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A Review on Electrochemical Discharge Machining Variants with Magnetic Field Assisted Electrochemical Discharge Machining.

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Abstract
Variants of the ECDM process are developed as a result of some of the enhancements. For additional process enrichment, the research community has created Magneto aided ECDM. A thorough analysis of these recent advancements in the ECDM method, its variations, and MHD-based ECDM is provided in this review article . Research potentials are recognized and presented as future research opportunities. Researchers that focus on the impact of controllable parameters on the rate of material removal and width overcut have already completed the majority of the work on traditional ECDM. The hydrodynamic regime must be controlled in order to fabricate deep micro channels. The gas film properties and bubble formation phenomena are governed by the hydrodynamic regime, which is key role for the creation.
The gas film properties and bubble formation phenomena are governed by the hydrodynamic regime, which is crucial for the creation of deep micro channels. The different voltage, concentration, and duty cycles cannot affect two important parameters (i) the thickness of the gas layer and (ii) the frequency of discharge. This study uses MHD convection to control the properties of gas films and the occurrence of bubbles.

1 Introduction

Considerable interest due to its amazing uses micro level product are used in a number of domains, including micro fluidics, micro electromechanical & biomedical systems[1]. Non-traditional machining methods are more cost-effective than lithographic procedures for small lot sizes. Electric discharge machining (ECDM) and laser beam machining (LBM) are examples of thermal energy-based technologies. LBM makes advantage of thermal energy for metal, polymer, and ceramic machining. It has a high maintenance cost and necessitates costly equipment. Moreover, its industrial applications are restricted by the presence of heat-affected zones (HAZ).[2].

There was a need for a machining process that can machine micro features over a wide variety of work materials, irrespective of material hardness, strength and conductivity. Thus electrochemical discharge machining (ECDM) were developed by Kura Fuji in 1968 s.

Their restricted usage stem from their inability to manufacture ductile materials. Chemical energy-based machining techniques create complex micro profiles with a smooth surface finish on a range of materials. However, the limitations of chemical processes are low aspect ratio structures, limited processing speed, and low dimension precision.[3]

In general, ECDM variants have proved their usefulness for micro fabrication. However, ECDM is also associated with limitations like low aspect ratio structures, low ac curacy etc. To overcome these limitations several external energies have been applied to the ECDM. This resulted in development of several ECDM process variants. Recently, the simultaneous involvement of these external energies with ECDM process, further developed new triplex hybrid methods. These triplex hybrid methods enhanced the performance meaningfully. Nonetheless research is still continuing to get the better results.

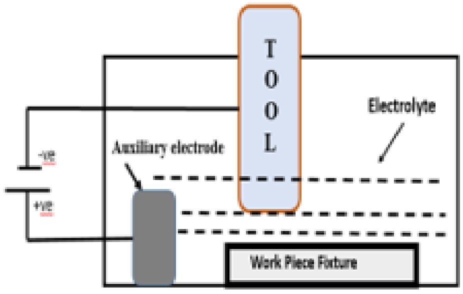

Fig.1 Line diagram of ECDM set-up.

1.1 Electrochemical discharge machining (ECDM)

Electrochemical discharge machining (ECDM) is one of the widely accepted hybrid non-conventional micro machining techniques, which is used to fabricate miniaturized products on electrically conductive.[4] and non-conductive materials [5]

Two electrodes—the tool electrode (cathode) and the auxiliary electrode (anode)—are submerged in an electrolytic solution as part of the ECDM setup. As illustrated in Fig. 1, the work piece is positioned beneath the tool electrode. The voltage across these two electrodes is supplied by a DC power source. An electrochemical cell (ECC) is created as a result. Because of the potential difference between the two electrodes, electrolysis takes place in ECC, forming bubbles of hydrogen gas at the tool electrode and oxygen gas at the auxiliary electrode, respectively. When the critical voltage is exceeded, the rate at which hydrogen gas bubbles form close to the tool electrode is higher than the rate at which bubbles float on the electrolyte surface, which guarantees that the hydrogen gas bubbles will remain near the tool electrode.

When hydrogen gas bubbles physically touched one another, a large single gas bubble was created, which later transformed into a hydrogen gas film surrounding the tool electrode.[6].The hydrogen gas sheet serves as an insulator surrounding the tool electrode and as a dielectric medium between the electrolyte and the cathode tool. This tool electrode insulation almost stops the current flow and creates a strong electric field (10 V/mm) across the dielectric film, which causes an arc discharge. Spark initiation occurs at the sharp edges of the tool due to the presence of high current densities there. [7]Subsequently, discharge location changes over entire face of tool electrode [5]During the discharge period, tool electrode bombards a large number of electrons on the work piece surface kept close to the tool electrode. Bombardment of these electrons raises the work material's temperature, which ultimately causes the work piece to melt and the material to be removed.[8]The discharge mechanism's schematic view, shown in Fig. 2[9], comprises the subsequent processes. (i) electrolysis; (ii) the production and buildup of hydrogen gas bubbles; (iii) the creation of gas films and bubble coalescence; and (iv) sparking. This discharge process has been explained in a variety of ways by numerous other researchers.

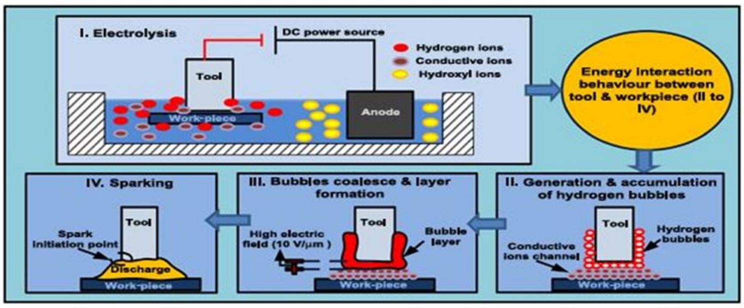

Fig.2 Mechanism of ECDM. [9]

According to experimental results, multiple process parameters that have a significant impact on process performance are directly and simultaneously involved. As illustrated in Fig. 3, these process parameters can be roughly divided into six groups.

Work piece, electrolyte, auxiliary electrode, tool electrode, power supply, and the existence of spaces between two electrodes and the tool-work piece are these categories. Fig. 3 displays the cause and effect diagram.

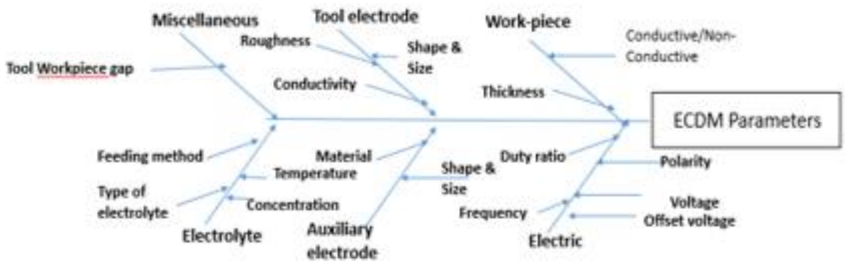

Fig.3 Ishikawa diagram of ECDM

2 ECDM classifications

Numerous tasks, including drilling, milling, cutting, die-sinking, dressing, and turning, can be carried out using the fundamentals of the electrochemical discharge machining process (Fig. 4)[9]. Regardless of the materials' electric conductivity, these processes work incredibly well to create a variety of profiles on fragile and hard materials. These ECDM process variations are covered in the following section.

