



Review

## Challenges and control strategies for disrupting passive oxide layer formation in electrochemical machining

Ritesh Kumar Upadhyay✉

Department of Mechanical Engineering, BIT Mesra, Off Campus Deoghar – 814142, India

Corresponding author: ✉ [ritesh.upadhyay@bitmesra.ac.in](mailto:ritesh.upadhyay@bitmesra.ac.in)

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### Abstract

Electrochemical machining (ECM) is a non-traditional, precision machining process involving the removal of material through anodic dissolution. It is commonly utilized for machining complex geometries in conductive materials, especially in aerospace, biomedical, and automotive sectors. While having numerous benefits, ECM also has a major challenge: the development of a passive oxide layer on the surface of the workpiece. The formation of this layer depends on various factors, such as workpiece material, electrolyte composition, current density, and machining conditions. If not properly controlled, it can cause poor surface finish, dimensional errors, and increased energy consumption. To counter this problem, several control strategies have been devised that play a crucial role in breaking down the passive film. This review critically analyses and compares these strategies for inhibiting passive layer growth in ECM. It highlights both traditional and established techniques as well as novel developments like hybrid ECM methods, AI-driven process optimization, and real-time monitoring systems. The review aims to provide a material-specific and application-oriented perspective, highlighting the advantages, limitations, and technical viability of each strategy. By integrating findings from experimental studies, simulation work, and emerging technologies, this review provides a comprehensive resource for researchers and practitioners seeking to enhance the reliability, performance, and precision of ECM processes in high-tech manufacturing.

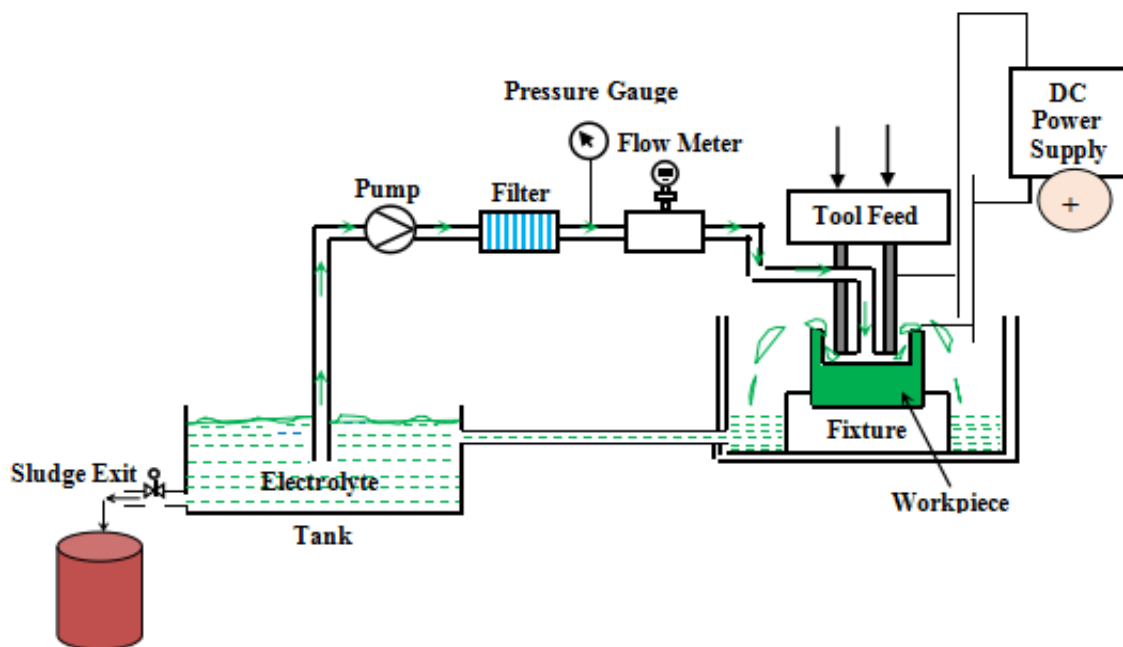
### Keywords

Material removal; anodic dissolution; material passivation; process parameters; control measures

### Introduction

Electrochemical machining (ECM) is a sophisticated and non-conventional machining process that utilizes electrolysis to remove material from electrically conductive workpieces immersed in electrolyte upon supply of DC current, as shown in Figure 1. In contrast to conventional techniques such as milling or drilling, which rely on direct mechanical contact between the tool and the workpiece, ECM does not involve physical contact [1]. This contactless machining significantly

reduces tool wear and enables the machining of complex shapes and subtle geometries that are difficult to achieve with conventional methods. Consequently, ECM has emerged as a method of choice in sectors where precision, surface finish and tool life are significant factors, such as aerospace, biomedical, automotive, and energy industries [2]. One notable disadvantage of ECM is the tendency for a passivation layer to form on the workpiece surface during the dissolution process [3]. The passive film thus formed is typically composed of metal oxides and hydroxides, resulting from electrochemical reactions in which the tool serves as the cathode, the workpiece as the anode, and the electrolyte. This layer acts as an ionic transport barrier, inhibiting the process of anodic dissolution during machining. This hinders not only the material removal rate (MRR) but also increases electrical resistance, leading to higher energy consumption and lower machining accuracy and surface finish [4]. The development and accumulation of this passive film are affected by several factors, including the type of material being machined, the composition and pH of the electrolyte, the current density, the temperature, and the machining time [5]. Materials such as stainless steel, titanium alloys, and nickel superalloys are especially prone to developing recalcitrant oxide layers due to their high corrosion resistance and tendency to passivate [6]. If not properly managed, the existence of this passive layer will negatively affect dimensional precision, lengthen machining time, and lead to inconsistencies in results [7]. To eliminate such problems, a proper understanding of the electrochemical mechanisms associated with oxide growth is crucial. Using optimized electrolytes, applying pulse power supplies, and using additional techniques like ultrasonic stirring are some ways of preventing or disturbing passive layer development. Controlling this effectively is necessary to maximize ECM performance, ensure process consistency, and provide the high accuracy demanded by modern manufacturing techniques.

