bottom. According to Gautam and Jain [11], a low rotational speed (below 25 rpm) enhances efficiency due to a stable gas film, whereas high speeds cause instability, reducing effectiveness. Electrode rotation also aids in dispersing discharge sparks, reducing tool wear. When using an eccentric electrode, the machining depth increases and reaches an optimal level when the eccentricity equals the tool radius (Fig. 7 [11]). An appropriate eccentricity improves electrolyte circulation, flushing debris out of the hole. A small eccentricity produces a flat hole (Fig. 7b), while excessive eccentricity causes a central protrusion (Fig. 7d), leading to debris accumulation, reduced conductivity, and slower machining rates.

4.4. Effect of voltage

Voltage critically influences ECDM performance through three primary mechanisms. Firstly, elevated voltage enhances hydrogen bubble generation, increasing discharge energy and initially improving MRR. However, beyond 100V, excessive gas formation leads to debris accumulation that surpasses the electrolyte's removal capacity [19]. Secondly, the resulting thermal effects induce micro-cracks, with complete ceramic fracture observed at this threshold [31]. Thirdly, voltage fluctuations modify the electrolysis mechanism, creating challenges in balancing discharge energy with process stability.

4.5. Effect of electrolyte concentration

The concentration of the electrolyte significantly affects the material removal rate (MRR) in the ECDM process. As the concentration increases, the electrochemical reactions between the anode and cathode intensify, generating more discharge sparks and gas bubbles, thereby improving MRR. However, when the concentration exceeds the optimal threshold (e.g., 250 g/l NaOH [32]), the discharge efficiency diminishes, leading to a reduction in MRR. On the other hand, the viscosity of the solution increases with concentration, enhancing the surface finish of the machined material.

In the case of using a mixed solution of KOH and NaOH, increasing the concentration from 5.5 wt% to 15 wt% [33] raises the electrical conductivity from 275 to 375 mS/cm, which promotes the chemical etching process. Similar results were observed in a study using NaOH solution on silicon nitride-based material [34].

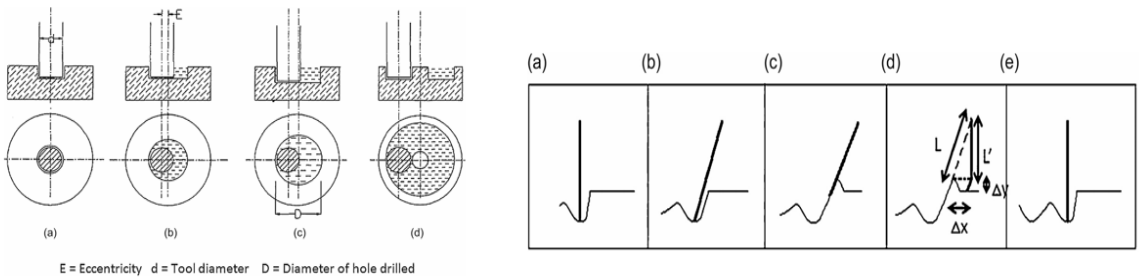

Fig. 7. Various rotation configurations of the tool-electrode during machining: (a) without eccentricity, (b) with eccentricity less than the tool radius, (c) with eccentricity equal to the tool radius, and (d) with eccentricity greater than the tool radius (E > d/2) [35]. The figure also illustrates the "stick-and-jump" phenomenon during machining: (a) the groove surface being machined, (b) the tool getting stuck due to raised surrounding material, (c) the tool bending and snapping upward, (d) the tool recontacting at a new position on the surface, and (e) penetrating the material at the new location [36].

4.6. Effect of Different Plant-Based Tool Tips on Material Removal Rate (MRR) at Cp = 0.5 g/ml

In a separate study, Singaravel et al. (2020) investigated the EDM machining of Inconel 800 using W–Cu, brass, and Cu electrodes with sunflower oil and kerosene as dielectric fluids. Their findings highlighted that vegetable oils can serve as effective dielectric fluids, providing higher MRR, EWR, and SR compared to kerosene. Khan et al. (2022) explored EDM machining of Inconel 625 using a Cu electrode and conventional EDM oil in the presence of a magnetic field. The magnetic field improved SR, MRR, and EWR. Finally, MCui and Kumar (2016) examined SR and MRR in the EDM of Inconel 718 using Cu electrodes and three types of dielectric fluids: waste Pongamia Pinnata cooking oil, mixed waste cooking oil, and conventional hydrocarbon oil. The waste cooking oils demonstrated superior MRR and surface finish compared to hydrocarbon oil, with the mixed waste oil delivering the best overall performance.