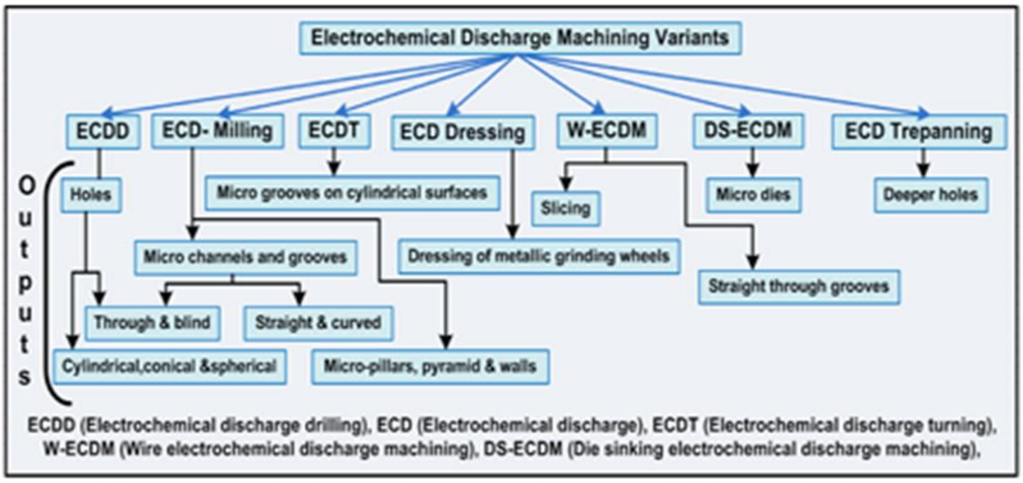

Fig.4 ECDM process classifications[9]

2.1. Electrochemical discharge drilling (ECDD) method

The need for accurate holes with a high aspect ratio on both thick and thin substrates is driving electrochemical discharge drilling, or ECDD. Many researchers have used the ECDD approach to drill through and blind microholes in order to meet the requirements of micro manufacturing.

Conductive materials such as cobalt, low-alloy steels, titanium, chromium, and nionic alloys have all been drilled using this technique. These materials' machined surfaces have a fairly smooth surface finish that resembles surfaces that have been electrochemically machined.[10]

The tool electrode moves gradually and under control along the z-axis to carry out the ECDD process. The procedure is complicated by the simultaneous interplay of discharge energy and tool electrode movements. The electrolyte, tool electrode, and power supply are some of the process variables that efficiently regulate the discharge energy. The section that follows provides specifics on a few noteworthy studies pertaining to ECDD process parameters.

For improved repeatability in the ECDD process, the gas film thickness must be decreased. The use of surfactants in the electrolytic bath has so been recommended by the literature. The thickness of the gas sheet is decreased when surfactant, or liquid soap, is added to the electrolytic bath. Lower energy disparities caused by intermittent discharges are the outcome of thin gas layers. As a result, the ECDD method yields reliable outcomes[11].

2.2 Electrochemical discharge milling

It is shown that the electrochemical discharge milling process is a promising technique for creating intricate three-dimensional microstructures out of quartz and glass. Numerous initiatives are made public for the surface texturing of micro channels[12], as well as for the creation of micro channels, micro grooves, etc. A rotating cylindrical wheel serves as the cutting instrument (cathode electrode) in this procedure. This tool follows a predetermined route. The tool rotation rate and tool travel rate are shown to be important process characteristics among the electrochemical discharge milling process parameters. In addition to producing micro grooves with sharp edges and reduced breadth, higher tool rotation rates aid in the removal of electrolyte replenishment issues.

It's interesting to see that the tool rotation rate has no bearing on the groove depth. Photographs of the microgroove machined at different depth is shown in Fig.5[13]

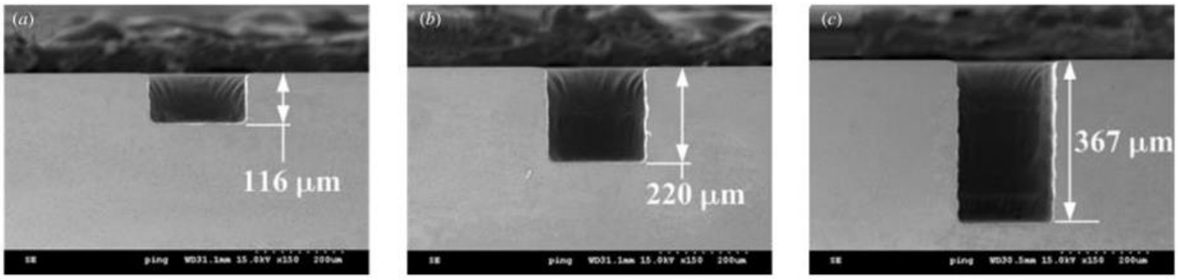

Fig. 5 Microgroove machined at depth of (a)100µm(b)200µm and (c) 350 µm.[13].

Compound system schematic diagram for ECDM and WEDG. The machining hand is the focal point of the setup. The EDM hand primary spin motor Z has the ability to move it up and down. The machining hand and tool can be positioned in relation to the WEDG and ECDM processing position when using an EDM X-Y stage is shown in Fig.6[13]

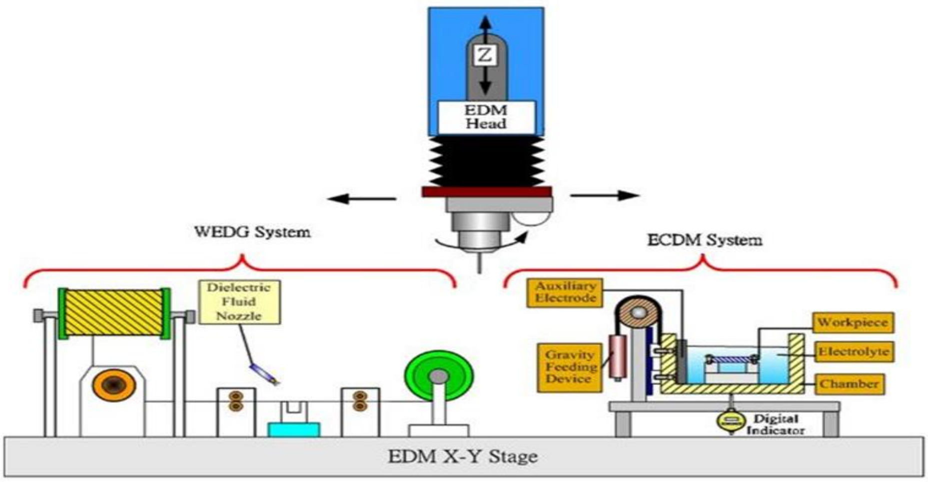

Fig.6 Compound system shows Electrochemical discharge milling [13]

A layer-by-layer material removal technique with a shallow depth of cut was added to the electrochemical discharge milling process in order to create the deep micro grooves. This layer-by-layer method makes it easier to discharge electrolytes at smaller and deeper gaps. Furthermore, it is possible to manufacture deeper micro grooves with a smooth surface finish.

