Electrochemical Micromachining: A Review on Principles, Processes, and Applications

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1 Introduction

Industries such as automotive, aerospace, electronics, optics, medical devices, and communications have experienced a significant increase in the necessity for large- and small-scale products and parts created from machining-impossible materials including titanium alloys, super alloys, carbides, tool steel, and carbides. Despite having remarkable properties, many of these materials are underutilized. Using traditional machining techniques like turning and milling on these materials is challenging. For example, titanium alloys tend to harden during work and have poor heat conductivity and high chemical reactivity, which leads to high cutting temperatures, tool wear, and strong adherence to the workpieces. A better option for creating precise 3D complicated shapes characteristics and parts out of difficult-to-machine materials is electrochemical micromachining (ECMM). This technique employs electrochemical reactions to selectively remove material from the workpiece, resulting in the fabrication of micro-objects with high precision and accuracy, including complex geometries and high aspect ratio structures. ECMM is a versatile and cost-effective method that can be applied to a wide range of materials, such as metals, semiconductors, and ceramics. Its ability to create microstructures with high precision and accuracy has made electrochemical micromachining a promising option for various applications, such as micro-electromechanical systems (MEMS), microfluidics, and biomedical devices. The utilization of challenging-to-process substances such as titanium alloy and Inconel alloy has notably risen in present times. There is a group of

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nickel-based superalloys that can uphold their durability despite being repeatedly exposed to elevated temperatures. This alloy possesses improved welding characteristics and has robust strength, high-temperature resistance, and protection against corrosion [1].

There are several variations of the process being researched around the world right now, including pulsed electrochemical machining (PECM), through-mask electrochemical micromachining (TMECMM), wire-electrochemical machining (Wire-ECM), jet-electrochemical machining (Jet-ECM), and electrochemical grinding (ECG). From a fundamental standpoint, all variations of ECM use the same material removal mechanism (anodic dissolution at the ionic level in the presence of electrolyte), but they vary in the size, form, and kinematics of the tool and workpiece [2]. The anodic dissolution rate, surface topology, and precision of the machined component or feature in the ECM process are influenced by the kinematics and elemental composition of the electrolysis in the electrode spacing. During any electrochemical reaction, mass movement significantly affects these parameters [3]. As the electrochemical dissolution process progresses, byproducts of electrolysis, such as air pockets and precipitates begin to form in the interelectrode gap and influence the electrical conductivity of the electrolyte. For better mass transportation, often a speed of (15–45 m/s) electrolyte jet is needed (hence, machining accuracy). Due to the electrolyte's high momentum, electrolysis products are efficiently and swiftly evacuated from the cutting zone as sludge. In the case of micromachining, however, issues including vibrations of the machine's structure and microtools as well as electrolyte loss must be dealt with. An alternative approach to isolate the dissolving region and promote effective sludge draining is to use a pulsating power source. In this scenario, the electrolysis is allowed to relax between two successive pulses by following the machining time with idle time. The alternating current method for various anodic dissolutions of low-carbon steel and copper was the prior name for the pulsing technique [3–5].

Until now, various experimental studies have been conducted on microelectrochemical machining to explore the impact of multiple process parameters on its performance. These parameters can be classified into six categories, as illustrated in Fig. 1 using a fishbone diagram. For the purpose of microelectrochemical machining, to obtain precise and controlled material removal, optimizing various machining settings is crucial. The tool feed rates, electrolyte concentration, electrolyte concentration, applied voltage, and pulse amplitude, all have an impact on how much material is removed from the surface and how rough it is.

The impact of various process parameters on the performance of micro-ECM is outlined in Table 1. This paper aims to bridge a significant gap in the current state of knowledge regarding ECMM and its hybrid variants. This review aims to better understand ECMM with microelectrochemical machining-based hybrid micromachining technologies in a single document because the creation of hybrid processes necessitates a thorough grasp of the parent process. While there are fundamental reviews on electrochemical micromachining in the literature, like those found in references [9–12], these articles only cover the early fundamental understanding of