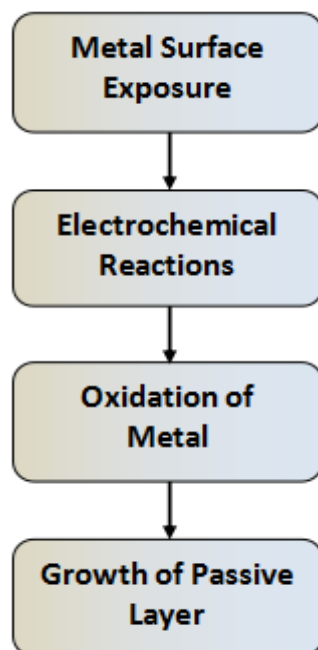


**Figure 1.** Electrochemical machining setup

### *Mechanisms of passive oxide layer formation in ECM*

Oxide layer formation and its growth during ECM are significant issues, especially when machining materials with high oxygen affinity, such as stainless steels, titanium alloys, and nickel-based superalloys. These materials tend to form a stable oxide layer on their surface as a corrosion protection mechanism in aggressive environments [8]. Although this passivation is desirable in most

applications, it becomes undesirable in ECM. The formed oxide film acts as an insulating barrier at the electrode-electrolyte interface, inhibiting the anodic dissolution process that is critical for effective material removal [9]. As the passive layer grows thicker, it results in a decrease in the MRR, enhances the resistance of the electrochemical cell, and leads to greater energy consumption. Additionally, the uneven dissolution caused by the presence of a layer affects surface quality and dimensional accuracy. A stepwise flowchart illustrating the mechanism of passive layer formation and its buildup is shown in Figure 2.



**Figure 2.** Process flowchart showing the stages of passive layer formation and buildup

### *Electrochemical reactions*

At the core of ECM, electrochemical reactions govern material removal, involving an anode (the workpiece) and a cathode (the tool) submerged in an electrolyte. However, unwanted side reactions contribute to the formation of a passive oxide layer [10]. The fundamental material removal reaction is presented in Equation (1).



where M is the metal,  $M^{n+}$  is the dissolved metal ion, and  $ne^{-}$  represents the number of electrons released. During anodic polarization, oxygen evolves from water oxidation as shown in Equation (2):



Oxygen bubbles at the workpiece surface cause localized current density variations, resulting in non-uniform machining [11].

### *Formation of metal oxides and hydroxides (passive layer growth)*

Dissolved metal ions react with oxygen or hydroxyl ions, forming oxide/hydroxide layers as presented in Equations (3) and (4) for iron-based alloys [12].



The  $Fe(OH)_3$  further dehydrates to form  $Fe_2O_3$  or  $Fe_3O_4$ , contributing to a stable oxide film that resists further dissolution.

Similarly, as presented in Equations (5) and (6),  $Ti^{4+}$  in titanium alloys reacts with water to form a stable  $TiO_2$  layer, releasing  $H^+$  ions, which indicates oxide film formation and local acidification.  $Ni^{2+}$  in nickel alloys reacts with hydroxide ions to form  $Ni(OH)_2$ , indicating the formation of a hydroxide layer.



These oxide films hinder ECM efficiency. The mechanism of oxide layer formation during electrochemical dissolution of a metal workpiece is illustrated in Figure 3.

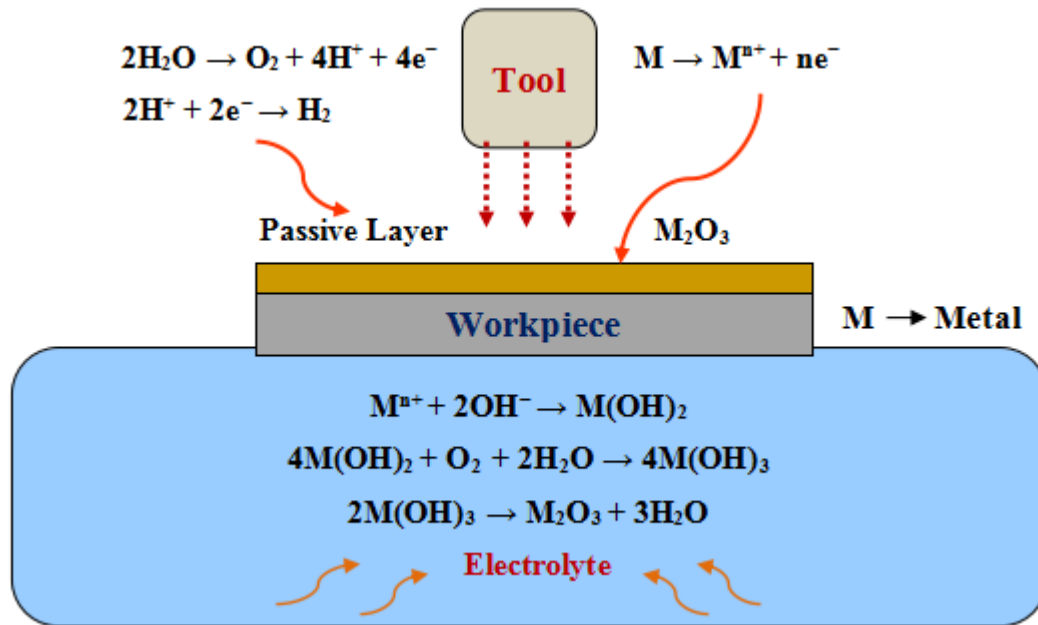


Figure 3. Oxide layer formation mechanism

#### Influence of workpiece material composition on passive layer formation

The composition of the workpiece material has a major influence on the properties and stability of the passive oxide layer. Various materials exhibit different levels of passivation due to variations in their electrochemical reactivity, oxide layer structure, and oxygen affinity, as well as the physical properties of the oxide films deposited on different metals [13]. For example, stainless steels, which are primarily iron-chromium alloys, exhibit high passivation through the formation of a stable chromium oxide ( $Cr_2O_3$ ) coating, which is highly resistant to dissolution [14]. Additional alloying elements, such as molybdenum and nickel, further enhance corrosion resistance and passive layer stability, presenting additional challenges in ECM [15]. Titanium and its alloys form a highly stable titanium dioxide ( $TiO_2$ ) layer, which is insulating and strongly adherent, significantly impeding anodic dissolution [16]. Likewise, nickel-based superalloys such as Inconel and Hastelloy form dense nickel oxide ( $NiO$ ) and nickel hydroxide ( $Ni(OH)_2$ ) layers that are difficult to remove because of strong metal-oxide bonding [17]. These alloys tend to require a suitable electrolytic environment with complexing agents, such as EDTA or citric acid, to facilitate oxide breakdown [18]. Aluminium alloys form a chemically resistant aluminium oxide ( $Al_2O_3$ ) film, requiring fluoride-containing electrolytes for successful oxide dissolution [19]. However, materials like copper and low-carbon steels do not exhibit much passivation. Copper does not form a stable oxide film under normal ECM conditions, whereas low-carbon steels form a porous iron oxide layer that does not significantly impede the machining process [20,21].