In order to complete the workpiece of specific shaped microstructures on pyrexglass , Zheng et al. taken the parameters : 40 V DC supply, pulse on:off ¼ 2 ms: 2 ms, tool rotation rate¼1500 rpm and tool travel rate¼1000 mm per minute.

Diagram(7)[13] showing process potential of electrochemical discharge milling process. The machining of these 3-D micro-structures are very excellent

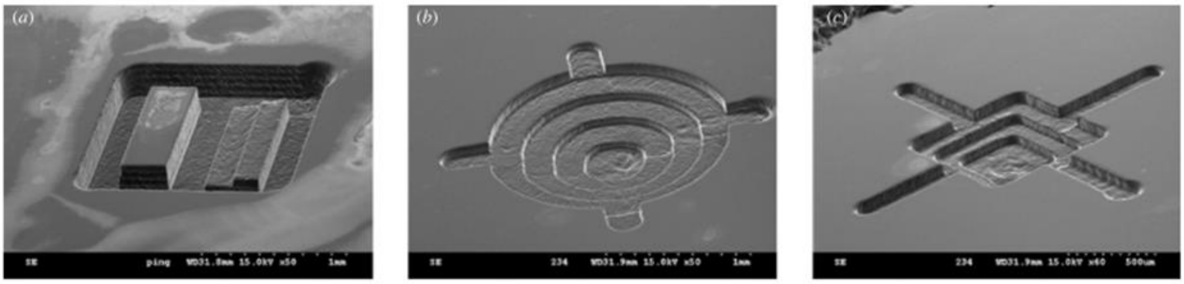

Fig. 7 Different types of 3D microstructures of Pyrex glass. [13]

2.3. Electrochemical discharge turning (ECDT)

One flexible application of the ECDM process for machining cylindrical parts is electrochemical discharge machining, which involves the work piece rotating continuously. Fig. 8[9] displays an ECDT schematic diagram. The rotating work piece is submerged in an electrolytic bath. During machining, the work piece's rotation makes it easier to feed new electrolyte via the small space between the tool and the work piece. One important process parameter that affects process performance is the work piece's rotation rate.

For an optimum level of rotation rate machining of narrow and deep groove with sharp edges is observed [14]. It is interesting to analyse that very high rotation speed lowers MRR, due to difficulties in film formation at higher rotation speeds as shown in figures (9) and (10) [14]

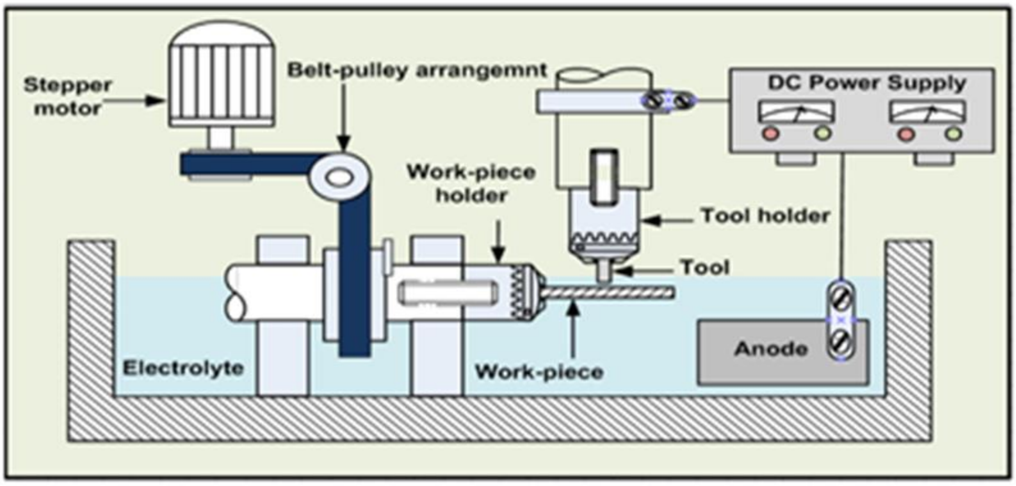

Fig.8 Line diagram of ECDT set-up[9]

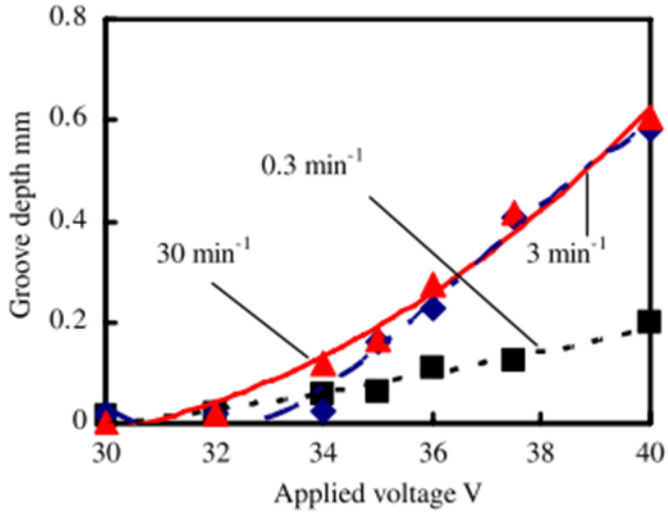

Fig.9 Curve between the groove depth and applied voltage.[14]

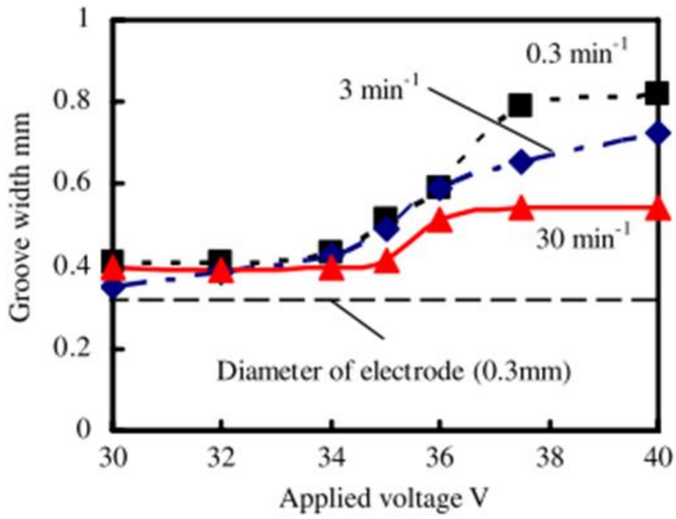

Fig.10 Curve between the groove width and applied voltage.[14]