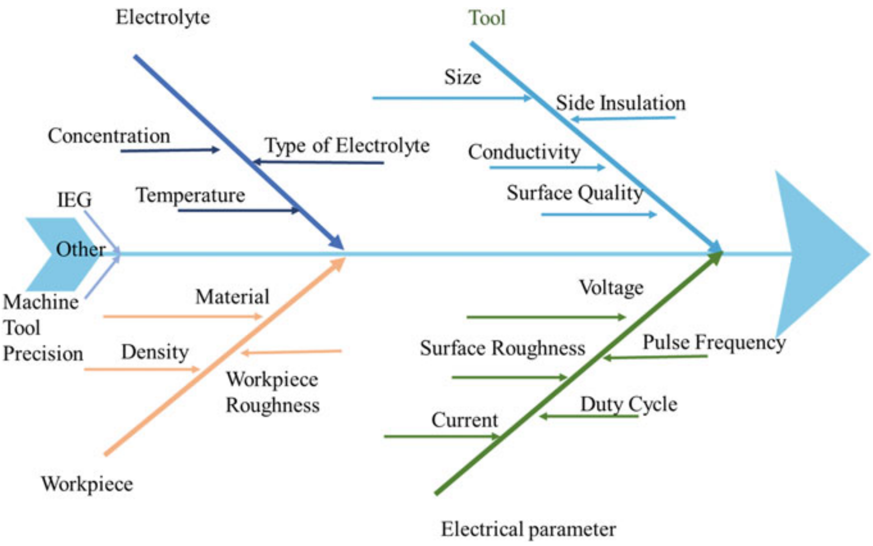

Fig. 1 Fish-bone diagram

the field. References [9] and [10] provided an early introduction to localized electrochemical machining processes many years ago, while Bhattacharya et al. [11] presented the basics of ECMM. Landolt et al. [12] focus on fundamental chemical factors, mass transport effects, passive oxide laser etching, and the formation of multilevel structures. A review of electrochemical machining drilling by Sen et al. [13] focused on hole quality and the effects of process factors. They did not, however, fully address issues like tooling, interelectrode spacing, energy sources, and the choice of electrolyte for particular materials. It should be noted that since the review was conducted, technology has rapidly progressed. A conference review article [14] provided a brief overview of ECM technology and did not go into the specifics of the processes involved. It mainly consisted of information gathered from existing literature on ECM. On the other hand, Leese et al.'s work [15] presented an overview of process parameters involved in ECM. In this review article provided, an overview of ECM technology by including the latest research from both academic and industrial fields. This article is aimed at audiences from both academia and industry.

2 Principle of Material Removal

The fundamental idea behind the removal of material in microelectrochemical machining (micro-ECM), which involves anodic dissolution of the workpiece, is the same as that in electrochemical machining. In contrast, the goal of microelectrochemical machining is to pinpoint material removal in order to obtain exact control

Table 1 Observed parameter of process performance in μ-electrochemical machining [6–8]

	Machining gap	MRR	Surface finish	Shape precision
Electrolyte concentration	✚	✚	⬇	⬇
Voltage	✚	✚	⬇	⬇
Duty cycle	✚	✚	⬇	⬇
Pulse on time	✚	✚	⬇	⬇
Pulse frequency	✚	✚	⬇	⬇

over the morphology. Compared to other localized material removal procedures, micro-ECM provides a number of benefits. For instance, because the dissolving takes place at the atomic level, it is unaffected by the workpiece's hardness, can be utilized to make complex shapes, and has no tool wear. As a result, the surface quality is very good.

Micro-ECM may be precisely controlled in micromachining by applying ultra-short pulse power. Furthermore, it is a non-contact technique that doesn't generate any machining forces, making size effects irrelevant. To improve process capabilities and widen the material processing area, micro-ECM can potentially be integrated with several other processes. Finally, electrical factors like electrical current and voltage as well as pulse properties like frequency ratio, on time, length, and pulse duration can be used to accurately control material removal rates in micro-ECM. The workpiece serves as the anode as well as the tools electrode as the cathode in an anodic reaction. The metallic workpiece goes through oxidation during this process, which releases electrons [16].

Various process inputs utilized in the electrochemical machining process are shown in Fig. 1 with the help of the Ishikawa diagram in which four main factors, i.e., electrolyte, tool used in the process, workpiece nature, and electrical parameters considered in the process are highlighted with their subparts.

Schematic diagram of ECM process with the pulse power supply is shown in Fig. 2. The main elements of the ECM process are connected in series.