4.7. Effect of Different Vegetable Oils on Specific Energy Consumption (SEC)

The SEC values in the EDM process using kerosene reached 1017.523 J/mm^3, whereas the SEC for biodegradable dielectric fluids was relatively lower. This highlights the importance of considering SEC values during process evaluation. To calculate CO_2 emissions, a standardized method was applied based on the IPCC report (Krey et al., 2014), following the study by Guan et al. (2018). The CO_2 emissions were determined by multiplying the SEC value by the average CO_2 emission factor of electricity (0.189 μg CO_2/J). However, when calculating CO_2 emissions from the EDM process using kerosene, it is necessary to exclude the CO_2 reduction achieved through the use of biodegradable dielectric fluids. Among these, olive oil demonstrated the highest CO_2 reduction potential compared to other biodegradable oils. The average CO_2 reductions of each oil relative to kerosene were as follows: sunflower oil 62.4%, sesame oil 83.1%, olive oil 84.1%, and soybean oil 77.3%.

V. SCOPES FOR FUTURE RESEARCH

The Electrochemical Discharge Machining (ECDM) process is an advanced technique; however, many physical phenomena, especially the roles of chemical and electrochemical reactions, remain poorly understood. In addition, the process parameters are still highly unpredictable, making it difficult to accurately forecast machining outcomes. Despite notable progress in machining hard-to-process materials such as glass, stainless steel, and metal matrix composites, challenges such as excessive cutting, surface roughness, micro-cracking, and heat-affected zones (HAZ) continue to persist.

To address these issues, future research should focus on improving material removal rate (MRR), controlling surface quality, and minimizing machining defects. This can be achieved by adjusting key parameters including voltage, pH level, electrolyte temperature, employing harder electrode materials, and optimizing the geometry of the tool. The use of pulsed power sources and specially designed electrodes, such as hollow or twisted types, is expected to enhance performance in deep hole drilling and improve electrolyte flow conditions.

Additionally, the implementation of high-speed cameras and real-time data analysis systems is recommended to better investigate the spark formation mechanism and the dynamics of gas film development. While traditional electrolytes like NaOH and KOH are commonly used, further exploration into alternative or combined electrolytic solutions could lead to more environmentally sustainable approaches.

To promote sustainable machining practices, future studies should also focus on clarifying the effectiveness of vegetable oils and waste oils in enhancing MRR, while reducing specific energy consumption (SEC) and CO_2 emissions during the EDM process. Comparing the performance of various biodegradable dielectric fluids—such as olive oil, sesame oil, and sunflower oil—under different machining conditions and materials is essential to determine the most optimal and eco-friendly solution.

Currently, the research team is developing rotating electrodes aimed at improving micro-hole drilling performance, particularly for achieving a depth-to-diameter ratio of ≥ 4. Although a ratio of 1.5 has been achieved, persistent challenges related to HAZ and cracking require further experimental investigation and optimization.

VI. CONCLUSION

Electrochemical discharge machining (ECDM) is an advanced machining technique that simultaneously integrates the mechanisms of both EDM and ECM, operating in different zones during the material removal process. This process is inherently complex and influenced by various factors such as the type and geometry of the electrode, surface wettability, feed rate, electrical pulse parameters, the type and temperature of the electrolyte, as well as the distances between the electrodes, the workpiece, and between the cathode and anode. Despite numerous efforts in modeling this process, its stochastic nature continues to pose significant challenges in accurately predicting machining performance.

ECDM is particularly effective for processing hard-to-machine materials such as ceramics and metal matrix composites. Commonly used electrolytes include NaOH and KOH, while tungsten carbide is a widely adopted electrode material. Various technical enhancements have been proposed to improve the efficiency of the process, including optimizing the electrolyte delivery system, rotating the electrode to disperse discharges, incorporating abrasive particles into the electrolyte, and maintaining a consistent gap between the electrode and the workpiece.

Notably, the use of vegetable oil as a bio-based dielectric medium not only improves machining efficiency but also reduces specific energy consumption (SEC) and CO_2 emissions, thereby contributing to the sustainability of the process. Furthermore, the combination of bio-dielectric fluids with external assistance techniques holds potential for enhancing discharge stability, increasing material removal rates, and expanding the applicability of ECDM.

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