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REVIEW ARTICLE

Recent trends on electro chemical machining process of metallic materials: a review

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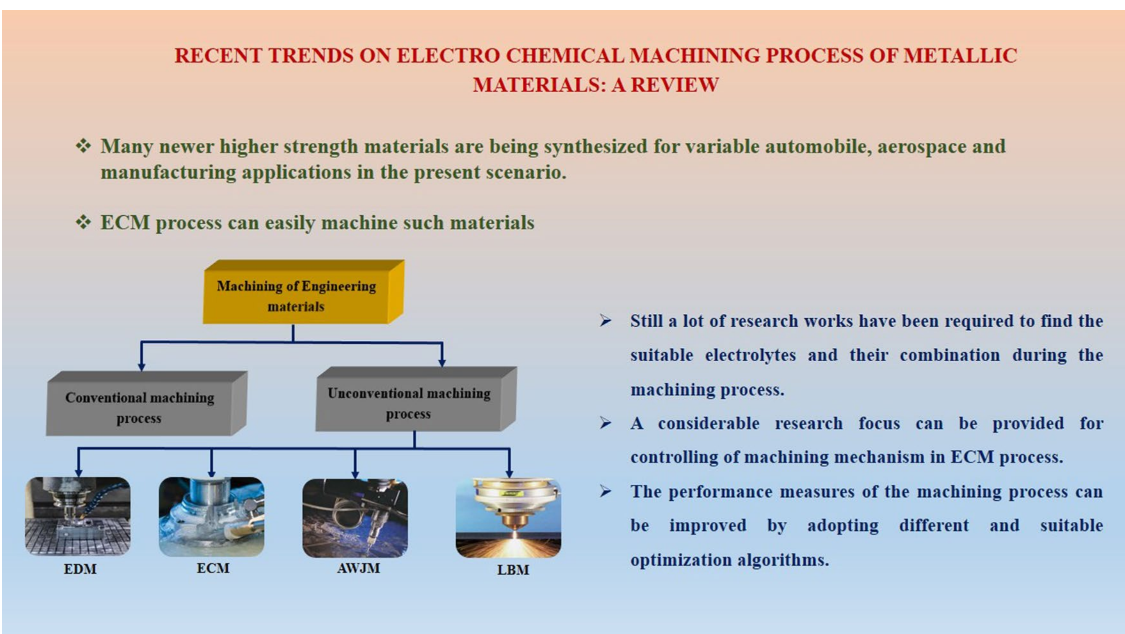
Abstract
Many newer higher strength materials are being synthesized for variable automobile, aerospace and manufacturing applications in the present scenario. Since it is very difficult to cut such materials using conventional machining process, it is important to utilize unconventional machining process. In the present study, a detailed survey has been made to analyze the influence of various process parameters, effects of electrodes, optimization and electrolytes on performance measures in Electro chemical machining process. The effects of pulse related parameters on electrode materials, coating materials and its thickness on material removal, overcut and surface topography were investigated under different perspectives such materials, electrolyte and machining parameters. From the detailed literatures, it has been inferred that still lot of research works have been required to find the suitable electrolytes and their combination during the machining process. It has also been found that the performance measures of the machining process can be improved by adopting different and suitable optimization algorithms.

Graphic abstract



Keywords Machining · ECM · Electrolyte · Surface · Optimization

Extended author information available on the last page of the article

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1 Introduction

In the present situation, many newer higher strength materials are being synthesized for variable automobile, aerospace and manufacturing applications [1]. With the development of more and more harder and difficult to cut materials, the use of conventional machining techniques such as lathe, drilling machine etc. to machine the workpiece becomes difficult and sometimes impossible. This has led to the introduction of unconventional machining process such as water jet, laser beam, ultrasonic and electrochemical machining. Since it is very difficult to machine such materials using conventional machining process, it is important to utilize unconventional machining processes such as electrical discharge machining (EDM), electrochemical machining (ECM), abrasive water jet machining (AWJM), laser beam machining (LBM) and ultrasonic machining (USM) process as shown in Fig. 1 [2].

ECM has a diversity of applications for industrial purpose and is a keyword in aerospace and automobile industries. However ECM process does not machine non-electrical conductive materials. ECM process is one of the most utilized machining techniques in the modern era. It is a non-traditional machining process (no direct contact between the workpiece and tool electrode) which makes use of the combination of electrical and chemical energies. Electrochemical machining refers to the anodic dissolution of the workpiece at the atomic level when an electric current is passed between two electrodes dipped in the presence of electrolyte. The main problem involved in EDM process is large machining time [3]. The tool wear is also major problem in such process. Since the machined profile is the exact replica of tool morphology, the tool wear should be reduced as much as possible. The white layer thickness (WLT) is also main problem in EDM process [4]. In ECM process, there is only negligible tool wear and WLT in ECM process owing to material removal mechanism by anodic dissolution. Hence the anodic workpiece specimen is only to be corroded in the machining process. AWJM produces higher taperness whereas LBM creates more thermal affected region [5]. While the abrasive particles is impacted with the specimen under higher pressure, the abrasive particles will deviate its path after hitting the specimen in AWJM process [6]. This may cause for more taperness in the AWJM process. Nevertheless, ECM process will not create taperness due to ability of mechanism [7]. However, the ECM process can create overcut, if the anodic dissolution is not uncontrolled one. It needs to be reduced in the machining process. In LBM process, the higher thermal energy is produced by photons due to the stimulated emission of radiation [8]. This can create more het effected zone in the specimen which may modify the physical characteristics of material [9]. The ECM process does not remove the material owing to the thermal energy. Hence such adverse effect may be reduced in ECM process. Therefore, ECM may be utilized for machining the higher hardness brittle material. The material removal in ECM process is happened using Faraday's laws. As per the Faraday's first law, the material removal is proportional to the amount of charge passed. Based on Faraday's second law, the dissolution of anodic particles is determined by current passed through it. Hence the ECM process is highly influenced by current density [5]. It is important to investigate the process for obtaining favorable machinability to control current density. This has made ECM as one of the most successful and commercially utilized machining techniques. The detailed advantages and disadvantages of ECM process is given as shown in Table 1 [6].