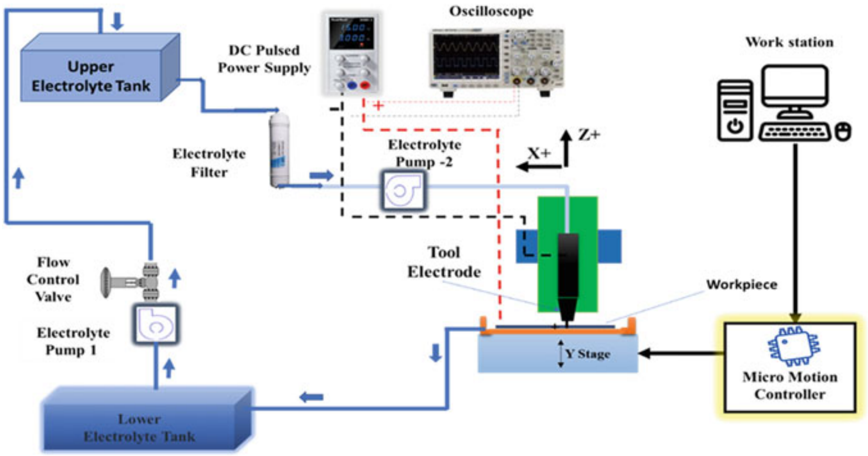

Fig. 2 Schematic diagram of ECMM

3 Literature Review

Kumar et al. [17] conducted experiments on the floating metal powder with moving on Stainless steel 316L through the ECMM process. The purpose of the experiment was to investigate the effectiveness of ECMM in cutting SS316L using citric acid as an environmentally friendly electrolyte. The results of employing copper powder material immersed in a citric acid electrolyte without the aid of a mechanical overhead stirrer were compared to those of using copper powdered material immersed in an acid electrolyte with that assistance. To determine the output performance characteristics, such as material removal rate and overcut, the researchers changed the input effect of various parameters, including operating voltage, pulse duration, and solution concentration.

A study conducted by Ayyappan et al. [18] investigate the use of a magnetic flux-assisted low-frequency vibrating tool as a productive hybrid ECM method to improve MRR and surface quality index. The researchers created a mathematical model that connected surface roughness with machining factors like voltages, solution concentration, and IEG. Despite its potential benefits, ECM was not widely used due to accuracy issues, challenges in tool design, and parameter control difficulties. Using contour plots, the importance of electrochemical machining process variables was examined.

Singh et al. [19] introduced a new experimental technique, known as “one parameter at a time” approach, to evaluate a diamond cut-off grinding system using electrochemical methods on a locally made setup. The study focused on the grinding of nickel-based superalloy (Inconel 925), which is challenging to machine using traditional methods. Electrochemical grinding is a valuable technique for machining conductive materials that are newly developed or difficult to cut.

Sethi et al. [20] investigate how nitinol dissolves electrochemically in different electrolytes for micro-ECM purposes. Nitinol is an ideal shape memory alloy for microelectromechanical systems, especially in biomedical applications, due to its super elasticity, biocompatibility, and shape memory effect. However, the conventional machining process for creating micro features on nitinol is difficult because of its temperature-dependent material transformation properties.

Ayyappan et al. [21] investigate the ECM properties of 20MnCr5 steel in their work. Certain mechanical regulating parts, which are challenging to produce using conventional machine tools, like pistons screws, spindle, overhead cams, gearboxes, and shaft, are frequently made of this type of alloy steel, particularly, 20MnCr5. To investigate the machining performance, the researchers used two electrolytes—aqueous potassium dichromate (K2Cr2O7) and sodium chloride (NaCl). K2Cr2O7 was added to the NaCl bath due to its oxidizing properties. The rate of material removal and surface roughness were the two variables that the study looked at in relation to common electrochemical machining parameters such voltage level, IEG, and solution concentration.

Cao et al. [22] study to investigate the behavior of TA15 anode in anode dissolving and obtain the necessary surface attributes for counter-rotating electrochemical machining. The researchers measured the anodic characteristics and examined the passive–trans passive behavior of TA15 using a polarized and voltammetry curve. Unfortunately, limited research has been done on the anodic behavior of the counter-rotating state. A quantitative dissolution model was developed to explain the electrochemical dissolution and structural evolution of the revolving surfaces after electrochemical impedance spectroscopy was used to investigate the electrode structure at various phases.

Rahi et al. [23] conducted a study to use an electrochemical method to cut metal matrix composites. However, they faced two significant obstacles: low material removal rate and oxide layer buildup on the machined surface. To overcome these issues, they proposed a hybrid approach combining conventional grinding and electrochemical machining. To test this approach, they designed an electrochemical surface grinding experiment to compare its effectiveness with the ECM method for cutting the challenging Al-SiC-Gr metal matrix composite.

Rajesh et al. [24] examined how several electrochemical hole-digging process variables, such as supply voltage, electrolyte solution, and pulse duration, affected the rate at which material was removed from aluminum 7075 alloy composites containing silicon carbide and fly ash particles. These composites have potential applications in the construction of trusses, frameworks, and vessels that hold pollutants, dairy, and other acidic substances in areas with high salt concentration, as an alternative to stainless steel, which is commonly used to prevent corrosion.