### *Effect of electrolyte properties on passive film formation*

The electrolyte plays a crucial role in ECM by affecting both passive oxide layer growth and material removal efficiency [22]. Its composition determines ion transport, reaction kinetics, and passive film behaviour during anodic dissolution. Electrolyte pH is a key factor: acidic solutions ( $\text{pH} < 7$ ), such as HCl,  $\text{H}_2\text{SO}_4$ , and  $\text{HNO}_3$ , promote oxide breakdown via high  $\text{H}^+$  concentrations, enhancing reactivity and dissolution [23]. However, strong acids may cause uncontrolled corrosion, limiting their use in precision applications. Neutral electrolytes ( $\text{pH} \approx 7$ ) such as  $\text{NaNO}_3$  and NaCl offer controlled dissolution with minimal side reactions, making them ideal for maintaining surface integrity [24]. Alkaline electrolytes ( $\text{pH} > 7$ ), including NaOH and KOH, promote the formation of stable oxides/ hydroxides, such as  $\text{Al}(\text{OH})_3$  and  $\text{Fe}_2\text{O}_3$ , which reduces removal efficiency and surface quality [25].

The conductivity of the electrolyte influences ionic mobility and current distribution [26]. High-conductivity electrolytes, such as NaCl,  $\text{NaNO}_3$ , and  $\text{H}_2\text{SO}_4$ , enable uniform charge transfer and efficient oxide disruption [27]. Low-conductivity solutions, such as distilled water, cause non-uniform current flow, passive layer buildup, and poor finishes [28].

Electrolyte flow rate is equally critical. High flow rates enhance mass transport and clear by-products from the interelectrode gap [29], reducing passive film formation and improving machining consistency. Low flow rates cause by-product accumulation, promoting passivation, uneven removal, and reduced accuracy [30].

Temperature also impacts ECM. Elevated temperatures increase oxide solubility and dissolution rates, benefiting passivation-prone metals [31]. However, excessive heat may degrade tooling, decompose the electrolyte, or trigger side reactions, compromising surface quality. Low temperatures hinder ion mobility and conductivity, reducing efficiency and raising energy consumption [32]. An optimal temperature range of 30 to 60 °C is crucial for maintaining a balance between dissolution, passive film disruption, and system stability.

In summary, achieving high-performance ECM requires careful control of electrolyte pH, conductivity, flow rate, and temperature to minimize passive layer formation and maximize material removal efficiency.

### *Role of process parameters on oxide layer development*

In ECM, the formation and disruption of the passive oxide film are controlled by key machining parameters, including voltage, current density, interelectrode gap, flow rate, tool feed, machining time, and pulse characteristics. Applied voltage directly impacts the electric field between the tool and workpiece, thereby influencing anodic dissolution [33,34]. Low voltages fail to break passive films on metals like titanium, while excessive voltages enhance oxidation, stabilizing these films and reducing surface finish quality [35]. Thus, maintaining optimal voltage is essential for uniform oxide breakdown.

Current density influences MRR; moderate levels enhance it, while extremes cause localized heating or poor dissolution [36]. The inter-electrode gap affects both the electric field and debris flushing. Tight gaps improve dissolution but hinder flushing, promoting oxide accumulation; wider gaps lower field strength but improve debris removal [37]. Tool feed rate affects fresh surface exposure; inappropriate rates either overload the gap with by-products or limit dissolution time [38]. Electrolyte concentration also governs conductivity; higher concentrations improve MRR but may trigger side reactions or erosion [39].

Pulse parameters in pulsed ECM further influence performance. Short, controlled pulses help disrupt oxide layers and renew the electrolyte, whereas continuous DC can risk electrolyte degradation and permanent passivation [40].

Oxide formation naturally occurs during anodic reactions, creating a barrier that inhibits further dissolution [41]. Without regular disruption, this layer restricts electrolyte contact, reduces MRR, and destabilizes the process, especially under high voltage conditions, as illustrated in the graph shown in Figure 4. This can cause unstable machining conditions and variable removal rates, particularly at higher voltages where the oxide layer tends to grow more rapidly [42,43].

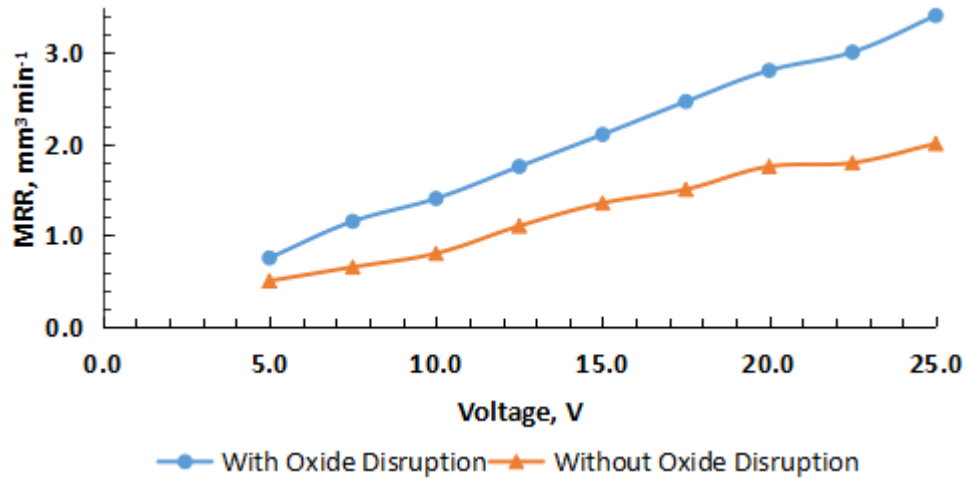


Figure 4. MRR in ECM with and without oxide disruption

In ECM, the lack of oxide disruption leads to the buildup of passive films, causing non-uniform material removal and surface defects such as pitting and increased roughness [44]. Thicker oxide areas resist dissolution, while thinner regions dissolve faster. Under steady DC conditions, uncontrolled oxide growth degrades surface finish. Conversely, disruption techniques such as pulsed current, ultrasonic agitation or tool vibration enable consistent passive layer breakdown, exposing fresh metal uniformly [45]. This results in smoother surfaces and stable dissolution fronts, minimizing over-etching and maintaining integrity [46]. Research shows that with oxide disruption; the surface roughness decreases consistently as voltage increases. Figure 5 illustrates this, comparing surface quality at different voltages with and without disruption, underscoring the importance of oxide control in optimizing ECM performance [47,48].

