Synergies in Machining: Advancing Electrochemical Machining through Process Integration

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ABSTRACT

The synergies attained by integrating electrochemical machining (ECM) in the area of modern manufacturing processes are thoroughly reviewed in this research. Utilizing the concepts of electrochemistry, electrochemical machining is an unconventional manufacturing technique that precisely removes material from parts while providing special benefits like high accuracy, the ability to handle complicated geometry, and less tool wear. Hybrid processes that use the advantages of each machining technique have been developed as a result of the combination of ECM with other techniques. These combinations have combined benefits that are explained in terms of increased surface finish, increased machining efficiency, and broader applicability to a larger range of materials. The assessment also focuses on new developments in hybrid machining methods, such as the integration of ECM with other manufacturing techniques. With an emphasis on decreased energy usage and waste materials, the economic and environmental effects of ECM integration are also taken into account. This thorough review concludes by synthesizing the state of the art in electrochemical machining integration across a range of machining processes. The synergies that result from these linkages show how advanced manufacturing may be made more effective and efficient overall, opening the door for more advancements in the sector. For scholars, practitioners, and industry professionals looking to harness the power of ECM integration for creative machining solutions, the insights offered in this paper are an invaluable resource.

Keywords:
Hybrid Machining, Electrochemical Machining, Surface Quality

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1. Introduction

Along with standards and quality requirements increasing, products are getting lighter, smaller, and more compact. In numerous goods from the automobile, jewellery, healthcare equipment and the aviation sector, micro-machining is becoming more and more common. Micromilling, laser machining, and electrodischarge machining (EDM) are only a few examples of the various micro-machining methods. Every micro-manufacturing technology evolves constantly, and new technologies are also being introduced into the original group of micro-technologies as a result of new findings from research and the increasing need for more precise, flawlessly machined micro-surfaces. These demands also include unique specifications for the integrity of the machined surface, such as demands on roughness appropriate for optical applications and the absence of defective layers following the machining process (Ivanov et al., 2015).

In light of the reason that electrochemical machining (ECM), and particularly electrochemical micromachining (μECM), doesn't generate any defective layers after processing, this technique has drawn interest from researchers (Ivanov et al., 2015). Electrochemical machining (ECM) stands out as an unconventional process wherein material dissolution occurs at the anode. Its distinctive capability to machine materials without regard to their mechanical strengths positions it as a preferred method, particularly in the machining of challenging materials like single crystals and nickel-based alloys (Tchoupe et al., 2022). Furthermore, it seamlessly integrates high machining rates with minimal tool wear, making it an economically and

ecologically viable choice for such materials. Within the ECM process, an electric potential is employed among the cathode (functioning as tool) and the anode (functioning as workpiece). Both components are segregated by a narrow working gap filled with a liquid electrolyte. Material removal occurs through the transpassive dissolution of the workpiece, following the principles of electrolysis (McGeough, 1974).

2. Working principle

The electrolysis laws of Faraday, which postulate that the amount of material dissolved from an electrode is directly proportional to the electric charge passed through the electrode, form the basis of ECM, a non-conventional manufacturing method that utilize electrochemical reactions to extract material from a work-piece (Brandt, 1989). ECM is an electrolytic method that relies on the workpiece's anodic dissolution. The process of electrolysis involves the transfer of current across a pair of electrodes in an electrolyte, an electrically conductive solution, in order to complete circuit (Cornell, 2010).

3. Need for integration and synergy in machining processes

Improving productivity, accuracy, and overall performance during production requires integration and synergy in machining processes. Process optimization is greatly enhanced by the smooth coordination and cooperation of different manufacturing phases and techniques.