The impact of several factors on the macroelectrochemical machining of aluminum alloy 7075 composite with silicon carbide and fly-ash was examined by Chinailli et al. [25]. To examine the effects of process variables such voltages, solution concentration, interelectrode spacing, as well as drilling time, the researchers employed a central composite design technique. According to the study, drilling time, voltage, and electrolyte concentration all had a substantial impact on the drilled hole removal rate of material and surface quality. The surface morphology and elemental makeup of the drill holes were also examined by the researchers using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX).

Singh and Sharma [26] investigated the usage of innovative thermoplastic slit profiles in electrochemical machining (ECM). The performance of the thermoplastic slit profiles in comparison to traditional slit profiles was assessed using a micro-ECM setup in terms of the amount of material removed and surface quality. The study found that the thermoplastic slit profiles produced a higher MRR and a lower SR compared to the conventional slit profiles. The researchers also observed a longer tool life for the thermoplastic slit profiles, indicating that they had less tool wear compared to the conventional slit profiles.

Vijayakumar et al. [27] studied the optimizing electrochemical micromachining (ECMM) process for a copper alloy. The removal rate of material and surface quality are two examples of the output parameters that the authors investigate using a (RSM). Voltage, solution concentration, and IEG are the three input parameters that are varied in the experimental design. The authors use a Box-Behnken design to generate 15 experimental runs, with the removal rate of material and surface quality observed from each run. The resulting data is used to build regression models for each output parameter, which are then optimized using a multiobjective genetic algorithm.

Aravind and Hiremath [28] developed a model to optimize the microelectrochemical machining (micro-ECM) parameters for machining holes on copper plates. The impact of various input variables, such as ion concentration, voltage, and machining time, on the rate of material removal and surface morphology of the machined holes was examined by the researchers using a mathematical model and the response surface methodology (RSM). The surface shape and elemental makeup of the machined surface were further examined using an EDS and a scanning electron microscopy. The findings demonstrated that a greater MRR and a lower SR were produced by the ideal set of input parameters.

Kumar et al. [29] investigated the use of electrochemical jet machining (ECJM) for surface finishing of an additively manufactured (AM) part. The researchers used a stainless steel AM part and evaluated the surface roughness (SR) and material removal rate (MRR) of the part using ECJM. To examine the impact of various parameters, including electrolyte concentration, tools feed rate, and applied voltage on the SR and MRR, the study employed a Taguchi-based methodology.

In order to increase the removal rate of material (MRR) and decrease sludge formation during the ECM of the Monel 400 alloy, Nagarajan et al. [30] examined the application of a meta-heuristic approach. To examine the impact of multiple input factors, including machining voltage, solution concentration, tools feed rate, and machining time on the MRR and sludge formation, the researchers employed a Taguchi-based design of experiments (DOE) strategy. The grey wolf optimization (GWO) algorithm was employed in the study to enhance the input variables and improve the efficiency of the machining. The results showed that the GWO algorithm produced better results compared to the Taguchi-based DOE approach in terms of MRR and sludge reduction.

Deepak and Hariharan [31] investigated the influence of auxiliary electrodes and magnets on electrochemical machining (ECM) of SS304 using NaCl and NaNO3 electrolytes. The experimental setup involved a stainless steel workpiece, a copper auxiliary electrode, and a magnet, which were placed in the electrolyte solution. The outcomes showed that the addition of copper auxiliary electrodes reduced the surface roughness of the machined surface, with a smoother surface being produced by the NaNO3 electrolyte than by NaCl. The presence of a magnet had a considerable impact on the rate of machining, with the magnetized setting outperforming the non-magnetized setup.

Kumar et al. [32] investigate the impact of tool rotation on the fabrication process of micro-tools using electrochemical micromachining (ECMM) technology. ECMM is a non-conventional process that is used to fabricate micro- and nano-scale features on conductive materials. The study evaluates how the ECMM process is affected by two alternative tool rotation speeds. The researchers have found that a fast-rotating tool produced a more even distribution of material removal throughout the tool surface, producing a smoother tool surface and a more exact shape. They also found that higher rotation speeds allowed for a faster fabrication process, with a higher material removal rate.

Sahai et al. [33] investigate a new method for micromachining silicon using a combination of electrochemical and spark-assisted milling techniques. The study aims to develop an efficient and cost-effective method for fabricating microstructures on silicon, which is an important material for microelectromechanical systems (MEMS) and microfluidics. The researchers first developed a mathematical model of the M-ECSMM process, which takes into account the various parameters involved in the machining process, such as voltage, current, and electrolyte concentration.