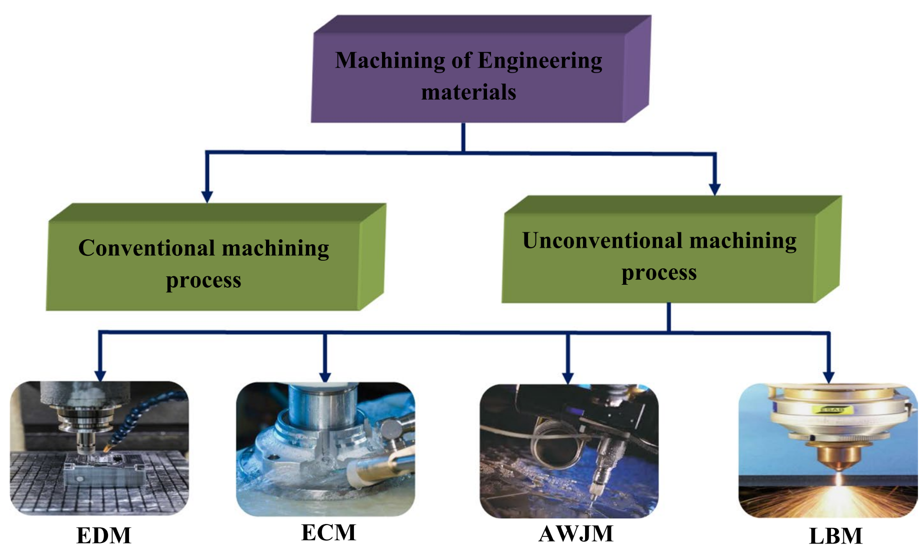


Fig. 1 Machining of engineering materials

Table 1 Advantages and disadvantages of ECMM process

Process	Advantages	Disadvantages
ECM	Can easily machine higher hardness materials	Higher machining cost
	No tool wear	Electrolyte may corrode the equipment
	No residual stress produced	Larger production floor
	No burrs from the machining	Only electrical conductive materials can be machined
	High surface quality	Not environment friendly process
	High accuracy of machining	

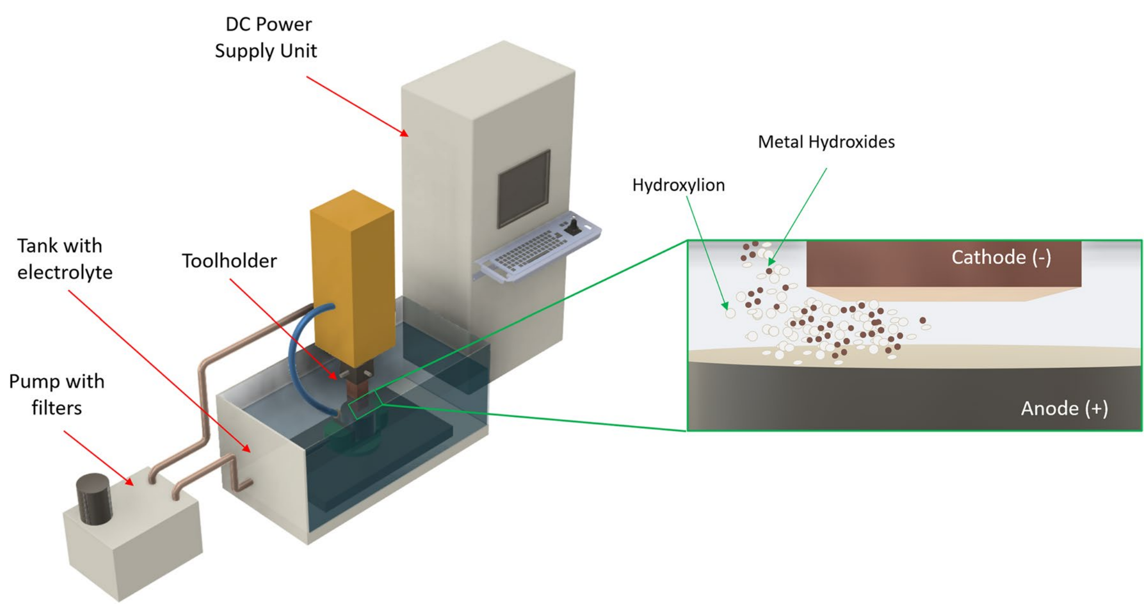


Fig. 2 Schematic representation of ECMM process

The schematic principle of electro chemical micro machining (ECMM) process is shown in Fig. 2. Since the ECMM process needs many improvements to reduce its demerits as listed in Table 1 in the all aspects of the method, a large number of researches are being carried out in the Electro chemical micro machining (ECMM) process. The classification of the research works is given as shown in Fig. 3. From the figure, it is learnt that coating the tool electrode and optimizing the input process parameters for achieving better performance measures such as material removal rate, surface roughness and overcut have significant roles in ECMM research.

2 State of art in ECM process

The way of surveying of ECM process in the present study is performed as shown in Fig. 4. Since the electrochemical micromachining process involves non-linear nature owing to the exponential relation of material removal with current density, it needs to be reduced to control the anodic dissolution on the machined specimens in ECM process. The essentials of ECM process mechanism and research works done from the foundation to the improvement of the ECMM process within the past decade [10].The researches in ECM process are related to get better process performance measures such as unit removal and machining dimensional accuracy. The new research trends were presented to enhance the performance characteristics such as design of micro tool and development, function of inter electrode gap, power supply, controlling of micro-spark creation in inter electrode gap (IEG) and electrolyte selection etc. [11]. It has been discussed regarding improving the machining accuracy, new material machining and complex shape generation in ECMM process.

The development of innovative tools for enhancing the surface quality of specimen is a major research area in ECM process. It was presented a review on generating