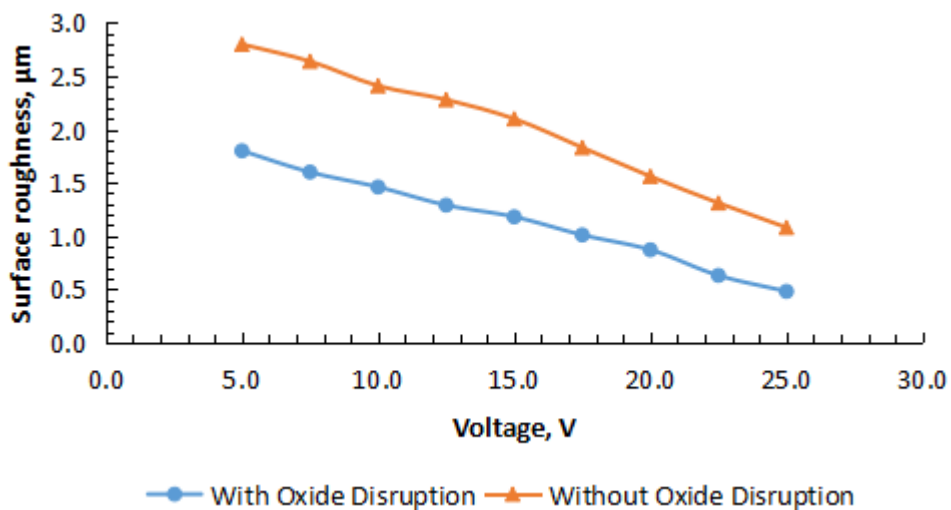


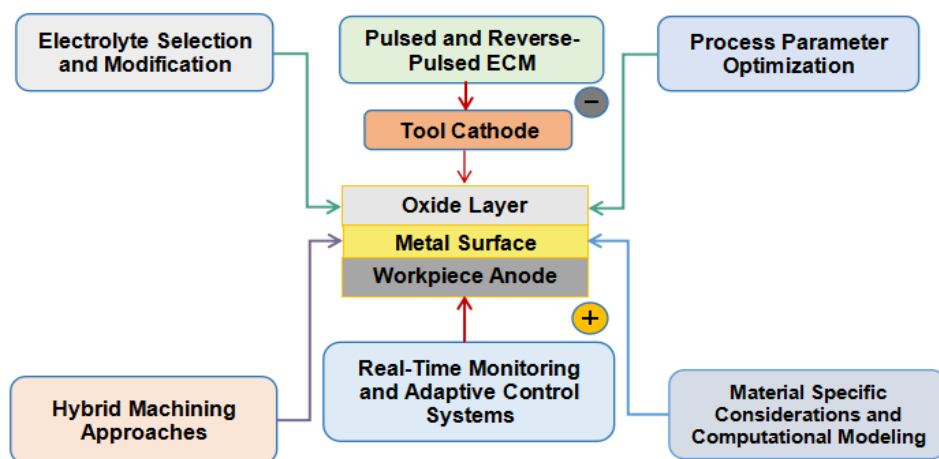
Figure 5. Surface roughness in ECM with and without oxide disruption

Given the persistent challenges of passive oxide layer formation in ECM, this review presents a focused and comparative analysis of control strategies specifically designed to address this issue.

Unlike broader reviews, it focuses on the mechanisms, impacts, and suppression methods of passive film formation across various materials and machining conditions. Five core strategies are examined: electrolyte modification, pulsed/reverse-pulsed ECM, hybrid techniques, process parameter optimization, and real-time adaptive control systems, including AI-based methods. Each is discussed from a material-specific standpoint with quantitative metrics such as MRR, surface roughness, and oxide thickness. Reported improvements include MRR increases up to 45 %, surface roughness reductions by 30 to 60 %, and oxide thickness decreases by several micrometres under optimized conditions [49,50]. The review also highlights the role of advanced computational tools and real-time monitoring technologies in enhancing accuracy and process reliability. This synthesis bridges experimental, simulation, and application-based research, offering a comprehensive reference for improving ECM's industrial viability.

#### Literature review on control strategies for passive oxide layer disruption

The literature provides insights into controlling passive oxide layers in ECM by understanding material electrochemistry and electrolyte chemistry. Although beneficial in its natural state, the oxide layer hinders anodic dissolution in ECM. Various strategies have been explored to weaken or eliminate it for uniform material removal [51]. A schematic illustrating the effects of these strategies on oxide formation is shown in Figure 6.



**Figure 6.** Control strategies impacting the passive oxide layer disruption

#### Electrolyte selection and modification

Electrolyte selection plays a pivotal role in ECM performance, impacting dissolution efficiency, surface finish, and compatibility with workpiece materials. Common choices include sodium chloride (NaCl) and sodium nitrate (NaNO<sub>3</sub>), favoured for their conductivity and ability to interact with passive oxide films [52,53]. NaCl, rich in Cl<sup>-</sup> ions, effectively disrupts oxide layers like Cr<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>, making it suitable for stainless steel and titanium alloys by forming soluble metal-chloride complexes [54,55]. NaNO<sub>3</sub>, being less aggressive, offers electrochemical stability and is better suited for moderately passivating materials, though it may require enhancement for more resistant substrates. Additives such as chelating agents or oxidizers are often introduced to improve passive film breakdown [56]. Moreover, inhibitors help to control electrochemical conditions and prevent unwanted side reactions, contributing to stable operation. Thus, tailoring electrolyte composition, including additives and inhibitors, is essential to balance aggressiveness, conductivity, and process control for optimal ECM results. This strategy is presented with a material-specific perspective, highlighting how different electrolytes interact with varying levels of material passivation. For

instance, NaCl proves highly effective for stainless steel and titanium alloys, while a mixed ethylene glycol NaCl electrolyte enhances surface integrity in Cu-based shape memory alloys. The performance is substantiated through quantitative measures such as MRR ( $0.323 \text{ mg min}^{-1}$ ), surface roughness ( $0.384 \mu\text{m}$ ), and reduction in oxide thickness, which contributes to more stable and uniform anodic dissolution [57]. Studies have shown that optimized electrolytes can reduce oxide film thickness by several micrometres, improving machining consistency and dimensional accuracy [58]. Chelating agents such as ethylenediaminetetraacetic acid (EDTA), citric acid, and oxalic acid are widely used in ECM to form stable metal-ion complexes, facilitating oxide layer dissolution and improving surface finish and machining uniformity [59]. Surfactants enhance electrolyte wetting and lower surface tension, aiding in debris and oxide removal from the machining gap [60,61], which stabilizes current density and reduces localized heating. De-passivating ions like fluoride or chloride actively dissolve passive films, particularly on  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$  surfaces, by forming soluble complexes [62]. Inhibitors are added to prevent localized corrosion and unwanted side reactions, maintaining electrolyte stability. Optimized additive combinations enhance material removal, precision, and surface quality. Maintaining stable pH is equally crucial, as anodic reactions and gas evolution cause local pH fluctuations [63,64]. Buffer systems such as phosphate, borate, or citrate regulate pH within the optimal range (6 to 8) [65], with phosphate buffers being especially effective. pH control is critical in micro-ECM and with highly passivating materials [66].