Table 1 Need for integration and synergy in machining processes

SN	Need	Explanation	Reference(s)
1	Improved Efficiency and Productivity	Production flow becomes more streamlined and effective when machining operations are integrated. As a result, there can be less idle time in between machining processes.	Goh and Nee (1998), Kapoor and Devor (1999), Sharma and Dvivedi (2023)
2	Enhanced Precision and Quality	By reducing errors and fluctuations, the synergy between machining procedures ensures a consistent and superior result. Integration of systems allows for real-time feedback and communication, which enables quick modifications.	Goh and Nee (1998), Kapoor and Devor (1999), Sharma and Dvivedi (2023)
3	Cost Reduction	Integration contributes to material waste reduction, energy consumption minimization, and resource optimization. Long-term, this can result in significant cost reductions.	Dirven (2023), Sharma and Dvivedi (2023)
4	Flexibility and Adaptability	Combined manufacturing systems offer increased adaptability to shifting production needs. This flexibility is essential in the fast-paced manufacturing world of today.	Chen and Frank (2019), Javaid et al. (2022)
5	Technological Advances and Industry 4.0	This combination facilitates the use of cutting-edge technology in machining operations, including artificial intelligence and the Internet of Things (IoT).	Bi et al. (2014), Sharma (2019), Javaid et al. (2022)

4. Design components for hybrid machining

An interdisciplinary field, design for hybrid machining involves creating a mixture of operations (refer Fig. 1) while considering the physics of those operations, in addition to creating specialized machine tools (Saxena et al., 2018).