2.4. Electrochemical discharge trepanning

By separating the tool axis from the spindle axis, the electrochemical discharge trepanning process gives the tool electrode an orbital motion. This procedure is thought to be a practical and cost-effective way to create deep holes. By creating through holes on alumina and quartz materials that are 1.35 mm and 2.35 mm deep, respectively, Jain et al. were able to relieve the ECDM process's limited depth constraint. Chak et al. substituted a spring-fed abrasive particle embedded tool for the gravity-fed tool in order to increase the surface quality and hole depth. Rougher surfaces and these abrasive particles, respectively, produce better cutting action and high frequency electrical discharges. This makes it possible to have a machined surface with a greater material removal rate. . Additionally, an abrasive electrode helps lower the average taper value from 13.411 to 2.051. According to experimental findings, a pulsed DC power source improves process efficiency.[15]

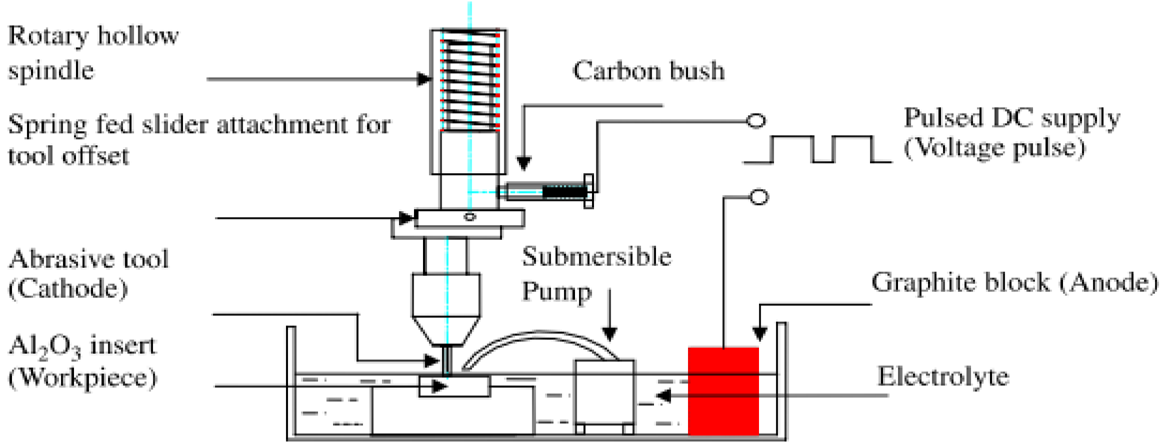

Fig11 Line diagram of spring fed offset tool used for trepanning in ECDM.[15]

2.5 Powder mixed ECDM

Powder mixed electrochemical discharge machining (PM-ECDM) is a triplex hybrid technique based on ECDM that is produced by mixing abrasive particles in electrolytic fluid[16]. For improved machining of alumina and borosilicate glass, respectively, researchers have suggested conical and cylindrical-shaped grinding wheels.[17]. To machine metal matrix composites , alumina and glass materials this method has been attempted fully[18][17].

When graphite abrasive particles with a diameter of 10 mm are mixed with sodium hydroxide electrolytic solution during the machining of borosilicate glass, the surface roughness improves from 4.86 to 1.44 mm[19]. When abrasive powder is mixed into electrolytic media, the bubble accumulation layer surrounding the tool is disrupted, changing the discharge pattern. This lowers the gas film's critical breakdown strength and, ultimately, the discharge energy per single spark pulse.[20].

Discovered that the surface roughness of borosilicate glass is improved from 4.86 µm to 1.44 µm by adding conductive graphite particles to 30% NaOH.[21]

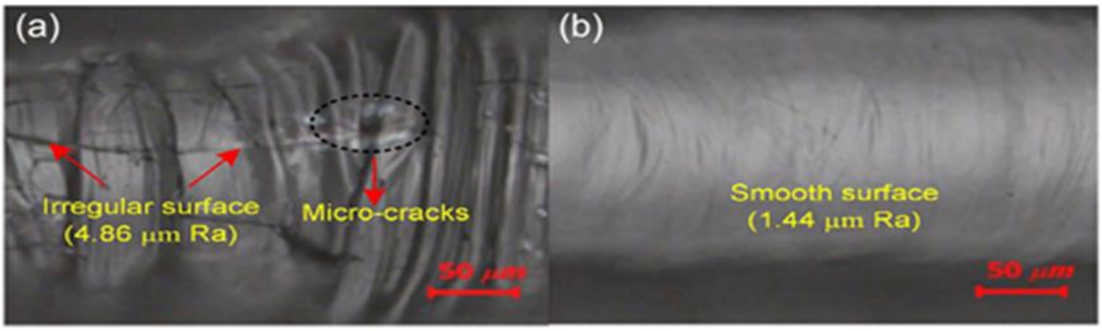

Fig.12 Photo of machined surface by (a) Traditional ECDM, (b) Powder mixed ECDM[19]

2.5.1 Electrolyte and its role

The electrolytic media in ECDM serves a crucial purpose in terms of process precision, efficiency, repeatability, and machined feature quality. Both electrodes are connected by electrolytic medium, which also facilitates the movement of the ionic current throughout the electrochemical cell (ECC)[22].

Bubbles of oxygen gas are produced at the auxiliary electrode and bubbles of hydrogen gas are produced at the cathode electrode (tool electrode) by electrolysis. Additionally, the tool surface is surrounded by a single large gas bubble (gas film) formed by the coalescence of hydrogen gas bubbles. This gas film's behavior demonstrates

how electron bombardment on the work piece surface increases the electrolyte's temperature surrounding the tool electrode.
The high temperature of the electrolyte encourages chemical etching of the work piece surface[13][23].

The process parameters related to the electrolytes, as shown in Diagram 13.[22]

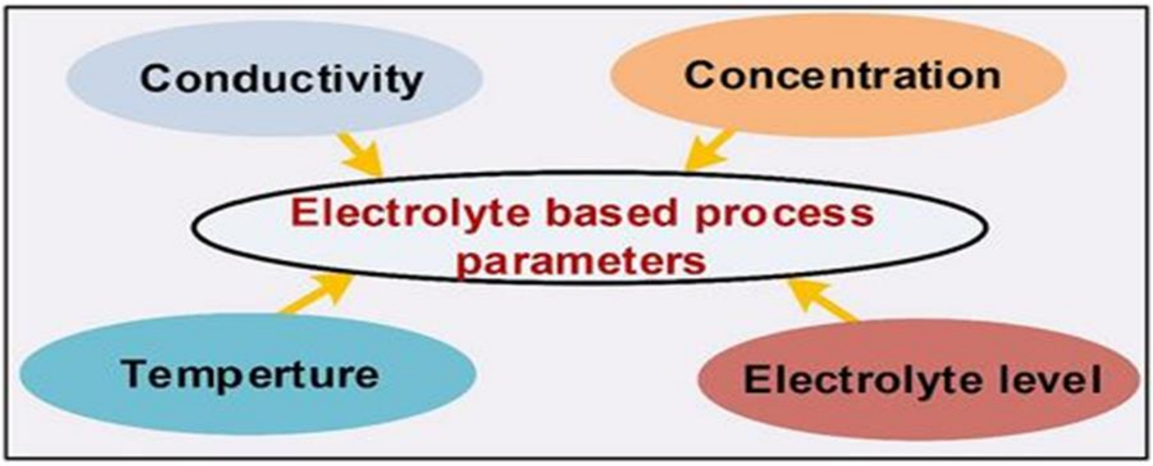

Fig. 13 Process variables of electrolyte[22].