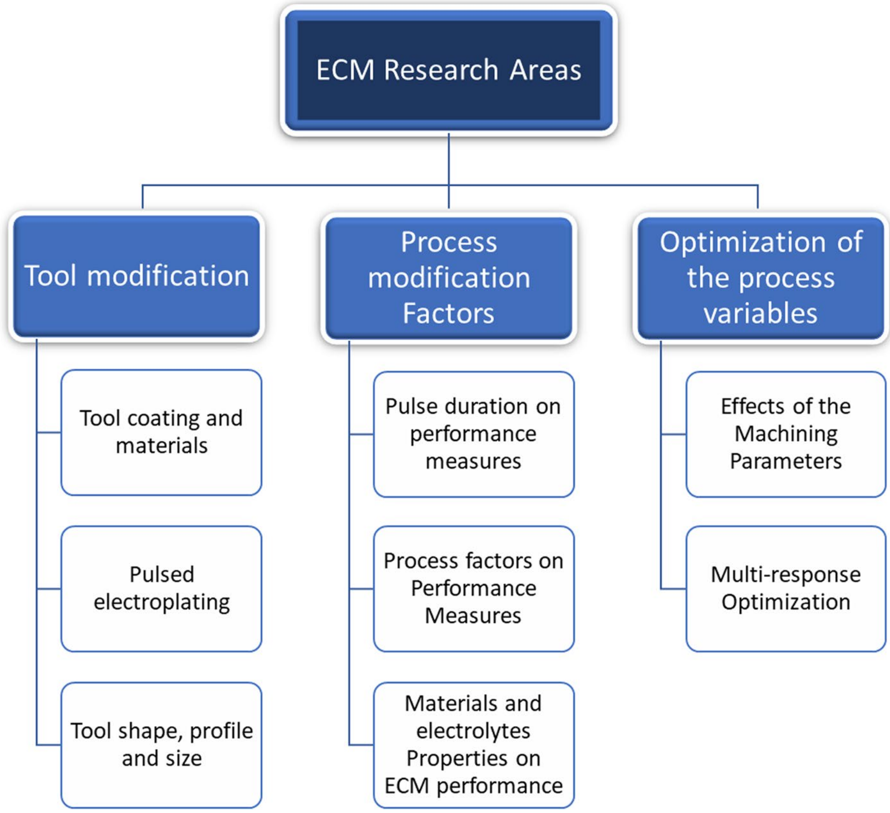


Fig. 3 Research areas involved in ECMM process

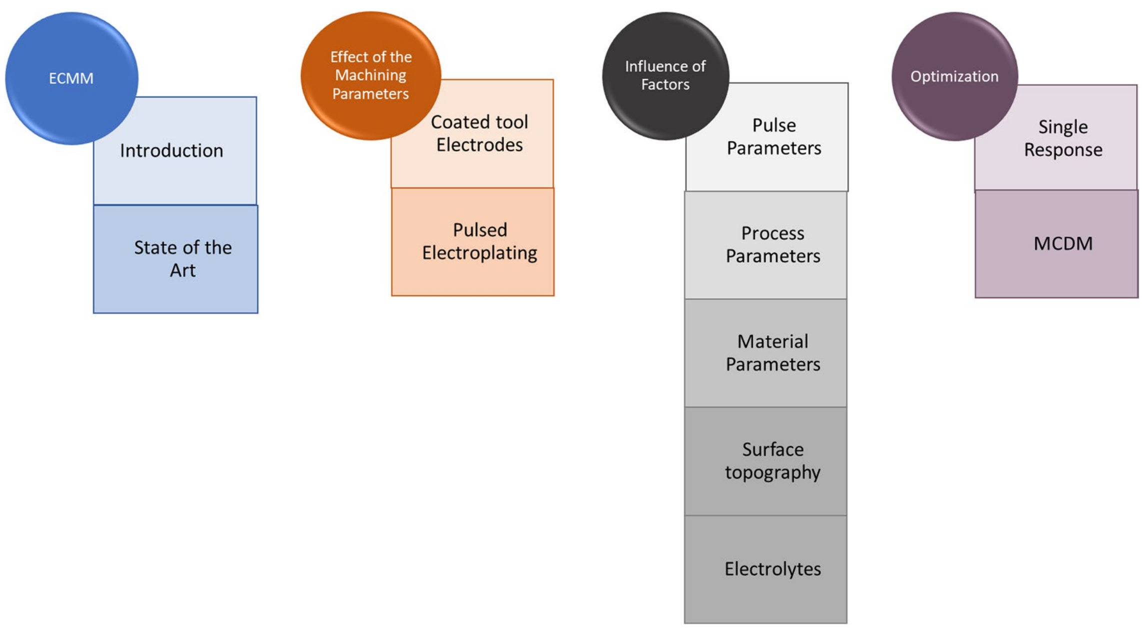


Fig. 4 Survey performed in the present study

the macro, micro and nano size complex shape components from difficult-to-cut materials in ECM process and future trends of its applications [12]. The study of the input process parameters on surface topography of the specimen had been taken by few researches. The recent developments and issues were discussed in ECM process to maintain narrow gap between tool electrode and workpiece during machining process to obtain accuracy. The smaller value of IEG is used to control the micro craters generations in the machining surface. It was stated that the overall machining efficiency has been mainly influenced by input process parameters [13]. The stress-free micro-hole has been produced with complex shapes for automobile and aerospace applications.

An endeavor has been made to develop an ECMM process for carrying out innovative research to control the ECMM process parameters to get better machining accuracy [14]. The developments of ECMM process are in the field of design of tool, pulse period for current, micro-size shaping, surface finishing, numerically controlled—ECM, ECM environmental concerns, hybrid process and industrial application for various industries. the electrochemical machining process for drilling of macro to micro holes with accurate surface and for the application of computer, electronic, micro-mechanics and aerospace industries. This paper represents the new developments and recent trends for machining micro-level quality hole in difficult-to-machine materials [15]. The improvement of accuracy was discussed by the reduction of sludge using passive electrolyte. The waste generation from machining surface has minimum machining allowance to increased localization effect for improving performance of ECMM process. The passive electrolyte like 20% of concentrated $NaNO_3$ has been used to achieve better machining characteristics such as higher unit removal and machining dimensional accuracy [16]. The study of pulse electrochemical micromachining process for stress, burr and crack free of micro components on machining surface was performed. The influence of process parameters such as applied voltage and feed rate on performance measures has been studied. The reduction of inter-electrode gap is used to increase localized anodic dissolution for improved accuracy in ECMM process [17].

The recent trends and study of micro electrical machining process like micro ECM, EDM, ECDM and hybrid machining has been investigated [18]. The fabrication of micro-level 3D complex structure is on various materials such as conductive and non-conductive materials. The improvement of productivity and machining accuracy from experimental analysis has been studied. The ECMM setup was developed for producing circular hole using different material and different shape as a cathode and different material of workpiece depending on the oxidation values. There is no-physical contact between two surfaces such as anode and cathode and the machining accuracy is based on the chemical reaction and electrical power supply in the machine zone [19].

It was analyzed the influence of process parameters such as current density, electrolyte concentration, pulse period and dissolution efficiency on performance measures. The pulse period of 1 to 10 ms and smaller level of inter-electrode gap (10–50 μm) has been maintained to achieve better machining accuracy. The empirical model has been developed for ECM machining characteristics and optimizes the process parameters based on output response [20].