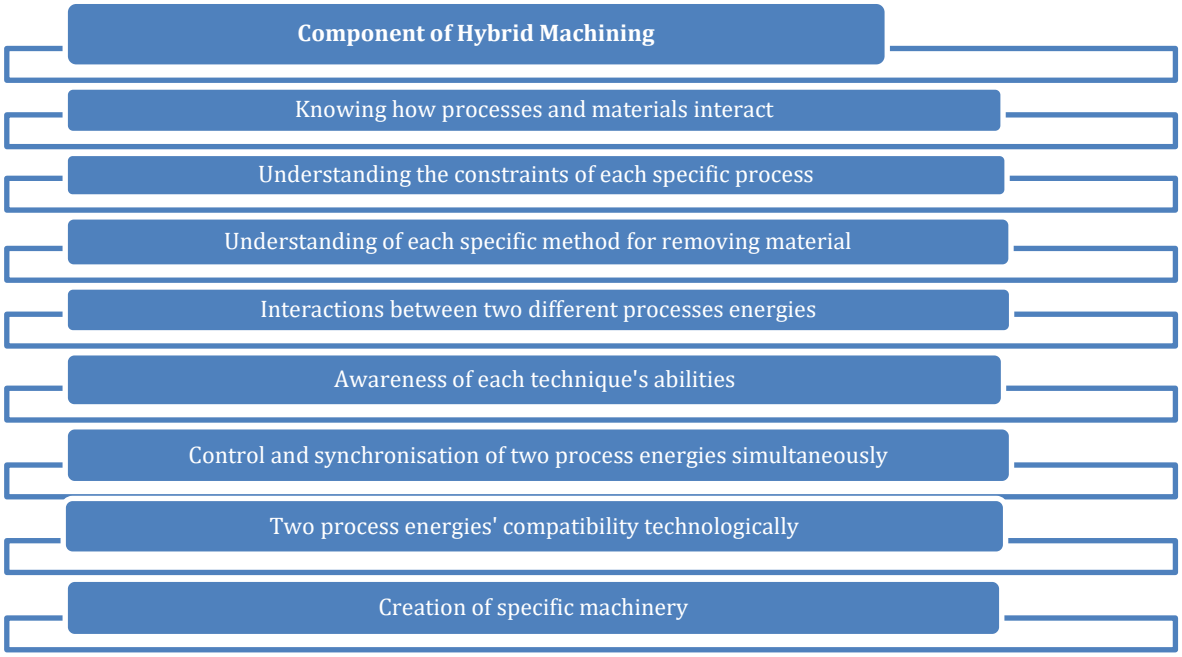


Fig. 1 Design components of hybrid machining

5. Integration of ECM with other machining processes

Dabrowski et al., (2006) investigated polymeric electrolyte-based electrochemical aided abrasive flow machining (ECAFM). Discoveries are Surface roughness is primarily determined by the type of abrasive paste used. It's ambiguous how electrochemical assistance affects surface roughness. El-Taweel, (2007) designed a setup for integrated electrochemical turning and magnetic abrasive finishing lowering the surface roughness and raising the MRR. According to the study, surface quality improved by 33% while machining efficiency rose by 147.6%. Zhu et al., (2011) carried out an experiment employing ECM-Grinding on SS321. The ECM-Grinding process's parameter levels were varied during experiments. According to the study, the best surface roughness R_a is 0.21 m, and the ideal operating parameters for ECM-Grinding were working voltage 4.5V and feed rate 5.5 m/s. Zhu et al. (2011) conducted research indicating that Electrochemical Machining (ECM) and grinding offer greater benefits compared to traditional grinding. These advantages include reduced residual stresses, enhanced depth of cut, and prolonged wheel lifespan. Additionally, the combined ECM and grinding process surpasses the performance of ECM alone. The grinding wheel's abrasive action removes the passivation layer, aiding the ECM method through consistently revealing a new work-piece surface. In ECG (Electrochemical Grinding), employing a pulsed power supply is more effective than the conventional approach, enabling the adjustment of the steadiness among mechanical and electrochemical actions. Zhang and Xu, (2011) used laser drilling and Jet ECM to conduct experimental research on 321 stainless steels. They came to the conclusion that, when compared to laser drilling in the air, laser drilling with jet ECM can achieve a recast reduction of more than 90%. Liu et al., (2014) carried out an experiment using electrochemical magnetic abrasive finishing on Al 6061. They demonstrated that employing EMAF to polish Al 6061 produced noticeably better surface quality than doing so only with MAF. Surekar et al. (2014) investigated the factors influencing the rate material removal of Hastelloy C-276 in the electrochemical machining process. The results suggest that the highest material removal rate is achieved under the following conditions: a high feed rate of 1 mm/min, a minimum rate of electrolyte flow of 150 L/hr, and a high voltage of 16 V. Among these parameters, it is evident that the feed rate has the most essential impact on the rate of material removal. Wu and Zou (2015) utilized electrochemical magnetic abrasive finishing on machined aluminium alloy. They

created a step-by-step technique, using electrochemical material removal in the first stage before completing with magnetic abrasives to accomplish a surface roughness Ra of 0.030 m for aluminium. In contrast to alternative manufacturing technologies, Klink (2016) have analyzed the likenesses and dissimilarities resulting from the unique physically active principles of electrolysis by ECM and thermal elimination of material by EDM. Lastly, a generic methodology has been introduced for EDM and ECM systems that facilitate a uniform evaluation of material loadings and consequent surface integrity by taking into account distinct process parameters. Goel and Pandey (2016) used the ultrasonic assisted jet electrochemical micro drilling technology to conduct experimental research on copper. They came to the result that the voltage (290 V), electrolyte concentration (1.25 mol/l), and electrolyte pressure (0.2 MPa) combinations that produced the largest MRR of 9.31 mg/min were the ideal ones. Van Camp et al. (2018) created a setup for milling Ti6Al4V using a hybrid mechano-electrical process. They came to the conclusion that MECM, as opposed to ECM, boosted machining efficiency by 60%. Saxena et al. (2018) studied that combining electrochemical and electro discharge process energy is known as electrochemical discharge machining (ECDM). The delay period in the EDM process is employed for electrochemical dissolution, subsequently transitioning into melting through spark discharge, in accordance with the ECDM principle. In the ECDM process, optimal process parameter control can result in high surface polish, dimensional precision and a smaller HAF (heat affected zone). The ECDM method leads to the removal of material in a specific area through the combination of melting and evaporation. Saxena et al. (2018) studied the processes of ECM and laser-chemical machining which have been created through the overarching goal of achieving a manifold improvement in MRR (Material Removal Rate) and the accuracy in the removal of material through chemical/electrochemical means. Simultaneously, these processes aim to minimize thermally induced defects associated with laser machining. The primary mechanism of material removal involves electrochemical breakdown, with the laser fulfilling several roles contingent on fluences. The laser contributes to the elimination of the passivation layer, facilitates localized heating of work-piece to enhance dissolution kinetics, and the active participation in material removal can occur when utilizing high pulse energies. The integration of Laser Electrochemical Machining (LECM) yields superior surface finish, minimal thermal defects, and enhanced precision compared to standalone ECM and laser machining processes. Farwaha et al. (2019) successfully machined and completed cylindrical work pieces made of 316L stainless steel utilizing the UEMAF (Ultrasonic Assisted Electrochemical Magnetic Abrasive Finishing) technique. At optimal levels, the UEMAF procedure led to an 82% enhancement in surface finish. Chen and Sundaram (2020) investigated the use of ECDM for micromachining nonconductive materials such as glass. Utilizing a mixed electrolyte of 1.2 M H_2SO_4 and 0.8 M Na_2SO_4 reduces surface damage brought on by thermal and chemical causes during ECDM glass milling. Kumarasamy et al. (2020) conducted micro-hole machining on Hastelloy C276 using the micro-electrochemical machining process with various electrolyte solutions, including NaCl, $NaNO_3$, and a hybrid mixture consisting of NaCl, $NaNO_3$, and citric acid. The outcomes indicated that the hybrid electrolytic combinations outperformed the others with regard to Material Removal Rate (MRR), overcut reduction, conicity reduction, and the creation of more circular holes. Study by Heidemanns et al., (2022) assessed the impact of various flow channel diameters on the outcomes of the machining process. The development of additive manufacturing has made it possible to implement novel flushing ideas in ECM. The accuracy of the machined workpieces was found to be significantly impacted by the various designs. Ultimately, the fundamental process behind the creation of the detected deviations may be found using CFD simulations of the electrolyte flow. Rech et al. (2022) introduced an innovative method for polishing metallic substances, combining drag finishing and electrochemical polishing (PEMEC). The study reveals a synergistic effect between abrasive and chemical mechanisms, enhancing the material removal rate and yielding smooth surfaces within a few minutes. Mandal et al. (2023) explored the viability of producing micro-holes in C103 niobium-based alloy for high-temperature applications through the powder-mixed micro-electrochemical discharge machining (PMECDM) process. In contrast to the MECDM process, where the material removal rate (MRR) was 2.01 mg/min with a corresponding surface