(a) Concentration

On the machined surfaces, chemical etching also produces various surface textures. Abou Ziki and colleagues investigated the various surface texture patterns[24] .
In contrast, S.K. Jui et al. investigated how electrolyte concentration affected the micromachined 3D features' form correctness. It was found that when the electrolyte concentration rose, so did the microholes' entrance and exit diameters.[25] Therefore, it was advised to use a low electrolyte concentration of 1 M to lessen surface roughness and overcut. Similarly, when the electrolyte concentration dropped from 0.8 M to 0.4 M, Kolhekar and Sundaram discovered a 32.35% improvement in surface roughness.[26]

(b) Temperature

A greater rate of material removal is ultimately the consequence of an enhanced rate of sparking caused by the increased rate of gas bubble formation at the tool electrode.[27]

With increase in electrolyte temperature, the degree of dissociation increases which increases the electrolytic conductivity**.**

(c) Conductivity

Zaytsev and Aseyev found that the electrical conduc tivity of solution is the function of temperature and electro lyte’s concentration. He reported that for low concentration, the electrical conductivity of weak electrolytes is nearly proportional to the electrolyte concentration. P. Gupta reported the improvement in MRR and depth of cut by 44% and 11.42% respectively, when the electrolyte level reduced from 4 to 1 mm.[28]. It is difficult to reduce the electrolyte level because of the high temperature surrounding the tool electrode, which causes the electrolyte to evaporate.
Lately, Pu et al. [29].

(d) Level of Electrolyte

To address the issue of micro structuring on various non-conductive materials, sodium hydroxide has been used to machine the borosilicate glass's micro channels and micro holes (through and blind).[30][31]. The unstable gas film decreases the machining efficiency, and thereby increases the heat affected zone (HAZ) and hole over cut.

The use of low electrolyte levels reduces the peak current and side discharges and thereby concentrates the sparks at tool tip that helps to achieve high machining depth with low overcut and HAZ[32].

2.5.2 Electrolyte Feeding types

Here we are taking various electrolyte feeding methods for ECDM

1 Stagnant Feeding Method

Within the electrolytic bath, there is no movement other than this swirl activity. Thus, the temperature of the stagnant electrolyte rises with extended machining times.

1.1) Stirring Assisted Stagnant Feeding Method (SASFM)

This electrolyte's movement clears the debris from the gap and keeps it from adhering to the tool's and cavity's edges while also supplying new electrolyte for electrochemical reactions. Jawalkar et al. used this idea to create microchannels using the electrolyte stirring aided rotary tool ECDM technique, which resulted in less stray cutting and HAZ[33].

1.2) Vibration Assisted Stagnant Feeding Method (VASFM)

By ensuring sufficient electrolyte flow between the machining gaps, these ultrasonic vibrations subsequently encourage a steady discharge at the hydrodynamic regime. The electrolytic media was subjected to 1.7 MHz ultrasonic vibration by M.S. Han et al.[34] in order to provide steady discharges during deep drilling of glass substrates.

2) Electrolyte Flowing Method

The stagnant electrolyte feeding method in ECDM is ineffective in keeping the electrolyte temperature consistent during the machining process and removing debris from the machining zone. To remove the debris from the machining zone and provide the fresh electroyte, researchers proposed to flow the electrolytic media in between the narrow gaps. Electrolyte flow method provides fresh electrolyte, removes the debris from the machining gap and maintains constant temperature throughout the machinng process. The electrolyte flows over the machining zone in two ways, continuous and in the form of droplets (titrated flowing method). Next section describes the following elecrolyte flow feeding methods

2.1) Continuous Flow

Yan Zhang et al. compared the stagnant electro lyte feeding method with low and high pressure electrolyte flowing methods[23]. Zhang Yan et al.[35] reported Surface integrity with (a) stagnant and (b) electrolyte flowing method that the larger inner diameter of tube electrode could effectively improve the flushing conditions and facilitate better removal of debris.

2.2) Titrated Electrolyte Flow Method

During the micro slitting of quartz glass material, Kuo et al.[36] investigated that the titrated flow method exhibited 2000 μm deep grooves with 190 μm grove width by using brass (diameter 150 μm) tool, which was far better than the continuous flow method. For further enhancement in surface quality, Kuo et al.[37]added SiC abrasive powder to the electrolytic media that successfully polished the machined surfaces.

2.5.3 Electrochemical discharge grinding (ECDG)

Electrochemical discharge grinding (ECDG) is a triplex hybrid machining method that incorporates the combined action of three different processes namely mechanical abrasive cutting, electro chemical dissolution action and electric discharge erosion[9].

The abrasive cutting action also removes the material from work surface through mechanical abrasion [38]. Material removal mechanism for ECDG process [17].

3. Magnetic field assisted electrochemical discharge machining (MAECDM)

Cheng et al. installed a magnetic unit within the tool chuck to improve machining efficiency and create precise micro holes. This led to the development of the magnetic-field-assisted electrochemical discharge machining process (MAECDM). As seen in Fig14[9], MAECDM is comprised of a unique magnetic tool chuck to hold the tool electrode.

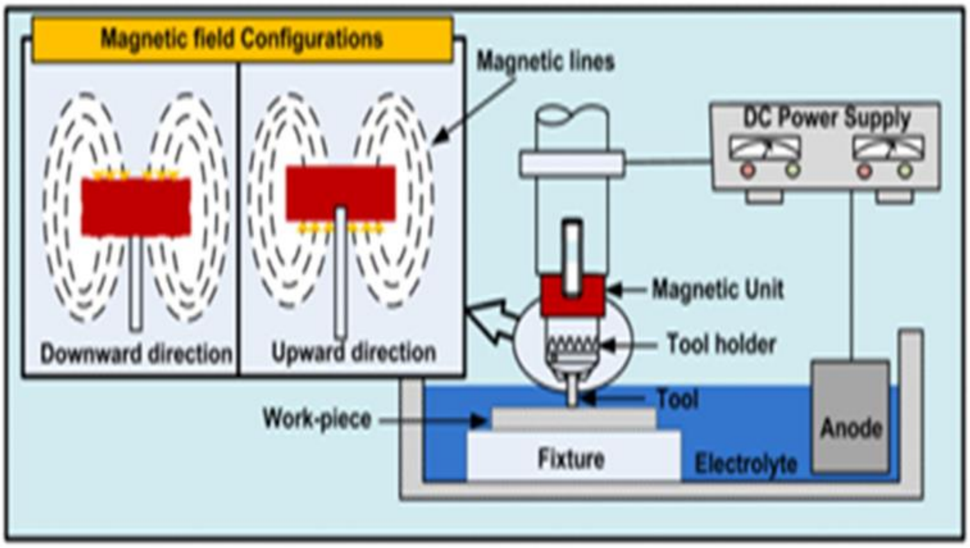

Fig. 14 Line diagram of MAECDM set-up[9]

Use of this concept permanent magnet was taken at the bottom of fixture for more effective results.

