IARJSET

ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

Vol. 8, Issue 9, September 2021

DOI: 10.17148/IARJSET.2021.8931

Review of Electrochemical Machining process and machining parameters

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Abstract: The purpose of this study is to provide an outline of the electrochemical machining process as well as its concepts. It also focuses on a literature review to discuss key process parameters based on previous studies. Electrochemical machining has grown in importance as a significant electro-machining process with unique features. These machining processes provide a better or, in some cases, the only option for producing accurate 3-D complex shaped macro, micro, and Nano features and components from difficult–to–machine materials. Technological advancements in the electrochemical micromachining technique have been described.

keywords: ECM, electrochemical micromachining, PECM,MRR.

I. INTRODUCTION

ECM is a stress-free, heat-free machining method. Electrochemical machining (ECM) is a non-traditional machining technology that can machine any conductive substrate, regardless of its physical qualities, such as hardness. Because of its ability to process substrates without leaving a faulty surface layer, ECM has become a popular approach. Electrolysis is used in ECM; a small gap between two electrodes is maintained while a favourable voltage is placed between them to remove material from the workpiece. [1] Surface finish, machining resolution, and machining rate are all modified to get the required machining results. Despite the fact that ECM provides atomic-scale machining accuracy, it is not as widely employed as the other technologies due to stray erosion and inconsistencies during machining.

II THE ECM PROCESS

Electrochemical machining is an electrolysis-based machining process. To execute chemical reactions at the electrodes, electrolysis involves the passage of current between two electrodes immersed in a conductive fluid called an electrolyte. A work piece, which is the positively charged electrode known as the anode, and a tool, which is the negatively charged electrode known as the cathode, pass current. The electrolyte transports electrons in the form of ions. Material can be deposited or withdrawn from the electrodes depending on the applied potential. According to Faraday's Law, anodic dissolution removes material.

$$m = \left(\frac{Q}{F}\right)\left(\frac{M}{z}\right) \qquad \text{.....(1)}$$

Where m is the mass removed in g, Q is the charge passed in C (Q=It where I is current and t is time in s), F is Faraday constant (96485 C mol-1), M is the molar mass of the work piece in $\frac{\mathbf{g}}{\mathbf{mol}}$ and z is the valence number (number of electrons transferred per ion) which is a dimensionless number.

Electrochemical machining (ECM) is a non-traditional machining technology that removes material through anodic dissolution during an electrolysis process [3, 4]. Between a pre-shaped cathode tool and an anode workpiece, a D.C. voltage (10-25 volts) is delivered across the inter-electrode gap. The electrolyte (for example, NaCl aqueous solution) flows across the inter-electrode gap at a high rate (10-60 m/s) (0.1-0.6 mm). The current density is normally between 20 and 200 Amperes per square centimetre. The electrochemical properties of the metal, the electrolyte properties, and the electric current/voltage supplied all influence the anodic dissolution rate, which is determined by Faraday's laws of electrolysisOn the workpiece, ECM creates an approximate mirror image of the tool. ECM has several advantages over other traditional machining processes (such as turning and milling), including its applicability regardless of material hardness, the absence of tool wear, a comparable high material removal rate, a smooth and bright surface, and the production of complex geometry components with stress-free and crack-free surfaces [5]. Turbine blades, engine castings, bearing cages, gears, dies and moulds, and surgical implants are among the various industrial applications for ECM.