3 Effect of tool modifications on ECMM performance

The tool electrode characteristics can affect the anodic dissolution happened in ECM process. The influence of various tool properties such as good electrical and thermal conductivity, better chemical stability, high corrosion resistance, good machinability and withstanding electrolyte pressure without any vibration in ECMM process has been discussed in this section. The direct and pulse electroplating method was used to coating the nickel material over tungsten electrode and finding the influence of process parameters on coating characteristics. Finally, the pulse electroplated nickel coated-tungsten electrode has been selected for machining work piece using ECMM process. The coated tool electrode has higher corrosion resistance and good electrochemical stability effectively utilized for ECM tool because it increases tool life, productivity and machining accuracy [21].The computational method was studied for finding the interfacial stress between the electrode substrate and acrylic resin insulating coating durability. The experimental and theoretical values are verified to improve the coating durability. The electrode tip angle increased (0° to 18°) for machining hole in the order of 1.1 mm diameter and 2.1 mm height with optimized insulated tool structure [22]. Owing to the controlled pulse energy, the tool coating can lower surface roughness in ECMM process as shown in Fig. 5.

3.1 Effect of tool electrode modifications on performance measures

Since the ECM process is influenced by current density, the tool properties such as electrical conductivity and shape can influence the performance measures. The coating over tool electrode can modify the current density during the process due to its ability on changing the electrical conductivity. The influence of certain electrochemical process parameters was studied on response such as material removal rate (MRR), radial overcut and conicity factor while machining aluminium metal matrix composites. It was concluded that characteristics of the tool electrode has considerable influence on machining aluminium metal matrix composites (aluminum 6061 with 12% composition of ground granulated blast furnace slag reinforcement). The heated electrode using furnace has improved the MRR by 88.37% due to ability on improving anodic dissolution. It has also decreased conicity factor by 33.33% and radial overcut by 37.03% with the factors of 8 voltage, 35 g per liter of electrolyte concentration, 90% duty cycle and 60 °C temperature of electrode [23].

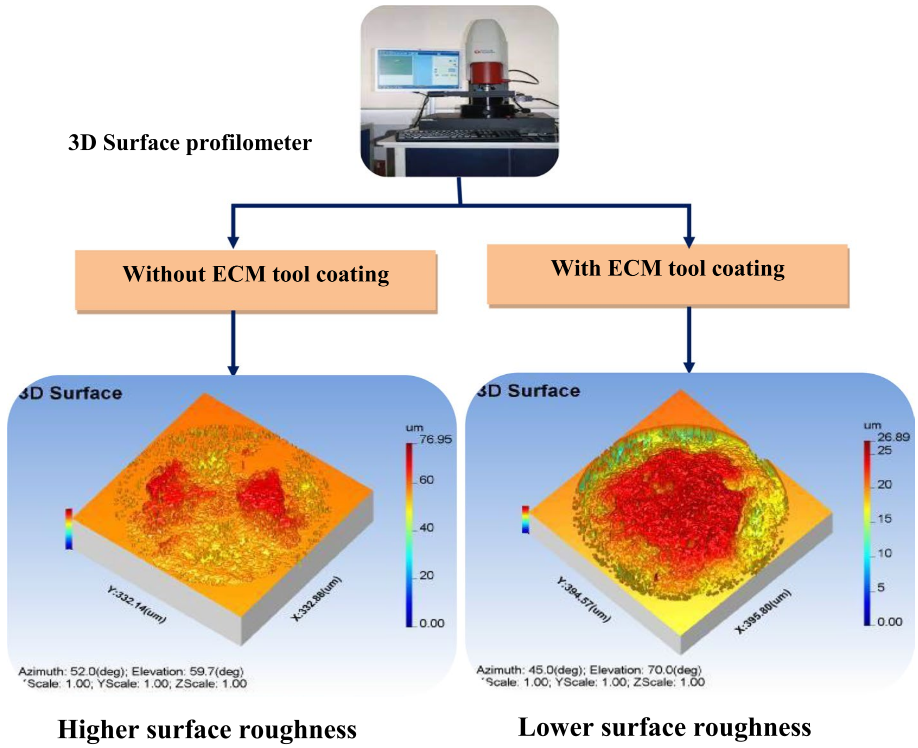


Fig. 5 Effect of tool coating in ECMM process

The making of aircraft blade cooling holes was investigated in electrochemical micro machining process by varying process parameters such as voltage, solution concentration and machining clearance on surface quality and machining accuracy. The computational fluid dynamics (CFD) simulation has been used to evaluate the eddy current distribution and electrolyte flow velocity field on micro hole generation [24]. The experimental process has been conducted with input process parameters such as applied voltage, types of electrolyte, feed rate and duty cyrcle on MRR, circularity, conicity and overcut with different process level using copper tool electrode. The composite electrolyte (combination of NaCl and $NaNO_3$) has most significant parameter for machining SS 304 alloy using ECMM process [25]. ECM process is used in making advanced and complex shapes in aerospace fuel injection and orthodontic industries. This study predicts the localized dissolution and predicts the most influential electrolyte. Experiments have been conducted to study the machinability on SS304 with 20% of concentrated sodium nitrate electrolyte using copper wire electrode. The use of pulse voltage with passivating electrolyte was found to mitigate the sludge generation and improve accuracy in the terms of better overcut and conicity [26].

The accuracy improvement is a major deal in most of the industries seems to be the major challenge. This study presented a method of improving the machining accuracy using a helical micro electrode by the insulated coating for avoiding side cut machining. The simulation indicate that the electrically non-conductive coated helical tool brings down the current density at the side gap area of the machined hole and hence reduces the stray material removal on machining surface owing to the enhancement of current density. It has been experimentally observed that the machining accuracy and the process stability was significantly improved [27]. The rotary tube electrode with 0.7 mm diameter and helical distributed jet flow holes was used on machining Inconel 718 alloy using Electro chemical cutting. The input process parameters such as high rotational speed of tube electrode, low pulse voltage (22 V) and large electrolyte pressure (2.5 MPa) was utilized machining Inconel alloy and to control material removal rate (MRR) and machining accuracy to meet the micro-machining requirements [28]. The effect of coated tool electrode on performance measures was investigated such as material removal rate, surface roughness, over cut and corrosion resistance as shown in Table 2.

3.2 Effect of pulsed electroplating characteristics on performance measures

Since the electrical power is supplied to the electroplating process in the form of direct voltage and pulses current, the effect of input process parameters for both electroplating process on performance measures is to improve coating process. The pulse electroplating process enhances the uniform coating, better surface finish of coating surface and higher adhesive bonding between two surfaces.