The electrolyte solution separates into positive and negative ions as electrochemical processes begin when the current enters the solution. Because the glass's chemical bonds are broken by electrochemical reactions, the negative OH ions migrate in the direction of the work surface. As the temperature rises, the rate at which negative OH ions etch glass increases, causing local glass machining by breaking (Si–O–Si) bonds. By introducing an increasing number of ions to the glass surface through the localized circulation of electrolytes, the etching rate can also be accelerated. The current study examines the bubble steering effect and localized electrolyte circulation caused by magneto hydrodynamic (MHD) convection. To achieve the MHD effect in the electrolyte solution, a permanent magnet is positioned adjacent to the tool surface. Electrolyte circulation is caused by the Lorenz force, which is the result of the cross-product of the strength of the electric and magnetic fields. The bubble departure phenomenon and the mechanism of gas film generation are impacted by the MHD effect[32].

Sparks appear at the boundary between the minor electrode and electrolyte when the applied voltage reaches a certain value in the electrolyte cell, which is made up of two electrodes of varying sizes. It results in electrochemical discharge, which is a decrease in the cell current.[39] Researchers have proposed conical and cylindrical shaped grinding wheels for better machining of borosilicate glass and alumina materials, respectively . This process has been attempted successfully to machine metal matrix composites[18] [40], alumina and glass materials.

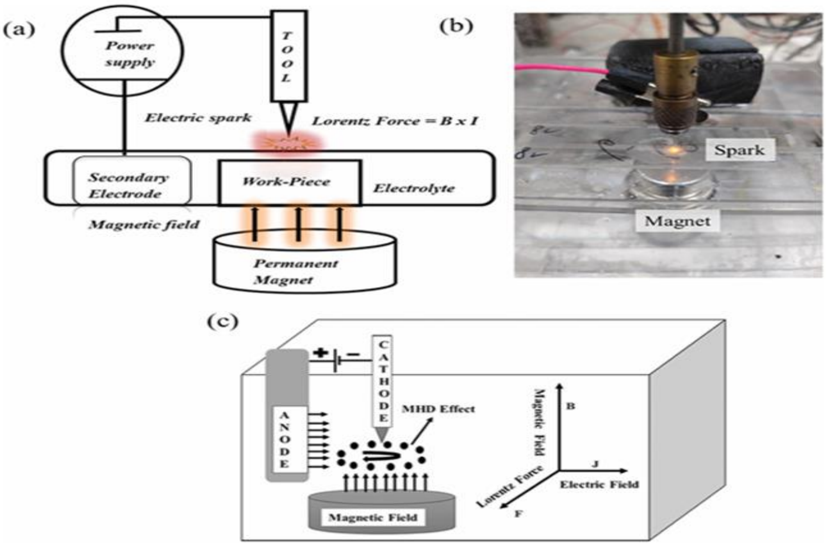

Fig.15 Showing (a)Various segments of magnetic-assisted-ECDM (b) Spark due to MHD convection (c) Movement of bubbles due to force.[39]

3.1 Mechanism of MAECDM

In MAECDM, hydrogen bubble formation occurs near the electrode surface when the DC power source connects with the electrodes and the minimum value of breakdown voltage affects the formation of film. The departure size with and without the MHD convection is given by formulas. Cb , Cs , ρg , ρl, I, and B are the constant coefficients, the density of hydrogen gas, electrolyte density, current and magnetic field, respectively. The model discusses the MHD effect on bubble growth and separation.[32]

This effect is varied by the magnetic field strength, which ultimately governs the process parameters and chemical dis- solution. A higher magnetic field produces more steering effects around the tool, which disturbs the bubble and film formation cycle. The direction and magnitude of FL play an essential character in the bubble growth stage. When FL and Fb act similarly, the aggregate impact will upsurge the bubble detachment frequency. It also drops the bubble send-off size compared to the non-magnetic field. The force elements are presented in Fig. 16.

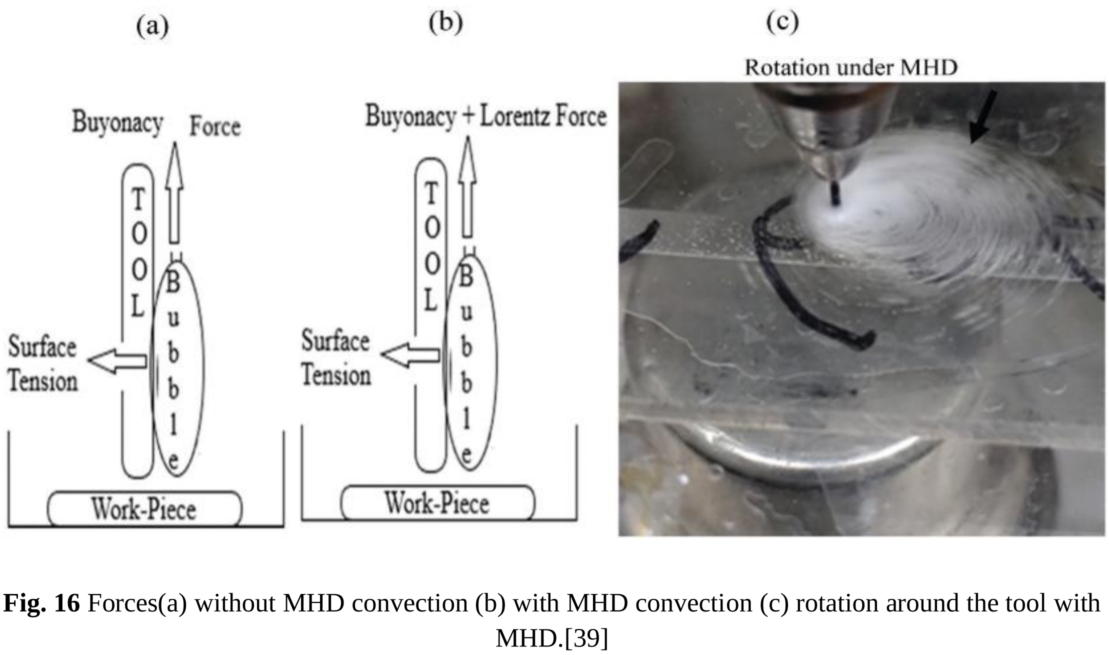

Fig. 16 Forces(a) without MHD convection (b) with MHD convection (c) rotation around the tool with MHD.[39]

The mathematical expression of Lorentz force

$$F_L = J \times B$$
$$F_B + F_l = F_S$$
$$F_B = \frac{\pi}{6} d^3 (\rho_L - \rho_G) g$$
$$F_S = \pi d_C \gamma \sin\alpha$$
$$R_d \text{ (With MHD)} = \sqrt{\frac{C_s \sigma - 4(B \times I)}{C_b g(\rho_l - \rho_g)}}$$
$$R_d \text{(Without MHD)} = \sqrt{\frac{C_s \sigma}{C_b g(\rho_l - \rho_g)}}$$