4 Future Scope and Research Aspects for Research in ECMM

Electrochemical micromachining (ECMM) is a specialized field that involves the use of electrochemical processes to fabricate miniature structures and devices with high precision and accuracy. The technology has numerous applications across several industries, including microelectronics, medical devices, and aerospace. In recent years, there has been a growing interest in the use of ECMM for fabricating micro-electromechanical systems (MEMS) and microfluidic devices. These tiny devices have the potential to revolutionize several fields, including biomedical research, drug delivery, and diagnostic testing. The future scope of research in ECMM is quite promising, and some of the key areas of focus include:

1. Development of new electrochemical machining techniques: Researchers are constantly working to improve existing ECMM techniques and develop new methods that can produce even more precise and complex structures.

2. Advancement of MEMS technology: The development of MEMS technology is a major focus in ECMM research, and future advancements in this area could lead to the creation of new devices with improved capabilities and functionality.
3. Integration of ECMM with other fabrication techniques: The integration of ECMM with other fabrication techniques such as photolithography and 3D printing could lead to the creation of even more complex structures and devices.
4. Applications in biomedical research: ECMM has several potential applications in biomedical research, including the fabrication of microscale sensors for monitoring biological processes and the creation of microfluidic devices for drug delivery.

Overall, the future scope of research in ECMM is quite broad, and continued advancements in this field could have significant impacts across several industries.

5 Conclusion

Based on a study of numerous machining methods, researchers have concluded that ECMM is highly useful for machining aero-engine components, biomedical components, etc. This review article proposes a potential advancement in electrochemical machining or hybrid techniques, as well as the design of intricate machining profiles, numerical analysis of the electrochemical process, and prediction of anode shape using flow field simulation. The following recommendations are made for additional research.

1. Precision and necessary geometric accuracies can be challenging to achieve when machining high-strength material. Electrochemical micromachining (ECMM), one of the available machining techniques, is frequently used to make products of excellent quality from metals and alloys and can minimize machining time and expense. According to the available literature, it has been shown that employing the electrochemical micromachining technique to machine these high-temperature titanium alloys produced certain results that are appealing to users in the industry and provide room for future research.
2. The majority of research is focused on fundamental questions, such as how well different materials can be machined, how well processes can be developed, how to use pulsed power supplies, and how to use parametric studies to evaluate process performance. There are a few areas that still require investigation and are not fully developed: development of specialized machinery, evaluation of the micro-ECM process's product and process characteristics, the correlation between material clearance and micro-ECM pulses, interelectrode phenomena characterization using customized settings, multidisciplinary modeling, which takes into account bubble phenomena, mass and charge movement, and the fundamental concept of the micro-ECM process creation of ecologically friendly electrolytes and alternatives for acidic electrolytes.

3. The design and development of universal or multifunctional machine tools that can be used with multiple process energies, understanding of material removal mechanisms on different materials when two or more process energies act simultaneously in the same machining zone, and synchronization of two process energies on the same machining axis to control precision of material removal and shape control are a few of the critical elements that literature has not yet fully addressed. enhancing knowledge of the interplay between two process energy.
4. ECMM offers several advantages over traditional micromachining techniques, such as high accuracy, excellent surface finish, and the ability to machine complex geometries. ECMM can be used for a variety of applications, including microelectrodes, micromolds, microfluidic devices, and micro-sensors. The process capabilities of ECMM can be enhanced by combining it with other micromachining technologies, such as micro-milling, microgrinding, and laser machining, to form hybrid variants.
5. The development of micro-scale features on a variety of materials, including metals, semiconductors, and insulators, is made possible by the promising ECMM technology. Hybrid variants of ECMM can provide additional benefits, such as improved material removal rate, reduced machining time, and enhanced surface quality.
6. The development of a passivation layer on the workpiece surface, which can restrict the rate of material removal and lower machining precision, is one of the main difficulties faced by ECMM. Several approaches have been developed to overcome this challenge, including the use of high-frequency pulsing, the application of ultrasonic vibration, and the addition of surface-active agents.
7. The choice of electrolyte solution is critical for achieving high-quality machining results in ECMM. The electrolyte solution should have high conductivity, low viscosity, and high stability. The process variables, like feed rate, voltages, solution concentration, and current density, greatly affect how well the ECMM can machine materials.

Overall, ECMM and its hybrid variants offer great potential for producing high-quality microscale features on a wide range of materials, and further research and development are needed to fully explore their capabilities and applications.

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