The experimental investigation of removal of oxide layer formed over copper surface using acetic acid at lower than

Table 2 Influence of tool electrodes in ECM process

Process	Tool electrode	Modification coating	Inference	Applications
ECM	Tungsten electrode	Nickel	Higher conductive coating improves MRR [21]	Aero space, Air craft, orthodontic and MEMS applications
	Metallic tool electrode	Heated tool	The temperature of tool electrode affects ECMM process [23]	
		Inner hole	The inner hole reduces the surface roughness [24]	
		Composites electrodes	The composite electrode enhances the ECMM process [25]	
	Copper tool	Wire electrode	It reduces the overcut [26]	
	Micro helical tool electrode	Non conductive mass coated	It reduces the stray current [27]	
	Metallic tube electrode	Distributed jet-flow holes	The modified tool electrode improves process efficiency [28]	

room temperature was performed. The acetic acid chemical solution with 20% of concentration has been used to remove oxide layer such as cupric oxide, cuprous oxide and cupric hydroxide from the copper surface without any defect in copper film. The copper surface was treated by acetic acid solution at 35 °C.It achieved oxide-free copper surface and finally, copper surface was observed by X-ray photoelectron spectroscopy [29]. It was highlighted that the effects of direct current (DC) and pulse plating nickel coatings on copper substrate and the effect of pulse plating process parameters such as less current density and medium frequency on hardness, surface roughness, X-Ray Diffraction (XRD) and scanning electron microscope (SEM) analysis. The surface topography analysis has been used to find uniform coating and corrosion behavior on surface [30].

The continuous and pulsed electroplating process was used to coat the nickel material for corrosion resistance. The improvement of the machining characteristics such as corrosion resistance from morphology, pulsed nickel-coating, composition layers and crystallographic orientation were observed for nickel deposition. The coating morphology and crystal structure of deposits were observed by SEM and X-ray diffraction analysis [31]. It was presented the chromium coating over copper substrate using sulphate chromium (III) electrolyte by DC electro deposition process. The thickness of the chromium coating on copper substrate was affected by current density [32].

The tribological properties and structural characterization of thicker chromium coating for chromium (III) and chromium (VI) electrolyte used for electro deposition has been discussed [33]. The tribological property was improved by the chromium (VI) electrolyte and there is no change of wear resistance for both chromium (III) and (VI) electrolyte solution in electro deposition process. The microstructure analysis was used to find out the performance of coating substrate. The electro deposition of trivalent chromium coating from the level of 1-butyl-3-methylimidazolium-hydrogen sulfate ionic liquid solution and chromium (III) material reduction was discussed in two stages such as chromium (III) to chromium (II) and chromium (II) to chromium (0), respectively [34]. Finally, the surface morphology and composition of deposited surface are investigated using X-ray diffraction, energy-dispersive spectroscopy and scanning electron microscope to analyze the residual stress, components analysis and surface morphology. By adjusting the pulsed voltage waveform, a high voltage sequence on the cathode tool was generated, created plasma by induced hydrogen flow on the electrode surface, assisted the ECM in reducing the straightness errors on the microrod, and improved the efficiency of the machining process [35]. Using plasma assisted-ECM dramatically reduces surface roughness R_a from 1096 to 46 nm, demonstrating that it is a very effective way of improving the efficiency of ECM without compromising the surface's quality. Through pulsed ECM milling, the microgrooves were fabricated on flexible metallic foil using a tungsten arrayed micro tool [36]. It was determined which factors affect the inter-electrode side and bottom gaps using a mathematical model and a pulsed current used to refresh the electrolyte. Microgroove width and depth were found to increase with increasing pulse duty cycle and pulse period, as a result of a longer effective machining time. As a result, a pulsed current with a small pulse duty cycle and a short pulse period improved microgroove machining quality [37].

3.3 Effect of tool electrode shape, size and profile on performance measures

The size and shape of the tool electrode possess considerable influence on determining performance measures in ECMM process owing to its ability on determining the current density. The tool designing of suitable electrode for given profile and internal feature is of great importance for practical applications with ECM process. A fabricated prototype tool electrode with non-uniform conductive area ratio from its tip to the root could produce better machinability [38]. The tool shape for the desired vane geometry was determined by a self-developed algorithm. The simulated tool shape was experimentally validated by the performance of sinking experiments on an industrial ECM-machine [39]. A new hybrid concept that combines ECM with a robotic arm which can be called robotic electrochemical machining (RECM) and its components. It could produce the better and precision machining with higher accuracy [40]. A hybrid tooling concept for coaxial and concurrent application of electrochemical and laser micromachining processes was fabricated. The proposed hybrid tool was successfully capable of concentrating ECM process energies simultaneously in the same machining zone [41]. The wire electrode wear could be eliminated by the use of the wire electrochemical turning (WECT) method in which the tungsten wire electrode was continuously running. The ultra-short bipolar pulse current was generated by the electrostatic induction feeding method where a pulse voltage was coupled to the working gap through a feeding capacitance [42]. A finite element approach was proposed to accurately determine these electrode profiles in ECM process. The proposed method does not require Iterative redesign process. Hence it could provide an excellent convergence and efficient computing in ECM process [43]. In micro ECM process using ultra short pulses, the machining rate was significantly influenced by the tool electrode area. A simple insulation method using enamel coating on the side wall of the tool electrode was introduced to modify the tool electrode area in ECM process [44].

4 Process factors affecting the ECMM response parameters

The influence of various factors such as pulse period (Combination of pulse on time and off time), input process parameters, tool properties, material properties and various electrolytes on performance measures of the ECMM process are discussed in this section. The process parameters and pulse shape can affect the energy per pulse in ECMM process.

4.1 Influence of pulse period on machining characteristics

The pulse duration determines the amount of the pulse energy delivered across the machining process in ECM process. The effect of pulse duration and duty cycle on machining characteristics of ECMM process was investigated [45]. The micro machining technology has been used for many applications such as micro electro mechanical systems (MEMS) / nano electro mechanical systems (NEMS), biomedical and integrated circuits(IC) manufacturing field. The smaller inter electrode gap is maintained during machining process by varying input parameters such as applied voltage, pulse period, electrolyte concentration and duty cycle on machining characteristics like material removal rate and machining dimensional accuracy. The inter electrode gap can be measured and maintained using voltage sensor under potentiometer principles. The pulse duration determines the pulse energy in ECM process. The higher pulse energy produces the more deposition of removed anodic material over the machined surface owing to the excessive pulse energy as shown in Fig. 6. An experimental analysis of micro hole formation was conducted in nickel plate by varying parameters like frequency of voltage pulse and duty cycle on response parameters such as material removal rate, machining time, shape and size of machined hole and no. of short circuit detection [46]. The size and shape of micro hole are measured and evaluated to tool geometry.

A high frequency level of pulse electrochemical machining process was attempted to achieve better characteristics such as higher machining exactness, reduction of electrode passivation and to improve inter electrode gap electrolyte flow field [47]. The other input parameters are fixed and vary only on the pulse frequency to enhance the machining quality of the products. The effect of input parameters such as applied voltage, pulse period, electrolyte concentration, pulse frequency, hole depth and tool feed rate was investigated on performance measures like conicity and overcut [48]. A tungsten carbide (WC) tool electrode of 50 µm diameter has been used to produce micro-drilling on nickel plate having 200 µm thickness in ECMM process. However the carbon was deposited over the machined specimen.