Fig.17 Basic formulas applied

The "arc discharge" in gases is comparable to the discharge in the ECDM process. Electrolysis reactions occur when the ECDM cell is exposed to a DC voltage higher than the threshold value required to cause the discharge [8][41] . The Hall current sensor attached to the auxiliary anode transformed the current signal into a voltage analog quantity during the machining process. The data acquisition card then recorded the machining current signal, and the oscilloscope recorded the waveform of the applied voltage and discharge current.[42]

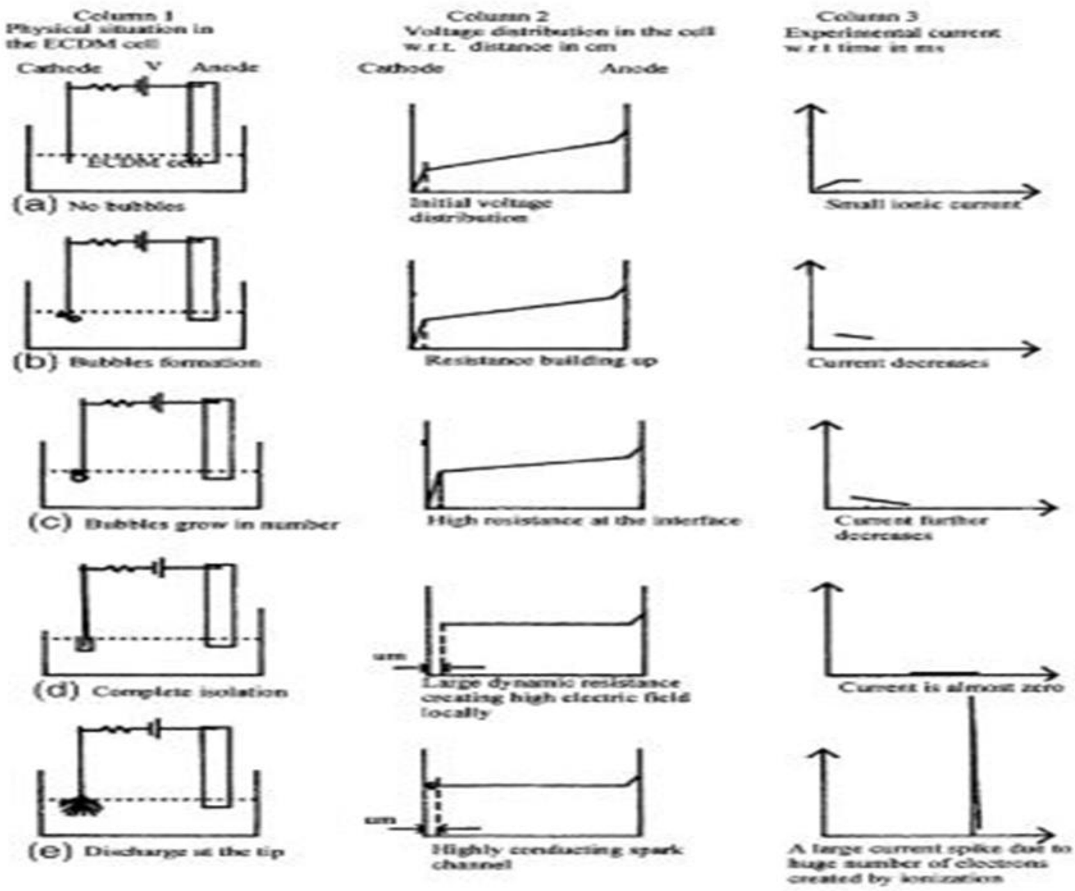

Fig. 18 Mechanism of discharge.[41]

3.2 Materials and methods

MHD convection is induced when the magnetic and electric fields are applied in the electrolyte domain. A permanent magnetic field was used in the electrolyte domain to induce MHD convection in the ECDM process. The experimental sets were fabricated to investigate the effect of MHD convection in the ECDM process. The setup consists of a DC power supply, primary and secondary electrodes, a magnetic fixture, an electrolyte chamber, a DC motor for tool rotation, and a stepper motor for axial movements. Experiments were conducted on glass work-pieces to fabricate micro-channels. Elements of the setup are shown in Figure19.[43]

A Z-axial linear guideway supported a Teflon tank, and the machining system was configured to operate in gravity-feed mode with a 0.45 N contact force between the tool electrode and the workpiece.[44]

$$\mathrm{MRR} = \frac{W_1 - W_2}{t}$$

$$\mathrm{WOC} = W_{\mathrm{channel}} - D_t$$

where W1 and W2 are the weights measured before and after the process. W Channel is the width of the channel, and Dt is the dia. of the tool., the work- piece must be free from moisture and cleaned with acetone before the measurement[45]. In addition to the material of the tool, the surface morphology of the tool is crucial for increasing machining efficiency.[46]

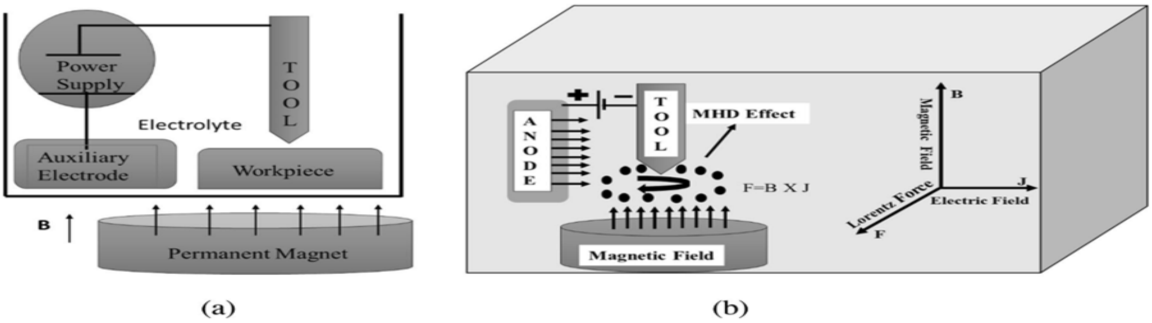

Fig. 19 (a) MAECDM (b)Direction of Force[43]

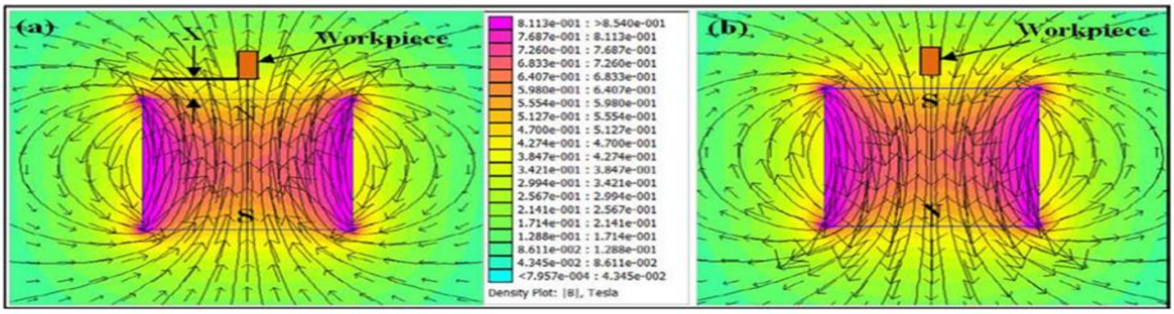

Fig. 20 Distribution of the magnetic flux density in permanent magnet: (a) job facing the north pole, (b) job facing the south pole[47]

In actual practice set of 2-3 permanent magnets can be taken to improve the effect on MRR[48]

By introducing a magnetic field into the system, magneto hydrodynamic (MHD) convection was created, allowing electrolytes to flow across the machining area and raising the frequency of sparks, which raised MRR[49].