#### *Pulsed and reverse-pulsed ECM*

Pulsed and reverse-pulsed ECM are advanced methods developed to mitigate passive oxide film formation, which obstructs material removal during machining [67]. Continuous DC ECM promotes stable oxide growth, reducing efficiency and accuracy. Pulsed ECM improves performance by introducing on-time and off-time intervals, allowing electrolyte replenishment, heat dissipation, and oxide dissolution through localized effects [68]. This enhances anodic dissolution and ion transport in the machining gap. Reverse-pulsed ECM further improves results by momentarily reversing polarity, creating cathodic conditions that destabilize oxide layers like  $\text{Cr}_2\text{O}_3$  and  $\text{TiO}_2$  on stainless steel and titanium, respectively [69,70]. These techniques improve surface finish, MRR, and dimensional accuracy, especially in passivating or hard-to-machine materials [71].

Pulse duration and frequency are critical. Short pulses deliver intense current bursts that disrupt oxide films before they stabilize, enhancing MRR and avoiding persistent passivation seen in DC ECM [72,73]. In contrast, long pulses or insufficient off-time can lead to electrolyte depletion and oxide reformation, reducing performance [74]. Although low-frequency pulsing may increase MRR, it can also trigger passivation if not properly managed [75]. Therefore, optimizing pulse parameters is essential for achieving efficient and consistent ECM results across different materials. This strategy is evaluated from a material-specific perspective, particularly for difficult-to-machine and highly passivating materials, such as Inconel 625 and titanium alloys [76]. Quantitative improvements in process performance have been validated through measurable parameters, including an increase in MRR (up to  $3.1587 \text{ mg min}^{-1}$ ), a reduction in radial overcut ( $71.96 \mu\text{m}$ ), and an enhancement in surface finish. Although direct data on oxide thickness reduction is limited, the improved dissolution behaviour under optimized pulse conditions strongly indicates effective passive layer disruption. These results confirm the suitability of pulse control for precise and efficient ECM across a wide range of materials [77].

### *Process parameter optimization*

Optimizing ECM parameters is essential for minimizing passive layer formation, enhancing MRR, and achieving high precision machining of complex, hard-to-machine materials. Applied voltage significantly influences electrochemical reaction rates; appropriate control prevents thermal instability and abnormal oxide growth, while fluctuations affect dimensional accuracy and surface finish [78]. The interelectrode gap plays a crucial role in electric field distribution and electrolyte flow. A balanced gap avoids arcing or voltage loss, maintaining uniform current and minimizing oxide buildup [79]. The electrolyte flow rate governs the removal of metal ions and by-products; a higher flow rate reduces passivation and maintains chemical stability [80]. Electrolyte concentration affects conductivity and dissolution kinetics, where optimal levels promote efficient ion transport without causing passivation or erosion. These parameter optimizations have demonstrated improved machining outcomes, higher MRR, better surface finish, and oxide disruption in materials like Inconel 625 and Nimonic-263. Electrolyte concentration and pulse frequency significantly affect surface roughness and roundness error, achieving minimum roughness and roundness error values. Findings of this study on micro-ECM of Inconel 625 underscore the vital role of optimized electrolyte conditions in enhancing surface quality during micro-machining of nickel-based superalloys [81]. The tool feed rate must be synchronized with the material removal rate. Too rapid feed rate will result in poor machining or tool-workpiece contact, while too low of a rate introduces passive layer build-up [82]. Simulation and experimental research on the micro ECM of Nimonic-263 superalloy showed that the process parameters, such as applied voltage, tool feed rate, and tool material, significantly affect MRR and surface roughness. The use of copper and SS304 electrodes with varying conductivity affected electrolyte characteristics and electric field distribution, validated through COMSOL simulations. These results show the significance of optimizing electrochemical conditions and tool-electrolyte interactions to improve surface integrity in precision machining [83].

### *Hybrid machining approaches*

Hybrid machining methods have developed as an effective means to overcome the limitations of conventional ECM, particularly in terms of passive layer disturbance. Ultrasonic-assisted ECM (UA-ECM) introduces high-frequency mechanical vibrations into the electrolyte, enhancing turbulence and disrupting passive film formation. Experiments have proved that ultrasonic assistance improves material removal rates, particularly in challenging-to-machine alloys [84]. Laser-aided ECM (LA-ECM) is another novel hybrid method which utilizes local heating to stress the passive oxide layer before electrochemical dissolution [85]. This method was found to be highly effective for machining ceramics and other non-metallic conductive materials that are prone to rapid passivation. Studies have shown that the use of ECM with mechanical micro-abrasion or brushing, which involves motion-controlled motion, still enhances passive layer disruption, leading to more consistent material removal [86]. These findings emphasize how hybridization can optimize ECM performance based on the specific characteristics of the workpiece material.

### *Real-time monitoring and adaptive control systems*

The complexity associated with the ECM process has necessitated the use of real-time monitoring systems to dynamically modify machining parameters and prevent passive layer effects. Electrochemical impedance spectroscopy (EIS) is the most widely utilized method for observing passive layer creation in real-time, with simultaneous corrective measures undertaken in real-time [87]. The use of AI and ML algorithms is also being investigated for predicting the response of the passive oxide layer and modifying the ECM settings to the optimal value. These advances have led to adaptive ECM

systems that automatically control electrolyte composition, pulse parameters, and machining conditions using real-time data [88]. Quantitative improvements in MRR, surface finish, and process stability have been reported where AI-driven adjustments dynamically respond to oxide layer formation. Real-time EIS feedback and sensor data help to regulate oxide thickness, ensuring consistent dissolution and enhanced machining precision. These advancements underline the potential of intelligent systems in tailoring ECM processes to specific material responses. On top of that, internet of things (IoT) enabled sensors to have also been integrated into ECM setups, transmitting process information to cloud-based systems for predictive maintenance and performance enhancement [89].