roughness (R_a) of 1.11 mm, PMECDM demonstrated an increased MRR (2.8 mg/min) and reduced surface roughness (Ra of 0.61 mm). Sharma & Dvivedi (2023) introduced a novel hybrid machining technique for Inconel 718, termed SECEDM (simultaneous electrochemical and electrodischarge machining). The results obtained indicate that, when compared to electrochemical machining (ECM) and electrodischarge machining (EDM), the SECEDM method provides approximately 261% and 141% higher material removal (MR) rates and 1.23% and 3.78% better overall hole circularity. Moreover, SECEDM facilitates more localized dissolution than ECM and surpasses the simultaneous micro-EDM and micro-ECM process (SEDCM) by a factor of seven in machining rate. Assistance from magnetic fields 304 stainless steel with a high-precision surface was created by Wang et al., (2023) using an electrochemical micro-machining technique. Measurements of surface roughness and observations of micro-morphology were made. The outcomes demonstrated that 10 minutes of magnetic field assistance electrochemical micro-machining produced the best surface morphology, with a roughness of roughly 0.30 μm. The surface roughness produced by the magnetic field assistance electrochemical micro-machining was less than that of the ECMM (electrochemical micro-machining) performed at the same processing time, suggesting that the magnetic field assistance helped to increase the machining efficiency. Kumar et al. (2023) conducted an analysis of the tribological properties of the SS316L part manufactured using laser powder bed fusion (L-PBF) and electrochemical jet machined surface. By preserving and enhancing surface integrity, ECJM has shown to be a viable substitute for post-processing an L-PBF part. On the completed samples, however, stray corrosion and uneven humps were noted. Hung and Zhang (2023) investigated the machining properties of ultrasonic broaching (USB) and in-situ UAECDM (ultrasonic-assisted electrochemical discharge grinding) to fabricate square microholes in quartz. This technique, implemented using CNC machine tools equipped with ultrasonic vibration spindles, has proven to be effective. The maximum difference in hole expansion at the inlet and outlet can be minimized to 4 and 3 μm, respectively, with tool wear ratios for the USB and UAECDG methods reported at 2.1% and 0.71% respectively. The impact of the machining gap on the blade's two sides during vibration-assisted pulsed electrochemical machining was investigated by Jiang et al. in (2023). The findings of the study indicate that when the gap between the cathode and the blade widens, the deformation of the blade also increases. After blades are machined, a two-step processing test is carried out to limit gap difference. It guarantees the accuracy of the machining process in addition to increasing processing efficiency. According to the experimental results, when the final gap difference is 0 mm, the blades' total profile error is approximately 0.05 mm, and their surface roughness is less than 0.13 μm, indicating high surface quality and profile accuracy. Using simulations, Thielecke et al. (2023) analyzed the electrical current induction during Nd-Fe-B machining using Pulsed Electrochemical Machining (PECM). The oscillation movement of the cathode, which is consistent with Faraday's law of induction, was indicated by the simulation results as the cause of the electrical current induction in the model geometry. Comparing this method of inducing current density to the current density produced by the external electric potential, a substantial difference is observed. Comprehensive investigation of monel-400 alloy electrochemical machining using various electrolytes studied by Sinha et al. (2023). The authors of this study enhanced machining performance through the application of meta-heuristic algorithms (MFO and GWO), resulting in a 0.242 g/min increase in material removal rate (MRR) and a 57.72 PPM rise in Nickel presence during the machining of Monel 400. The electrolyte has been found to have a significant influence on the μECM method and needs to be chosen according to the material of the work piece. Han et al. (2023) examined the use of a glycol-based electrolyte to enhance electrochemical discharge machining performance. They also suggested an energy-electricity regulation methodology to achieve precise electrochemical discharge machining. Based on the results, it was observed that there is the absence of a trans passive film on the work-piece, and a thin, stable gas film is present in glycol-based electrolytes. Adjusting the EDM energy (E) to approximately 10 n–14 n μJ (where n is the total pulse number) and the ECM electricity (Q) to approximately 0.5 n–1n μC enables achieving a low wire relative wear ratio and a small slit width. The goal of the Liu et al. (2023) study was to thoroughly explain the gap