Magneto Hydro Dynamics (MHD) on Y-SZ ceramics to evaluate the energy channelization behavior of u-ECDM. According to their research, MHD caused a 120% increase in the AR of microholes. Numerous hybridization strategies have been documented in the literature to address the issues with ECDM [50]. However, it was shown that the electrolyte temperature fluctuation during machining and the concentration gradient in the electrolyte bath cause the ECDM process to lose stability during machining.[48].

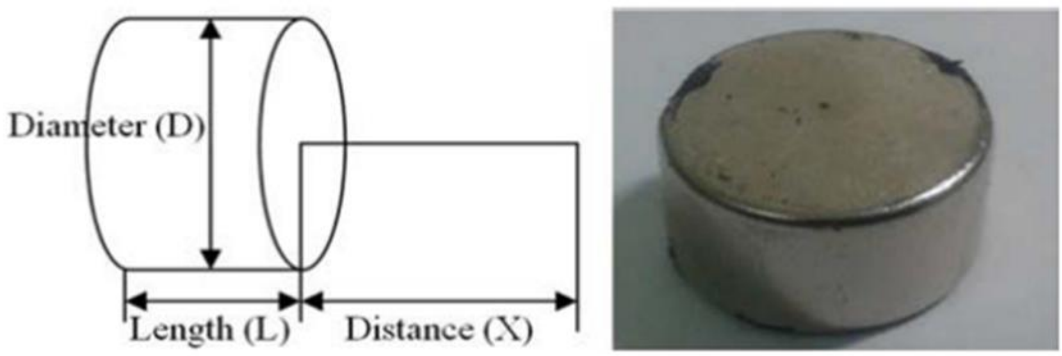

Fig.21 Photo of the Nd-Fe-B permanent magnet.[47].

Figure 22, shows a schematic of the experimental setup used for this study. A key component of this system is a small CNC machine that can be used for drilling, milling, and engraving.[41].

Higher MRR and more thermal flaws on the treated surface were the outcomes of increasing the applied voltage. According to Coteaţă et al., an applied voltage that is too high may limit MRR and result in suboptimal surface quality.[51]

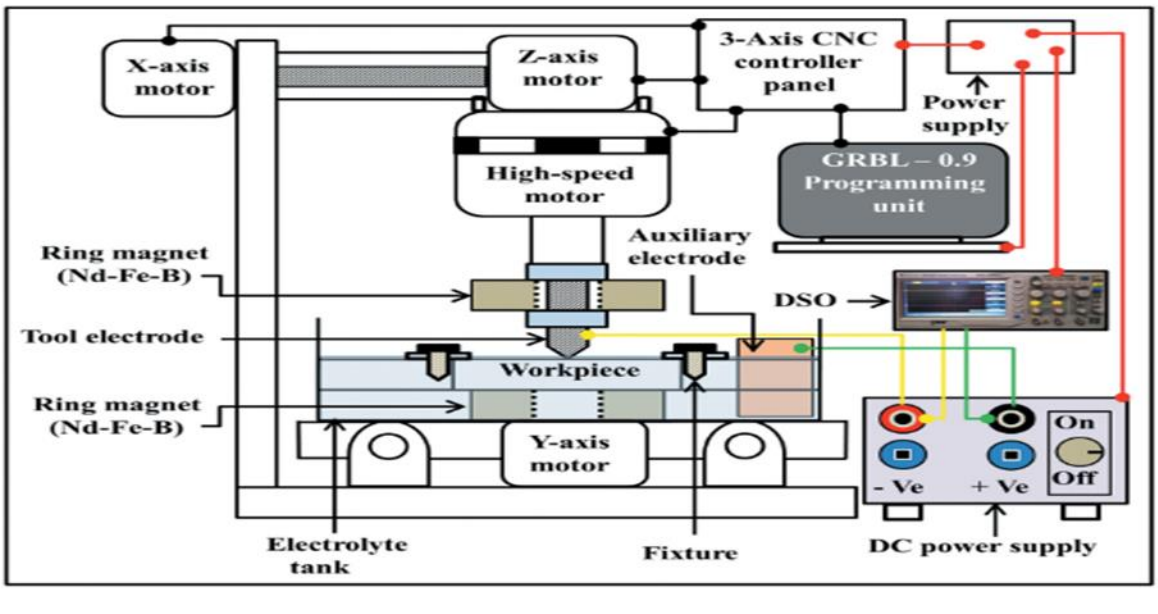

Fig. 22 Line diagram of the experimental setup[41]

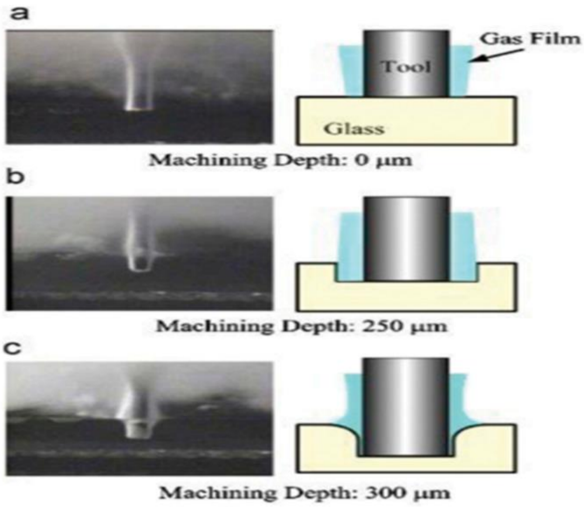

Fig.23 Gas film morphologies at different machining depths[46]

As illustrated in Fig. 23, more unstable and thicker gas films are said to be produced by holes deeper than 250 µm. However, research has shown that altering the tool's geometry can stop the gas film's quality from declining.[46]

4 Conclusion

The electronic packaging, medicinal, and space sectors all require micro channels. Glass and PFMA materials are the primary materials used in micro channel manufacturing. The production of microscaled complex profiles on challenging-to-machine materials with good surface quality and greater machining speeds is a significant advancement of electrochemical discharge machining (ECDM) variants . MHD convection was incorporated into the ECDM process to improve the machining performance. A deep micro-channel has been fabricated by incorporating MHD convection in the ECDM process. The magnetic field effect on steering action was also studied, and it was concluded that more revolving action was induced with higher magnetic strength, which improve machining characteristics. It prevents bubble accumulation and thick film formation on the tool edge, which generates a uniform surface.

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