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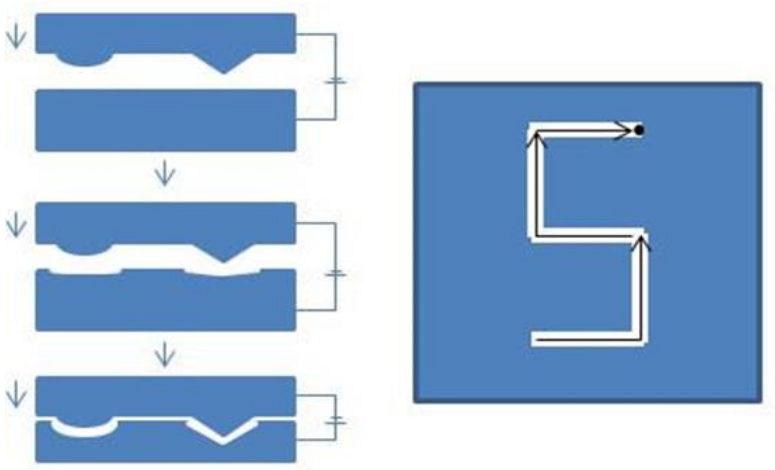

Figure 1: ECM Process as in [2] a) with a complex tool (viewed from the side) and b) with a simple cylindrical tool (viewed from above) The arrow shows the path of the tool. The black dot is the tool

To maintain a constant IEG, the tool in ECM is moved toward the work piece at a constant feed rate. The formation of a steady state gap is influenced by a number of factors that will be described later in this chapter. In the work piece, a negative copy of the tool is replicated. In a manner similar to computer numerical control (CNC) milling, a complicated tool can be built or a simple cylindrical tool can be moved in the X-Y plane to build complex features, as shown in Figure 1. Iron is known to actively dissolve in a simple salt solution of sodium chloride (NaCl) using the example of iron dissolution in sodium chloride (NaCl).. Ions in the electrolyte are affected by three transport mechanisms; diffusion, convection and migration. The migration of ions from a high-concentration region to a lower-concentration region is known as diffusion. The anode surface dissolves iron ions, which spread across a thin, stagnant layer of electrolyte at the electrode surface to the main electrolyte, where the concentration of iron ions is much lower. In the case of ECM, the electrolyte is driven through the IEG at high pressure and speed, carrying ions away from the IEG Positive ions are electrostatically drawn to a negatively charged cathode tool and vice versa, therefore migration is the movement of ions due to a potential field. The reactions in this case are as follows: iron is dissolved at the anode, and hydrogen gas is evolved at the cathode.

Anode: Fe Fe2+ + 2e-

Cathode: 2H+ + 2 e- H2↑

Because iron ions react with hydroxide ions in the solution to generate iron hydroxide (Fe$(OH)_2$), which is insoluble and precipitates to form a sludge, no iron is deposited on the cathode. The electrolyte is filtered to remove the solid reaction products. Figure 2 depicts the basic reactions that occur during ECM in a graphic depiction. Due to higher electrical resistivity in the IEG, the electrolyte is flushed through the IEG to remove reaction products that could create sparks or short circuits during milling. The electrolyte also eliminates heat generated by Joule Heating from the reaction zone.. A metal hydroxide layer could form on the work piece surface if the reaction products are not removed from the cutting zone, restricting the reaction.

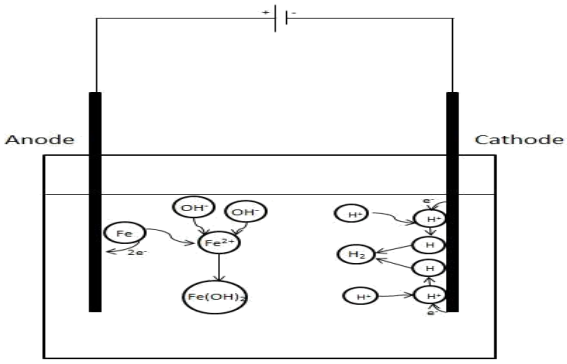

Figure 2 Schematic of the basic reactions during ECM [6]

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III ELECTROCHEMICAL MICRO-MACHINING

Electrochemical micro-machining (ECMM) is a more sophisticated variation of electrochemical machining (ECM), in which machining is limited to considerably smaller areas on the work piece in order to make micro-scale holes, shapes, and tools with high aspect ratios. Electrolyte selection, electrolyte concentration, pulse frequency and duration, IEG size, voltage, and feed rate are all parameters that affect machining precision.