An experimental investigation and theoretical model was described to analyze the performance on ECMM process [49]. The obtained results showed that shorter pulse on time and shorter voltage amplitude produced more accurate

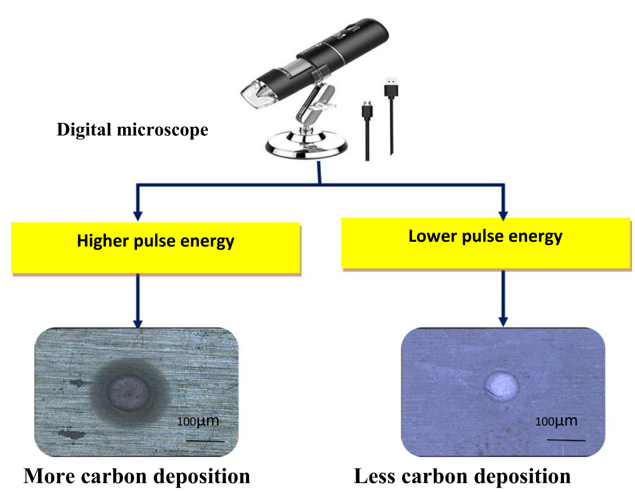


Fig. 6 Effect of pulse energy on heat affected zone

microstructure. The optimization of ECMM process was performed by varying input parameters such as electrolyte concentration, pulse on/off ratio, pulse frequency, machining voltage and tool vibration frequency on radial overcut and material removal rate using response surface methodology [50]. The micro-spark generated due to unit removal by uncontrolled electro discharges, irregular shape and size are produced in the machining zone. Therefore, the stray current region was reduced to eliminate the micro-spark generation.

The effect of side gap resulting from ECMM process was analyzed with wire (tungsten) as a tool electrode. The ultra-short voltage pulse was applied between anode and cathode to reduce the side gap [51].The side gap changed based on the input parameters such as pulse on time, pulse duration and applied voltage pulse. The electrochemical machining process is used to make micro grooves easily because it is a no tool wear process. The pulse voltage shape-tube electrochemical drilling process was investigated on nickel-based super alloy material by varying the working parameters such as voltage pulse on time, duty cycle, electrode tool feed rate, bare-tip length and applied voltage on output response like linear material removal rate, mass material removal rate and radial overcut [52]. The optimum process parameters have been found out to produce good-quality blind hole machining in super alloy-nickel material.

The wedge shape of micro tool fabricated from the stainless steel material using pulse-electrochemical machining process was discussed [53]. The Titanium-containing diamond-like hydrocarbon (Ti-DLC) material was used as a coat over the stainless steel tool before the Pulse-ECM process because it improves hardness and surface finish. The analysis of microstructure and mechanical properties for coated electrodes were studied by Raman spectroscopy and nano indention techniques. A ECMM setup for machining micro hole and micro channels was developed to machine electrically conducting materials [54]. The influence of working parameters such as electrolyte concentration, applied voltage and duty cycle are in the form of pulse and tool feed rate on response like machined hole diameter. The uniform width of micro channel has been generated during smaller gap lesser than 20 microns between the workpiece and tool electrode.

The effect of major process parameters was presented such as frequency, electrolyte concentration, applied voltage on material removal rate and overcut of drilling Al-10% TiC metal matrix composites in ECMM process using Taguchi-Grey relational approach [55]. From the results and analysis, it has been found that voltage and electrolyte concentration are the significant criteria that influence the overcut and MRR values. Finally, the confirmation test was carried out to enhance the performance measures like MRR (89.5%), overcut (57.9%) with accuracy using grey relational grade based optimization approaches (95.16%). The micro-tool electrodes fabrication having different tip end shapes was highlighted such as flat-tip, conical and spherical electrodes by different processes like electrochemical etching, single electric-discharge and electrochemical micromachining process. From the simulation and analysis results, it has been used to produce micro-level hole, complex shape of plane structure layer by layer and no-taper micro-level hole using the conical-tip, flat-tip and spherical-tip tool electrode in EMM process [56].The multiple tool electrode fabrication was described using composite processing techniques combining the two methods like EDM and electrochemical etching process for forming the micro-tool electrode array. The EDM process was used to make rectangular columns and further the micro-tool electrode array formed like cylindrical columns by electrochemical etching process [57]. Finally, the micro-tool electrode array has been utilized for cathode tool in ECMM process to produce accurate micro-hole. It was discussed the optimization of process parameters on electrochemical micromachining process using Taguchi-Grey relational analysis [58]. From the results, the machining voltage and electrolyte concentration have important parameters on MRR and overcut. The evolution process of micro through-slit array machine was investigated by JET-ECM. Different workpiece moving speeds were used in the experiments, and the evolution of the sectional profile agreed well with the simulation results [59]. The use of a low pulse duty cycle also enhanced electrolytic product transport in the small machining area and reduced the dimensional difference of micro through-slits with the same real machining time. The pulse duty cycle significantly affected the machining process with the same real machining time (ton). Micro through-slits should be prepared with a pulse duty cycle of 20%, which improves the material dissolution process and reduces dimensional differences [60].

4.2 Influence of process parameters on machining characteristics

Electrochemical micromachining (EMM) setup consisted of various sub-systems and components like micro-tooling system, electrical power and controlling system, controlled electrolyte flow system, and mechanical machining unit used to Control Electrochemical Machining (ECM) process parameters to meet micromachining necessities. The analysis on Electrochemical Micromachining (ECMM) of maskless copper plate by platinum micro tool and side wall is coated with silicon nitride (Si_3N_4) using Chemical Vapor Deposition(CVD) [61]. The influence of predominant process parameters such as machining voltage, electrolyte concentration and constant parameters are frequency of pulsed power supply and pulse on time on material removal rate and overcut. It was investigated the electrochemical micromachining(ECMM) process for the machining of maskless copper plate by platinum micro tool and side wall was coated with silicon nitride (Si_3N_4) using Chemical Vapor Deposition(CVD) [62]. The experiments are conducted and analyzed with the machining parameters like electrolyte concentration, pulse on time, machining voltage, frequency of pulsed power supply on MRR and accuracy. The machining parameters set as 10% of electrolyte concentration, machining voltage of 30 V and moderate pulse on time will create exact shape, moderate MRR and lesser overcut.