#### *Material-dependent factors and computational modelling*

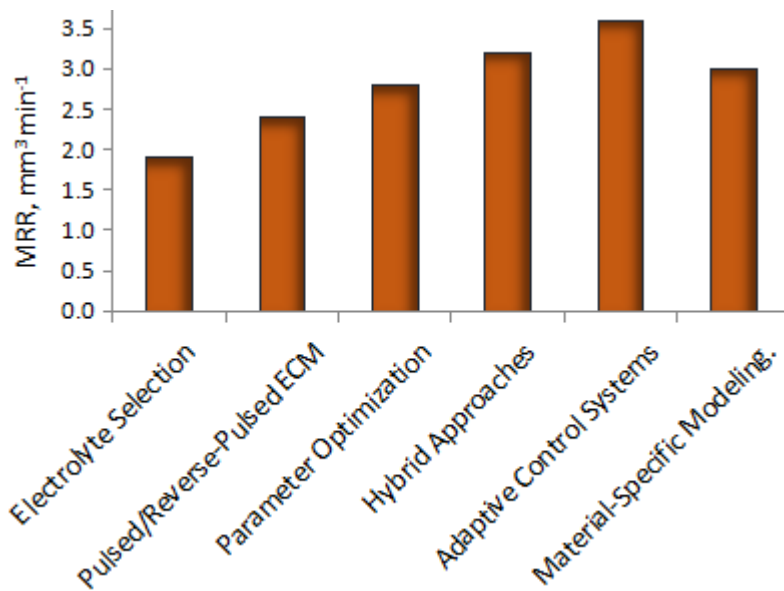
The relationship between the electrolyte chemistry and workpiece material properties is vital to ECM performance. Different materials passivate at varying rates, so it is essential to design specialised electrolytes to ensure maximum machining efficiency. For instance, stainless steels and titanium alloys, which are commonly used in aerospace and biomedical fields, have a high tendency to form a passive layer due to their affinity with oxygen [90]. In such cases, certain electrolytes containing complexing agents or active de-passivators need to be employed to ensure uniform material dissolution. Advancements in computational simulation and modelling have provided deeper insight into the behaviour and control mechanisms of passive oxide layers. Finite element analysis (FEA), computational fluid dynamics (CFD), and multi-physics simulations have been extensively used to predict passive layer growth, ion transport dynamics, and electrolyte flow patterns in ECM [91,92]. These predictive models enable researchers to design the optimal process parameters and electrolyte composition before conducting actual experimental trials, thereby saving considerable time and expense in process development. The literature highlights several control strategies for controlling passive oxide layer formation in ECM, each with specific strengths and limitations based on material type, machining conditions, and precision requirements. Electrolyte modification is a cost-effective method for chemically controlling oxide stability, but it may require the addition of additives or high flow rates to passivate materials. Pulsed and reverse-pulsed ECM dynamically disrupt oxide layers and enhance thermal regulation, improving MRR and surface finish, especially effective for titanium and nickel alloys, though requiring careful pulse parameter tuning. Hybrid methods like ultrasonic- or laser-assisted ECM enable mechanical or thermal oxide breakdown and are effective for high-strength materials, but involve higher cost and complexity, limiting them to specialized sectors. Optimizing parameters such as voltage, gap, and flow rate provides scalable efficiency gains but demands process stability and testing. Adaptive systems with real-time monitoring offer precise oxide control via AI or sensors but are expensive. Combining these strategies can achieve superior ECM outcomes across applications.

#### Comparative analysis of control strategies

##### *Comparison of MRR across control strategies in ECM*

The comparative bar graph shown in Figure 7 demonstrates the MRR attained through various advanced control approaches in ECM [93-96]. Such approaches have been investigated extensively in earlier research to optimize machining performance, especially MRR, which continues to be an important measure of process efficiency.

Electrolyte composition significantly affects MRR in ECM by enhancing ion transport through optimized conductivity, viscosity, and chemical stability. Pulsed and reverse-pulsed ECM prevents passive film formation, improving MRR and dimensional accuracy.



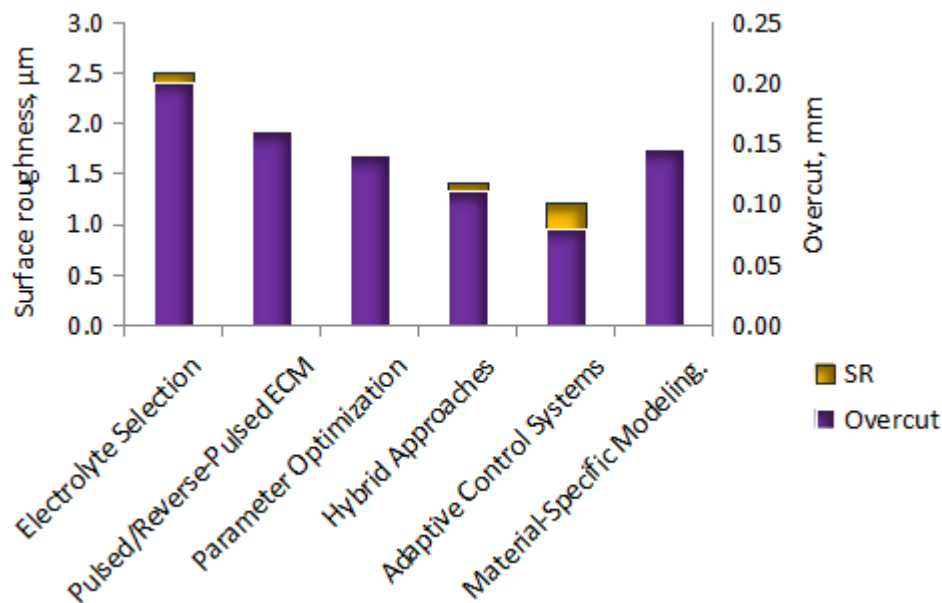
**Figure 7.** Comparison of MRR across control strategies in ECM

Optimized parameters, such as voltage, current density, interelectrode gap, and flow rate, further enhance dissolution while reducing stray corrosion. Hybrid ECM techniques, such as those utilising ultrasonic or laser assistance, enhance material removal.

Real-time monitoring with adaptive control dynamically adjusts parameters for consistent, high MRR. Material-specific strategies supported by computational modelling enable precision machining of complex alloys, prioritizing accuracy. These integrated approaches collectively aim to maximize ECM performance and machining efficiency.

#### Comparison of surface roughness and overcut across control strategies in ECM

The comparative bar graph illustrated in Figure 8 depicts the effect of different control strategies applied in ECM on two prime quality parameters: surface roughness and overcut [97-100].



**Figure 8.** Comparison of surface finish and overcut across control strategies in ECM

Both parameters directly control the dimensional accuracy and surface integrity of machined parts and have been extensively explored to maximize ECM performance.

Electrolyte selection affects surface finish by improving ion dissolution and flushing, moderately enhancing quality and slightly reducing overcut. Pulsed and reverse-pulsed ECM significantly lowers surface roughness and overcut by minimizing heat and passive layer formation. Optimizing parameters like interelectrode gap, current density, and flow rate stabilizes the electrochemical zone and improves uniformity. Hybrid strategies, such as ultrasonic-assisted ECM, enhance circulation and material removal for better finishes. Real-time monitoring and adaptive control dynamically optimize conditions, achieving minimal overcut. Material-specific strategies with computational modelling further improve precision, emphasizing advanced control methods for high-accuracy ECM performance.

*Effectiveness of various approaches for different materials*

The effectiveness of control strategies in ECM depends on the electrochemical and physical properties of workpiece materials. As shown in Table 1, material-specific characteristics significantly influence strategy selection and performance [101-103].