III.A Electrolyte Selection

In ECMM, the electrolyte is a critical parameter since it provides the conditions for reactions to take place, specifically a conductive environment. The ideal electrolyte would have a high conductivity, low viscosity, be non-corrosive, and be relatively affordable. Although many different electrolytes are utilised, sodium chloride (NaCl) and sodium nitrate (NaNO3) are the most commonly used. The electrolyte used is determined by the material of the workpiece and the intended outcome, such as precision, material removal rate (MRR), or surface finish. Table 1 lists different electrolytes for machining a variety of metals using ECM [8].

Passive and non-passive electrolytes are the two basic types of electrolytes. Nitrate and other oxidising anions are found in passive electrolytes. Due to the creation of a protective oxide film, these provide improved precision. In most cases, oxygen is produced in stray current regions. More aggressive anions, such as chloride, are found in non-passive electrolytes. [9] These electrolytes have a substantially faster rate of material removal than passive electrolytes, but their precision is reduced [10].

Acidic electrolytes are occasionally used to prevent the accumulation of solid machining products in the IEG, which can slow down machining. Because tungsten and cobalt may be machined simultaneously, tungsten carbide (WC-Co) is machined with sulphuric acid (H_2SO_4). [11] Some metals, such as tungsten in sodium hydroxide, have improved machining in basic electrolytes (NaOH). Aqueous electrolytes are used in all of the instances above. Because some materials are water-sensitive, an aqueous electrolyte isn't the best choice. Non-aqueous electrolytes, such as glycerol-based electrolytes, are employed in certain instances. Organic-based electrolytes have lower conductivities than aqueous electrolytes due to the difficulty of dissolving ions in them. This reduces machining speeds while improving machining precision. Electro-polishing, a variation of ECM, is typically done with high resistivity electrolytes, such as glycerol-based electrolytes, because the difference in current density between peaks and troughs is higher, resulting in preferential dissolution. [12]

III.B Electrolyte Concentration

In an ECMM, electrolyte concentration also affects machining accuracy and rates. The electrical conductivity of an electrolyte is determined by its concentration; the higher the concentration, the higher the conductivity. Many studies have been undertaken to see how electrolyte concentration impacts ECM and ECMM machining,[13];[14];[15];[16];[17];[18];[19];[20];[21];[22].When machining micro-features, accuracy is critical because errors seem considerably larger at this small scale.

[9]Observed that machining precision was enhanced with a moderate MRR with a lower concentration, greater voltage, and a moderate value for pulse-on time. In an oxygenated NaCl electrolyte for 20MnCr5 steel, [13] found that a greater concentration resulted in a higher MRR and better surface finish. [14]added that a higher electrolyte concentration ‘allows for more ions to be ionised,' resulting in an increase in MRR.[15] discovered that larger electrolyte concentrations resulted in higher dissolving currents, which is why highly concentrated electrolytes are used in ECM.[16] reported that a lower concentration, along with a higher machining voltage and a ‘moderate pulse on time,' provided more accurate forms at a moderate MRR because the stray current impact was reduced.

Table 1. Common electrolytes for a range of metals given by [23]

Metal	Electrolyte	Remarks
Aluminium and its alloy	NaNO3 (100-400 g dm^{-3})	Excellent surface finishing
Cobalt and its alloy	NaClO3 (100-600 g dm^{-3})	Excellent dimensional control, excellent surface finishing
Molybdenum	NaOH (40-100 g dm^{-3})	NaOH consumed and must be added continuously
Nickel and its alloy	NaNO3 (100-400 g dm^{-3})	good surface finishing
	NaClO3 (100-600 g dm^{-3})	good dimensional control, good surface finishing and low metal removal rate