effect in EJM using simulation and experimentation. When the gap is narrowed from 0.4 to 0.2 of the nozzle diameters, the jet-surrounding-film thins, but the jet profile remains nearly unchanged with varied gaps ≥0.4 of the nozzle diameter and only changes in length.

6. Challenges and solutions

Table 1 Challenges and solutions in integration of ECM with other machining processes

SN	Aspect	Challenge	Solution
1	Material Compatibility and Conductivity	For electrically conductive materials, ECM works incredibly well, but its compatibility with non-conductive materials might be limited.	Before applying ECM, take into account pre-treatment techniques like applying conductive layers to the material.
2	Surface Finish Consistency	Obtaining a consistent surface finish when combining ECM with other methods, since ECM often offers a better surface finish than many traditional machining techniques.	Enhancing Surface Quality through Process Parameter Optimization and Complementary Finishing Techniques
3	Tool Wear and Maintenance	Maintaining and reducing tool wear is important because, when combined with other machining processes, degradation of the tool electrodes in ECM can affect overall performance.	Adopt improved wear resistance materials and implement tool condition monitoring systems.
4	Process Control and Optimization	Developing effective control strategies for integrated processes to optimize surface finish, dimensional accuracy and material removal rates.	Creating efficient control plans for integrated processes in order to maximize dimensional accuracy, surface finish, and material removal rates.
5	Complexity of Integration	The overall complexity of the system could improve when ECM is combined with other machining processes.	Streamline the integration process by implementing automation and modular systems.
6	Energy Consumption and Environmental Impact	Addressing issues with energy usage and possible environmental effects of integrating ECM with other machining techniques.	Examine energy-efficient ECM configurations, put them into practice, and investigate hybrid strategies that optimize energy use.
7	Process Monitoring and Quality Assurance	Developing reliable monitoring methods for confirming the quality of the machined components during integrated processes.	Develop progressive monitoring and control methods that can adapt to variations in the combined methods.

7. Conclusion

The integration of electrochemical machining (ECM) reveals diverse synergies that hold significant promise for the future of machining. ECM's environmentally friendly characteristics, marked by minimal waste generation and the absence of thermal and mechanical stresses on the work-piece, align seamlessly with the growing emphasis on sustainable manufacturing practices. As industries worldwide seek eco-conscious solutions, the adoption of ECM emerges as a responsible choice, contributing to a more environmentally sustainable and efficient manufacturing landscape.

The collaborative benefits derived from combining ECM with other machining techniques further enhance its effectiveness. The hybridization of these methods not only results in improved material removal rates and enhanced surface finishes but also addresses intricate manufacturing challenges that might be difficult to solve with individual processes. This collaborative approach not only boosts the efficiency of machining operations but also paves the way for innovative advancements in product design and development. Undoubtedly, the incorporation of ECM will continue to be a central focus in shaping the future of precision manufacturing.

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