**Table 1.** Comparison of ECM control strategies based on workpiece material characteristics

| Control strategy                                      | Stainless steel                           | Titanium alloys                               | Nickel-based superalloys                | Aluminium/ /Magnesium           | Copper/ /low-carbon steel                               |
|---|---|---|---|---------------------------------|---|
| Electrolyte selection & modification                  | High (with Cl <sup>-</sup> additives)     | Moderate (requires aggressive electrolytes)   | Moderate (needs chelating agents)       | High (fluoride-based effective) | Sufficient (standard NaCl/NaNO <sub>3</sub> works well) |
| Pulsed & reverse-pulsed ECM                           | Very effective in reducing oxide regrowth | Effective, but oxide breakdown is challenging | Moderate                                | Highly effective                | Not essential, but improves surface finish              |
| Process parameter optimization                        | Improves efficiency & MRR                 | Limited by passive film resilience            | Requires tight control                  | Very effective                  | Highly effective  |
| Hybrid machining (ECM ultrasonics/ /laser/mechanical) | Effective for intricate features          | Highly effective                              | Highly effective                        | Moderate                        | Rarely needed   |
| Real-time monitoring & adaptive control               | Excellent for precision machining         | Crucial due to variable oxide stability       | Essential for consistency               | Useful for micro-ECM            | Optional  |
| Material specific considerations                      | Requires de-passivation agents            | Demands aggressive conditions                 | Needs complexing electrolytes           | Fluoride essential              | Minimal concern   |
| Computational modelling                               | Predicts oxide dynamics well              | Helps optimize electrolytes                   | Useful in electrolyte-agent interaction | Beneficial for film evolution   | Simple modelling sufficient                             |

Stainless steel and aluminium/magnesium alloys rapidly form passive films, requiring chloride or fluoride-based electrolytes to destabilize oxides and maintain conductivity. Titanium and nickel-based superalloys form highly stable oxides, which require aggressive electrolytes, such as chelating agents or advanced methods like pulsed/reverse-pulsed ECM, to periodically disrupt passive layers and improve removal without thermal damage. Hybrid machining methods enhance oxide disruption via localized energy or mechanical stirring, benefiting hard-to-machine, chemically stable alloys with low dissolution rates. Real-time and adaptive control systems address process instabilities in reactive alloys by dynamically adjusting parameters to maintain optimal conditions. Computational modelling aids in predicting oxide behaviour, electrolyte interaction, and material

response, supporting efficient control algorithm development and virtual optimization for complex, passivation-sensitive alloys. Thus, ECM control strategies remain highly material dependent.

### *Cost-benefit analysis of implementing control measures*

Control strategies in ECM must be evaluated for both technical effectiveness and economic viability. Table 2 outlines cost-benefit trade-offs involving investment, operational expenses, and efficiency gains [104-106]. Electrolyte selection/modification involves low-to-medium initial costs and moderate operating expenses, offering cost-effective performance in most applications. Pulsed and reverse-pulsed ECM techniques incur moderate equipment/control costs but provide high precision and oxide breakdown efficiency, justifying use in aerospace and medical sectors. Process parameter optimization, like voltage, temperature, and electrolyte flow, offers high ROI due to low cost and simplicity, with moderate performance gains, making it ideal for standard setups. Hybrid techniques (*e.g.* ECM with ultrasonic/laser assistance) yield high efficiency for hard-to-machine or valuable materials but are reserved for niche, high-cost applications. Real-time monitoring and adaptive systems demand high initial investment yet enhance precision and consistency in automated or high-precision environments. Computational modelling, despite moderate setup costs, provides long-term R&D benefits by enabling process design and minimizing experimental iterations.

**Table 2.** Cost justifications and efficiency gains of advanced control measures in electrochemical machining

| Control strategy                                      | Initial investment | Operational cost      | Efficiency gain                | Cost justification                                       |
|---|--------------------|-----------------------|--------------------------------|--|
| Electrolyte selection & modification                  | Low to medium      | Medium                | Moderate to high               | Cost-effective for most applications                     |
| Pulsed & reverse-pulsed ECM                           | Medium             | Medium                | High                           | Justified in aerospace, medical sectors                  |
| Process parameter optimization                        | Low                | Low                   | Moderate                       | High ROI due to simplicity                               |
| Hybrid machining (ECM ultrasonics/ /laser/mechanical) | Low                | High                  | Very high                      | Justified only in high-value or complex materials        |
| Real-time monitoring & adaptive control               | High               | Medium to high        | High                           | Best suited for high precision or automated environments |
| Computational modelling                               | Medium             | Low (simulation cost) | Indirect (design optimization) | Long-term benefit, especially in R&D setups              |

### *Industry-specific adoption and practical feasibility*

The effectiveness of ECM control strategies differs by industry due to variations in materials, precision, production volume, and cost constraints. Table 3 summarizes industry-specific priorities [107,108]. Aerospace requires high accuracy for heat-resistant alloys, employing pulsed ECM, hybrid techniques, adaptive control, and simulation to achieve dimensional precision and manage oxide layers. Automotive sectors focus on cost effectiveness, preferring optimized electrolytes and tenable parameters for efficient, economical machining. Biomedical fields need precise, contamination-free machining; hence, pulsed ECM, reactive electrolytes, and real-time monitoring are favoured for implants and tools. Defence applications adopt hybrid ECM and AI-driven optimization to meet diverse machining demands with moderate-to-high feasibility. The tool and die industries typically use basic ECM setups with minimal control strategies, due to the simpler shapes and cost considerations. For electronics and MEMS, micro-ECM with tight control and modelling ensures the production of intricate, miniaturized components, supporting both precision and high repeatability.

**Table 3.** Industry-wise preferred control strategies and feasibility

| Industry                 | Preferred control strategies  | Feasibility  |
|--------------------------|---|--|
| Aerospace                | Pulsed ECM, hybrid machining, adaptive control, computational modelling | High (due to need for precision and hard-to-machine materials) |
| Automotive               | Electrolyte selection, parameter optimization                           | High (focus on cost-efficiency and throughput)                 |
| Biomedical               | Pulsed ECM, real-time monitoring, aggressive electrolytes               | High (tight tolerances, biocompatible materials)               |
| Defence                  | Hybrid ECM, real-time systems, AI based optimization                    | Moderate to high (for advanced materials)                      |
| Tool & die manufacturing | Standard ECM with optimized parameters and electrolyte choice           | High (low complexity, cost-sensitive applications)             |
| Electronics/MEMS         | Micro ECM with precise parameter control and computational modelling    | High (for feature miniaturization and repeatability)           |

The comparative analysis shows that while electrolyte modification, pulse control, hybridization, optimization, and monitoring offer distinct benefits, their effectiveness depends on materials and conditions [109,110]. No single method suffices; instead, tailored combinations enable optimal ECM performance and guide future research, as detailed in the concluding section.