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Titanium and its alloys	NaCl (180 g dm) + NaBr (60 g dm^{-3})+ NaF (2.5 g dm^{-3})	good dimensional control, good surface finishing and good machining rate
	NaClO3 (100-600 g dm^{-3})	Bright surface finish, good, machining rate above 24V
Tungsten	NaOH (40- 100 gdm^{-3})	NaOH consumed and must be added continuously
Steel and iron	NaClO3 (100-600 g dm^{-3})	Excellent dimensional control, brilliant surface finish, high metal removal rate, fire hazards when dry
	NaClO3(100-400 g dm^{-3})	Good dimensional control, lower fire hazard, good surface finish and good machining rate
	NaNO3 (100-400 g dm^{-3})	Good dimensional control, fire hazard when dry, low metal removal rates, rough surface finish

[24] used ECMM to make cylindrical micro-tools and discovered that the reaction was non-uniform at greater electrolyte concentrations, presumably due to issues completely cleaning the IEG, which changed the conductivity of the fluid between the electrodes. In higher concentration electrolytes, this resulted in shorter cylindrical tools. The surface finish was harmed by higher concentrations (> 3 M). [24] discovered that the MRR was impacted by the anion type and concentration. Higher salt concentrations may facilitate the production of a salt coating on the anode surface, resulting in a superior surface finish. [26] subsequently observed that the current distribution is contingent on the electrolyte concentration. This was discovered during electrochemical deposition, a method that is similar to but not the same as ECM. The machining overcut increased when the sodium chloride concentration was increased during electrochemical micro-drilling using a mixed electrolyte of hydrochloric acid (HCl) and sodium chloride (NaCl)[27]. When combined with 0.3 M HCl, the overcut began to decrease above a specific concentration of NaCl (> 0.35 M). Because the mixed electrolyte containing 0.1 M HCl was not tested, it is impossible to know if this is a tendency that occurs frequently in ECM.

Using a sulphuric acid electrolyte, [28] produced micro-grooves in stainless steel. The concentrations were merely changed from 0.15 to 0.30 M. They saw a rise in overcut as the concentration was raised up to 0.25 M. The overcut began to shrink in size above 0.25 M. The decrease in machining was explained by an increase in gas bubbles formed at the micro-tool surface. [29] used a sodium nitrate electrolyte with concentrations varying from 0.4 to 0.5 M to machine a super-duplex stainless steel (SDSS) and found that the MRR increased with electrolyte concentration.

According to [30], a high electrolyte concentration boosts electrolyte conductivity, allowing for a high current efficiency. [31] stated that lower concentrations result in higher conductivities, which "requires shorter current channels and increases machining resolution." They also noted that the concentration that can be employed in ECM has a lower limit. This is due to insufficient ion content in the gap to fully charge the double layer capacity.

III.C Pulse Frequency and Duration

In order to attain better resolution, pulsed electrochemical machining (PECM) and ECMM use a pulsed potential rather than the constant potential used in ECM. Pulses are often delivered as a square wave with amplitude (voltage), frequency, and duration fluctuations. Figure 4 depicts an example of a PECM waveform..

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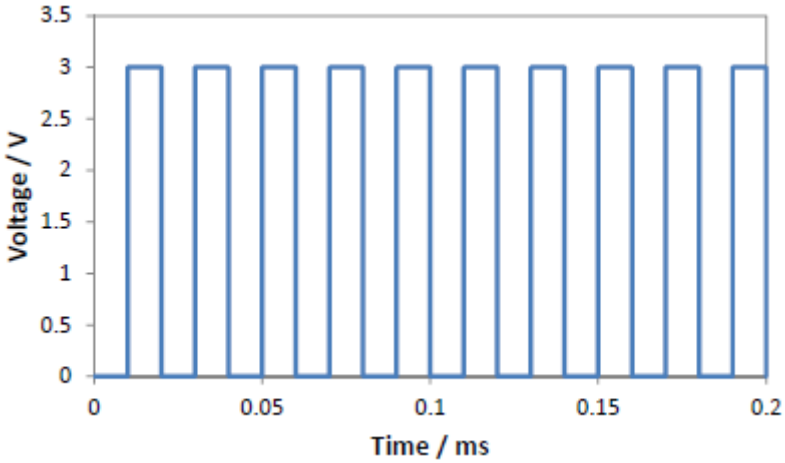