The electrochemical micromachining process has new possibilities to get better material removal mechanism. The empirical investigation of the surface finish region in cathode was presented for various applications such as medical implants, injection molding and friction pairs. The pulse-electrochemical machining (PECM) cathode was produced by EDM process and the PECM generated the fine surface finish, without the demerits of tool wear rate, heat affected zone and high machining time [63]. The STZFET-22 model can predict the anode profile on five zones such as front, side, stagnation, transition and stray current attack. It was discussed the influence of working parameters like machining voltage, electrolyte concentration, duty ratio and frequency on performances namely, overcut and material removal rate to find out using the L_{18} orthogonal array. The electrolyte concentration and frequency are the most significant parameters on performance measures like MRR and overcut. The confirmation tests were carried out to improve the response parameters [64].

An investigation was performed in the electrochemical micromachining (ECMM) process for the machining of special 304 stainless steel using Grey relational analysis optimization technique [65]. The influence of the process parameters like pulse-on time, electrolyte concentration, machining voltage on overcut and machining rate for various tool electrode tip shape like conical with rounded tip, flat tip, wedged electrode tip and truncated cone tip have been investigated. From their analysis they found out that the concentration and tool tip shape are the most important parameters to be taken care of when it comes to machining rate and low over cut. The experimental investigation of electrochemical machining was conducted on AA AISI 304 workpiece. The effect of independent parameters like applied voltage, current, electrolyte concentration, electrolysis time, feed rate on output response MRR and surface finish was studied [66]. The influence of applied voltage, electrolyte flow rate and feed rate was studied on performance measures like overcut, surface roughness and material removal rate of electrochemical drilling process with NaCl and $NaNO_3$ electrolyte solution in SAE-XEV-F valve steel material. Finally, the artificial neural networks (ANN) and co-active neuro-fuzzy inference systems were used to predict the output response namely, surface roughness, overcut and material removal rate [67]. It was found that when the machining is done with tool rotation then the circularity of the hole is good, but they also said that effective care has to be taken that the cylindrical tool which is fixed on the spindle should have minimized eccentric rotation so that the output diameter of the hole is not large than the expected value.

The experimental investigation of process parameters was presented on electrochemical machining in two aluminium alloy work pieces using NaCl electrolyte solution and the effect of independent parameters like electrolyte concentration, frequency, electrolyte flow rate and voltage on response parameters. The higher electrolyte flow rate, voltage and frequency were used to improve the performance like MRR and surface roughness [68].The influence of independent process parameters such as applied voltage, feed rate and inter-electrode rate was explained on MRR using brass CZ131 alloy material in electrochemical micromachining process. The high range of voltage and feed rate was used to increase the material removal rate with maintained constant IEG [69]. An Electrochemical Machining (ECM) was described for the machining of aluminium silicon carbide particle(Al/10%SiC) composite using response surface methodology (RSM). The influence of different process parameters such as electrolyte flow rate, electrolyte concentration, tool feed rate, applied voltage on MRR and Ra for electrochemical machining of LM25 Al/10%SiC composites using stir casting. They found an interesting conclusion where increase in any of the input parameters taken will result in an increase in the machining rate of the composite [70].

4.3 Effect of material properties on machining characteristics

The performance of electrochemical micromachining process is based on the workpiece properties like physical and electrical conductivity. The effect of electrochemical machining was attempted on nickel-based alloys and modern titanium for the application of aero engine components. The SEM and EDX analysis was used to evaluate the surface morphology [71]. The difficult-to-cut materials such as hastelloy C-276 (nickel based super alloy) were machined by electrochemical machining process due to its difficult to machine the materials in traditional machining process. The high voltage, feed rate and lower feed rate can achieve maximum material removal rate [72].The machining characteristics of nickel-base single crystalline material LEK94 on electrochemical dissolution process was analyzed [73]. The effect of input process parameters such as electrical conductivity of electrolyte solution and current density were investigated on MRR and surface quality. The accuracy of the surface could be increased at the range of higher level current density. The higher current density and flow rate of independent variables achieve higher removal rate on nickel material but lower current efficiency for iron material based upon the oxidation behavior. The anodic dissolution was improved based on the behavior of work piece properties like nickel and iron anode. The machining of micro-groove on shape memory alloy Ni–Ti was investigated using electrochemical machining process with short pulse period. The simulation analysis and practical values were compared and analyzed for varying process parameters on machining characteristics such as material removal rate and types of power source [74]. The influence of precise valency on unit material removal was experimentally analyzed in electrochemical machining of aluminium specimen using sodium chloride electrolyte solution. The anodic dissolution of aluminium in the form $Al^{3+}$is generated by the further series of chemical reaction to remove the material from the aluminium workpiece. The higher material removal rate was obtained with the increased voltage value [75]. The corrosion behavior of anodizing, electro polishing and mechanical polishing of stainless steel 304 workpiece was described using electrochemical measurement. The improvement of corrosion properties like anodizing < electro polishing < untreated was obtained from the nickel–chromium oxide layer formation during anodizing process [76]. The electrochemical machining of titanium work piece was investigated for the biomedical application. The influence of voltage and electrolyte flow rate on surface characteristics (R_a) like arithmetic average height, ten point height, maximum height of profile, skewness and kurtosis were studied[77]. The higher value of electrolyte flow rate and voltage increased material removal rate and its irreversible for better surface roughness and overcut.

A semi-finishing process using Jet-ECM was employed to flatten the Direct Energy Deposition-produced wave-like surface was investigated [78]. Since Inconel 718 has a wide range of applications, it was chosen as the material for the workpiece. The material's crystallographic orientation and grain size play a significant role in the electrochemical dissolution behavior of the material [79–81]. It can be said that Jet-ECM flattens a surface when the cathode passes over a wave-like surface due to a difference in the machining current. By removing more material in bulged areas than in sunken areas, the height fluctuations will be reduced significantly.

4.4 Influence of process parameters on surface topography

The surface topography is evaluated using the craters produced due to the material removal during the machining process. The size and distribution of the craters can be evaluated by the process pactors in ECM process. The selection of electrolyte can provide better surface finish in machining process as shown in Fig. 5. The optimal selection of electrolyte can provide better surface finish with equal and tiny craters. The controlling of micro spark and reduction of stray current effect was investigated by varying input parameters like electrolyte concentration, applied voltage, pulse on/off ratio and tool vibration frequency on performance measures using electrochemical micromachining process [82]. The SEM image was used to evaluate the surface characteristics and machining exactness. Finally, the higher electrolyte concentration, applied voltage and higher pulse on/off ratio to reduce macro-spark generation and response surface methodology (RSM) has been used to develop mathematical model for analyzing the results. The study on parametric optimization was studied in electrochemical machining process for the machining of titanium based alloy (Ti-6Al-4 V) using S/N ratio and ANOVA using MINITAB software. The electrochemical machining has a lot of applications like aircrafts, aerospace, automotive, medical, petroleum, textile and electronic industries etc.They used feed rate, voltage and electrolyte concentration as the main parameters. They found out that voltage is the most significant factor followed by concentration of electrolyte and then feed rate. They figured out that the material removal rate increases with raise in voltage and concentration of electrolyte [83].