### Research progresses on control strategies for disrupting passive oxide layer formation

ECM has made significant advancements over the past few years, with the need to machine hard-to-cut and intricate materials more accurately and efficiently. Among the major problems in ECM, one of the long-standing issues is the formation of passive oxide films on workpiece surfaces, which restricts anodic dissolution and reduces machining performance. Current research has focused on developing new methods and technologies to defeat this challenge and improve ECM efficiency.

#### *Novel electrolyte compositions for enhanced ECM performance*

Advancements in ECM focus on developing novel electrolytes to enhance efficiency and surface finish, particularly for high-passivation materials. Standard electrolytes, such as  $\text{NaNO}_3$  and  $\text{NaCl}$ , offer conductivity but struggle to dissolve stable oxide layers [111]. Reducing agents are added to break down or prevent passive film formation, enabling continuous anodic dissolution [112]. Some of the most used are gold nanoparticles (AuNPs), which are particularly useful in improving the electrochemical machining characteristics of 20MnCr5 steel alloy [113]. Copper ions ( $\text{Cu}^{2+}$  ions) facilitate the low-valence dissolution of metal atoms in iron-based alloys and prevent the accumulation of dissolution by-products, such as metal hydroxides and gas bubbles, near the tool cathode [114]. Besides these reducing agents, chelating agents such as EDTA, citric acid, and oxalic acid have been proven useful [115,116]. They become bound to the metal ions through the development of soluble complexes that compromise the integrity of passive layers; therefore, they are especially suitable for difficult materials such as nickel-based superalloys and copper alloys, where passivation greatly hinders ECM efficiency. Oxidizing agents such as potassium dichromate ( $\text{K}_2\text{Cr}_2\text{O}_7$ ) and hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) are also utilized in ECM environments where the degradation rate of oxides needs to be achieved quickly. These agents enhance the dissolution of metal oxides by adding more oxidative capacity, increasing the rate of reaction and supporting a more vigorous attack on the passive film [117,118].

#### *Computational modelling and simulation of oxide layer behaviour*

Computational modelling and simulation are essential for understanding oxide layer formation and growth during ECM, especially for passivating materials. Traditional trial-and-error approaches

are costly and time-consuming, prompting the use of numerical methods, such as finite element analysis (FEA), computational fluid dynamics (CFD), and multiphysics tools like ANSYS Fluent and COMSOL Multiphysics [119-121]. These tools simulate key phenomena, including ion transport, electric field distribution, current density, temperature gradients, and passive film behaviour. For instance, models help visualize oxide layer development and dissolution based on pulse regimes, electrolyte flow, and electrode geometries. This virtual analysis enables researchers to anticipate material response, fine-tune process parameters, and optimize ECM systems tailored to specific materials and geometries. Moreover, simulations significantly reduce the need for full-scale experimentation, saving time and cost while improving process reliability. Overall, computational modelling makes ECM more predictive, controllable, and adaptable, particularly for high-precision, performance-critical applications.

#### *Machine learning and AI-based optimization for ECM control*

Machine learning (ML) and artificial intelligence (AI) are transforming ECM by enabling real-time, data-driven process control. ECM involves complex, nonlinear interactions among parameters like voltage, current density, electrolyte chemistry, temperature, and flow rate, all affecting MRR, surface finish, and oxide behaviour. ML algorithms, neural networks, genetic algorithms, and reinforcement learning analyse extensive data to uncover patterns beyond traditional methods [122]. These models predict outcomes and support dynamic parameter control. AI-driven ECM systems self-optimize to reduce passive oxide growth or enhance surface quality. Multi-objective optimization enables simultaneous improvement in MRR, tool wear, energy efficiency, and dimensional accuracy. This intelligent control minimizes trial-and-error testing, shortens development time, cuts costs, and improves flexibility, especially useful when machining challenging or novel materials [123].

#### *Experimental studies on new materials and coatings*

With the rising demand for lightweight, high-strength, and corrosion-resistant materials in the aerospace, biomedical, and defence sectors, ECM research is increasingly focusing on advanced materials and coatings. Alloys like titanium aluminides, cobalt-chromium, and ceramic matrix composites exhibit strong passivation, forming stable oxide layers that hinder ECM [124]. To address this, researchers explore surface modifications that improve electrochemical machinability. Conductive polymer films and catalytic surface layers alter electrochemical responses; reduce oxide formation, and lower interfacial resistance. Additionally, nanostructured and thin conductive coatings enhance electrical conductivity and ensure uniform current distribution, enabling more controlled material removal [125]. These innovations enhance the understanding of material electrolyte interactions and facilitate the precise engineering of complex geometries, thereby advancing their application in next-generation high-performance materials.

## **Conclusion**

Passive oxide layer formation remains a major challenge in ECM, significantly reducing efficiency, accuracy, and material removal rates, especially in hard-to-machine, corrosion-resistant materials. This review synthesized passive film formation mechanisms and analysed control strategies including electrolyte modification, pulse current application, hybrid ECM, process optimization, and real-time monitoring. A key finding is the material and condition-dependent nature of oxide disruption. Pulsed/reverse-pulsed ECM improves surface finish and limits oxide buildup but is sensitive to pulse parameters and material properties. Electrolyte modifications with de-passivating or complexing agents enhance dissolution but raise environmental concerns due to the formation of toxic

byproducts. Hybrid methods (ultrasonic, mechanical, thermal) improve oxide stripping and machining stability but face complexity, energy, and cost barriers. Real-time adaptive control with AI and sensors offers precision but is underused due to integration challenges.

Research gaps persist: ECM still relies on trial-and-error and oversimplified models, failing to capture the dynamics of passive films. Environmental sustainability is a concern, as aggressive electrolytes like sodium nitrate or chlorate produce hazardous waste. The lack of integrated, smart ECM platforms limits adaptability and industrial scalability.

Future research should focus on sustainable electrolytes, ionic liquids, deep eutectic solvents, and biodegradable organics with full electrochemical and lifecycle evaluations. Advancing real-time monitoring (electrochemical impedance spectroscopy, acoustic emission) combined with machine learning can enable dynamic passivation control, but requires better sensor integration and noise-resistant algorithms. Multi-physics simulations that integrate electrochemical kinetics, heat transfer, fluid flow, and oxide growth will enhance predictive ECM design. Phase-field modelling and AI-augmented simulations, paired with experimental validation, will enhance understanding of oxide evolution. Hybrid ECM combining ultrasonic, laser, or plasma assistance offers promise but demands thorough process and cost analyses.

Overall, disrupting passive oxide layers in ECM requires a multifaceted approach that combines sustainable practices, smart control, and advanced process design. Interdisciplinary collaboration across electrochemistry, materials science, engineering, and AI is essential to advance ECM's accuracy, versatility, and eco-friendliness for future manufacturing applications.

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