Figure 4. Pulsed Potential Wave given by [2]

[32] seems to have been the first to design and implement a pulsed power supply in an ECM system. The goal was to use a short negative pulse after a positive pulse to eliminate the passive layer building on the work piece, improving material removal rates and allowing machining of difficult-to-machine materials like tungsten carbide (WC).

[16] found that while using pulsed voltage, the work piece dissolved consistently, whereas when using direct current (DC) ECM with a tiny IEG (inter electrode gap), deposits can accumulate on the tool, resulting in non-uniform machining at the work piece surface. [17] created micro-tools from WC-Co using a pulse power supply. They discovered that when the pulse on time grew, the cylindrical tool length increased as well, but that spark machining was initiated beyond 1800 ns, resulting in a decrease in surface quality.

With a low concentration sulphuric acid electrolyte with a frequency of 5 MHz and a duty cycle of 40%, [21] created taper-less holes in SS-304 stainless steel with a pulse on time of 80 ns. MRR increased as duty cycle increased, but reduced as frequency increased, according to [29]. They didn't think about how these characteristics affected the machining over-cut in this scenario. At the macro-scale, [30] observed that a short pulse on time combined with a long machining time resulted in a higher current efficiency. To make high aspect ratio holes and intricate patterns, [31]) used brief voltage pulses to limit stray machining. They discovered that machining resolution was optimum when a shorter pulse was combined with a low electrolyte concentration.

[33] is credited for using pulsed voltages to improve ECM resolution and expand ECM's use to micro- and nanotechnologies. According to their calculations, a 30 ns pulse should result in 1 m resolution machining. [34] came to the conclusion that the IEG may be regulated by changing the pulse on time, which regulates the hole diameter. This can be changed throughout the machining process, resulting in holes with a smaller entrance hole on the outside than on the interior, as shown in Figure 5.

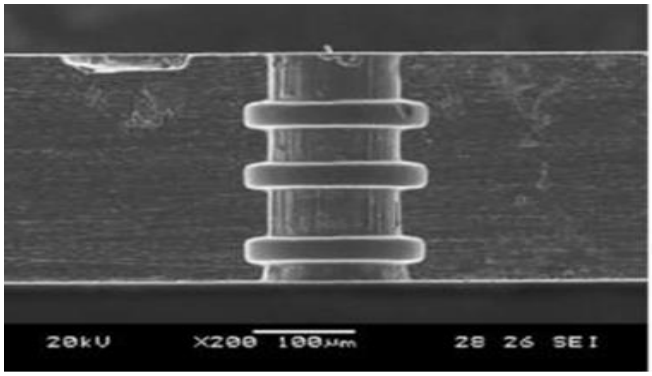

Figure 5. Groove array in a micro-hole [34]

III.D Inter-Electrode Gap (IEG)

Figure 6 shows how the potential varies over the IEG. Maintaining a constant gap during machining is a challenge that many researchers have attempted to overcome by modelling and in-line measuring techniques. Because the ohmic drop produced by the electrolyte resistance is lowered as the IEG decreases, the applied potential must be reduced to attain the machining potential.

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[35]found that a lower IEG resulted in a greater MRR. [34] discovered that the working gap differed depending on the pulse voltage and length. Figure 2-6 shows how they used this finding to construct complicated interior shapes. By lowering the voltage and electrolyte concentration, [36] was able to reduce the IEG to micrometre scale, resulting in greater resolution machining. Due to the little amount of material lost with each pulse, [37]found it much easier to control the IEG when nanosecond voltage pulses were applied.

With a smaller IEG, [38] saw a better surface finish. [39] found that IEG grew linearly with pulse duration when the pulse was very short, while [40] found that a reasonably high feed rate with a low applied voltage resulted in a tiny IEG. [41] claimed that employing tools with a reduced surface area allowed for a smaller IEG, which enhanced machining resolution.

[42] developed a model to find the lowest IEG, with electrolyte boiling as the limiting factor. The IEG and the growth of bubbles in the IEG, as well as how this influenced machining, have previously been modelled by the same author [43]. A very thin layer of bubbles or an equitable distribution of bubbles throughout the gap resulted in equal machining throughout the entire electrode contact, according to the researchers.

Other researchers devised ways to keep the desired IEG distance constant throughout milling. [10] stated that poor IEG control resulted in poor tool replication; in their case, the surface smoothness was harmed, and [44] stated that proper IEG control was necessary to avoid short circuits or arcing during machining. To maintain the IEG, [33], [16], and [24] all employed a current detection approach.. Between the tool and the work piece, a modest voltage was connected, and the tool was progressively advanced towards the work piece while the current was monitored. The tool is stopped and retracted by the chosen IEG distance once the electrodes are detected to be in contact.

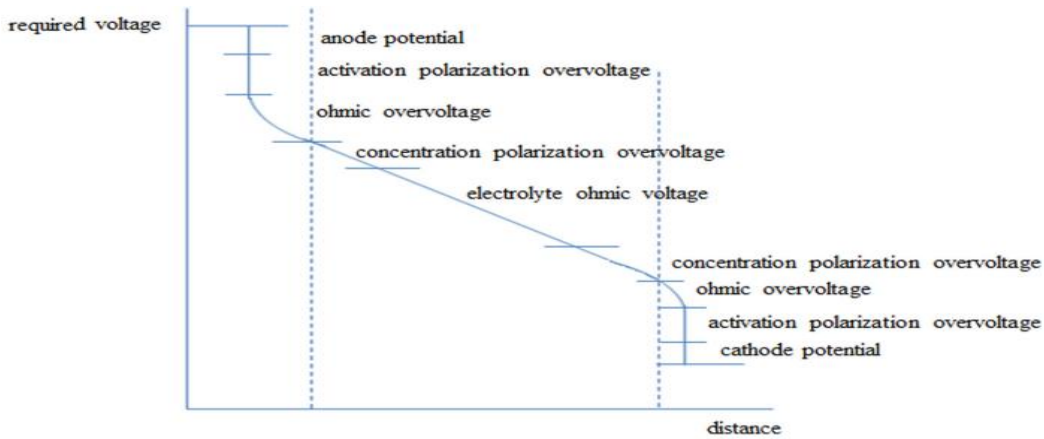

Fig.6 Potential profile within the IEG[2]

III.E Voltage

The applied voltage in ECM will effect the amount of material removed through the relationship V = IR, where V is the voltage and R is the resistance, according to Faraday's Law, equation (1). [45] The resistance of the electrolyte is R in this situation. With these two equations, it's reasonable to assume that a greater voltage will result in a higher current flowing, increasing the amount of material removed over the same time period as a lower voltage. This has been proven by a number of studies. The MRR dropped when the potential was raised over a certain voltage (which was determined by the work piece material and electrolyte mix). An increase in hydrogen gas production at the tool electrode was used to explain this. These trapped bubbles enhanced the electrolyte's resistivity, lowering the current density at the work piece and lowering MRR[16]; [28]; [35].

While a greater voltage results in a higher MRR, it also has additional consequences that could be deleterious to machining. [32], [46], [25], and [47] all mentioned that high voltages caused tool damage due to sparking, which reduced machining accuracy. [48] studied electrochemical spark machining and discovered that increasing the voltage enhanced tool wear. A higher applied voltage also improved the surface quality, according to several authors. As the voltage was increased, [46]; [12]; [49]; [50]; [13] [49] saw an initial improvement in surface finish.. Surface roughness increased when the voltage was increased above 6 V in their case. A lower applied voltage may result in a higher surface quality, but at the expense of a lower MRR, according to [51].

III.F Tool Feed Rate

In ECMM, the too feed rate is a critical parameter for minimising overcut, maximising MRR, and maintaining constant IEG. [32] noted that the feed rate is influenced by the current density, and [52] added that the feed rate affects the IEG.

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When the current density is larger, more material is removed per unit time, allowing for a faster tool feed rate. The use of a constant feed rate during ECM has been reported in a number of articles.The goal was to keep the IEG constant throughout the machining process by using a feed rate that matched the dissolving rate. ([53]; [54]; [55]) Researchers discovered that if a high feed rate was utilised, the IEG quickly shrank in size, finally generating a short circuit that caused sparks and damaged the tool or work piece. [47]; [25]; [37]; [46]; [55]; [21] discovered that the maximum feed rate that did not cause sparking between the electrodes was the optimum feed rate.

While the majority of writers used a set feed rate throughout machining, [56]and [54] kept the IEG constant by altering the feed rate accordingly. This prevented the equilibrium IEG from forming, allowing for a smaller IEG to be maintained throughout the machining process.

IV OTHER ALTERATIONS TO ECM

Other changes to the ECM process will be investigated now that all of the common factors controlled for exact ECM have been evaluated. All of the changes were made to increase MRR or reduce machining overcut. The addition of ultrasonic vibrations (USV) to either the work piece or the tool was one of the most typical ECMM modifications[57]; [36]; [49]. When the amplitude and frequency of the USV were increased, it was discovered that it improved ion transport and surface roughness. Instead of vibrating one of the electrodes, [58] pulsated the electrolyte. The authors reported an improvement in the surface roughness and increased MRR when the electrolyte pulsating frequency was increased. A maximum frequency of 20 Hz was applied.

Researchers began looking into ways to limit and manage the potential field between the tool and the work piece in order to increase machining precision. Because the tools were insulated, machining in the side gap was not possible. Another change was the creation of a dual-pole tool. After the cathodic tool was insulated, an insoluble anodic layer was applied on top. By modifying the electric field within the gap, this lowers the likelihood of over-cutting owing to stray machining[59];[22].

The confined etchant layer method (CELT), a comparable technique, was developed in 1992 [60]. The electrochemical production of corrosive substances in the vicinity of the electrodes was used in this procedure. A micro-electrode was used to restrict the machining, and an excess of a sequestering ion was used in the electrolyte to prevent the corrosive ions from building up away from the tool electrode.

V CONCLUSION

The effects of electrolyte choice, concentration, pulse frequency and duration, IEG, voltage, tool feed rate, and other modifications such as the application of ultrasonic vibrations to one of the electrodes have all been studied extensivelyThere has also been very little research into ECM machining of semiconductor materials other than doped silicon materials. A wide variety of semiconductor materials are increasingly being used in electronic equipment, some of which are brittle and difficult to machine using traditional machining processes. It is proposed that ECM be tested to see if it is a suitable machining method for some of these semiconductors, such as indium antimonide (InSb) and gallium arsenide (GaAs). Another fascinating area is superconductor machining. Most high temperature superconductors are based on the perovskite crystal structure, which has internal layers that are critical to the material's superconductivity. Through the application of physical pressure on the material, traditional contact machining techniques can damage these layers. ECM is an excellent technique for machining superconductors because it is non-contact, stress-free, and heat-free..

Also, to the author's knowledge, no work has been done to compare the results obtained in ECM for polycrystalline, monocrystalline, and amorphous materials and investigate the effect of crystal structure. This would be useful for improving machining outcomes and manufacturing microelectromechanical systems (MEMS) devices, as well as evaluating the limits of attainable roughness and feature size.

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