The basic phenomenon in electrochemical machining process was studied taking place during machining. It was found that the success of electrochemical machining lies in localizing electric field by means of partly insulation. Hence the electrode is insulated during machining [84]. The voltage between the cathode and specimen can be switched on and off during machining for this behavior of localization to sustain. Thus this method of switching on and off will therefore be considered a gap control strategy during machining to produce better machining accuracy products. The experimental investigation was performed of micro electrochemical machining on workpiece surface for the application of micro grooves, mini-hole and insulating groove features. The short-pulse current and small inter electrode gap was maintained for improving micro machining in ECM process [85]. The influence of reciprocated traveling wire-electrochemical machining process was investigated on surface quality. The insulation method was used to reduce the stray current region, and experimental and simulation values were compared and evaluated [86]. The high current efficiency was investigated on machining S-03 stainless steel work piece for aerospace application using electrochemical machining process with NaCl and $NaNO_3$ electrolyte solution [87]. The influence of current density on responses like machining time, surface finish and grain boundary corrosion rate was evaluated. The experimental investigation of rotating tool electrodes was conducted on electrochemical micro drilling process that has advantages like no tool wear rate, high MRR, stress or burr free and low surface roughness. The influence of process variables such as machining voltage, frequency, electrolyte concentration, tool diameter, tool feed rate, tool rotation speed and hole depth on responses like MRR, conicity and overcut were analysed [88].

The micro-tool electrode was fabricated for precise electrochemical machining process made by combination of photolithographic and electroforming process. Characterization of structure and replication accuracy was determined by X-ray diffraction and scanning electron microscopy method [89]. The micro-tool electrode was developed using reverse of micro electrochemical machining process and investigated the tool length, tool diameter, shape and size of micro tool by varying applied frequency on MRR, number of short circuits and machining time. The size and shape of micro hole and tool geometry was compared and evaluated [90]. It was suggested that using ultra-short voltage pulses between a work piece and tool electrode in an ECM environment will produce three dimensional machining of conductive materials with micro-level precision. They used tungsten as workpiece, in which their main intention was to produce micro probes. They used three electrolytes to tackle different problems, of which H_2SO_4 is used to remove the passive layer from tungsten carbide solution. When different sizes of microprobes are required they used NaOH as electrolyte with varying ultra short pulse voltages [91]. The HCl can be used as electrolyte which produces probes of good surface quality for quality holes.

4.5 Effect of various electrolytes and flow types on machining characteristics

The electrolyte flow differentiates the ECM process with electro plating process. The electrolyte flow ejects the removed the anodic materials from the machining zone in the ECM process as shown in Fig. 7. The effect processes variables like current density and electrolyte flow rate on performance measures such as surface finish and unit removal of metal from the machining surface. The machining of titanium alloy (Ti-6Al-4 V) was discussed in electrochemical machining using pulsating electrolyte with varying frequency and amplitude parameters. The lower surface roughness and higher material removal rate were observed in proper selection of process variables for automobile, medical and aerospace applications [92].

The influence of process parameters was evaluated on material removal rate using copper tool electrode in electrochemical machining process. The circular hole produced on stainless steel -304L workpiece was analyzed by S/N ratio and ANOVA techniques using Taguchi optimization. The effects of cobalt material from the workpiece specimen to generate Co^{2+} ion (divalent) during dissolution decreased the secondary passivity. The cobalt has secondary significance than chromium metal and it was observed by X-ray photoelectron spectroscopy. Finally, the highest material removal rate was observed from the maximum percentage of cobalt composition in ECM process [93].

The surface characteristics of iron workpiece were investigated in electrochemical machining process using sodium nitrate solution. The Fe^{3+} and Fe^{2+}were formed in workpiece surface and was first time monitored by UV–VIS spectroscopy analysis. The passive layer formed over the iron surface to predict the overcut and increased the surface finish properties. Potentio dynamic and EIS measurements were used to investigate passivation behavior. A quantitative measure of the polarization resistance was made, and comparisons were made between the corrosion resistance and structural compactness of passive films formed in various neutral solutions [94]. The optimal level of electrolyte concentration

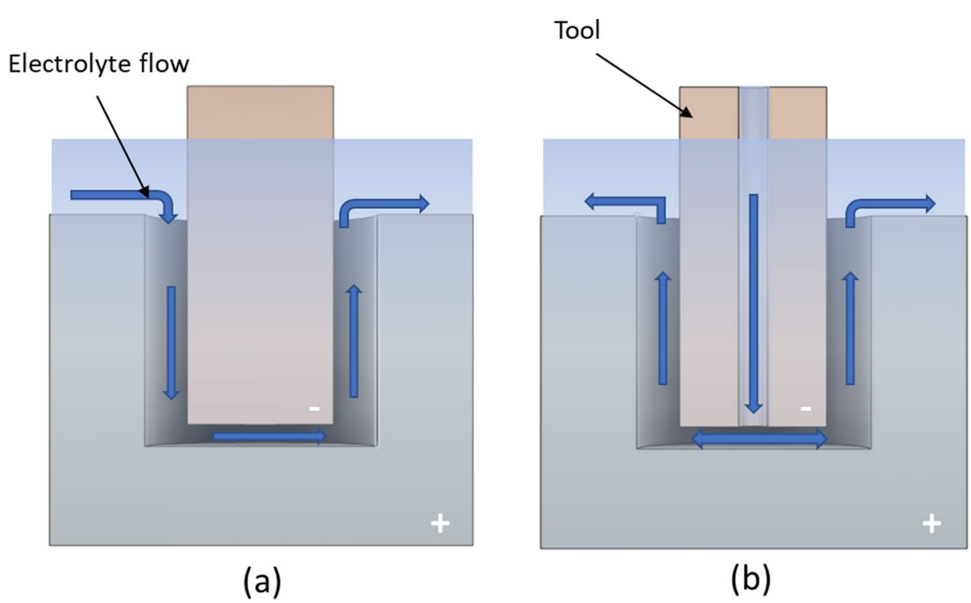


Fig. 7 Schematic electrolyte flow in ECM process

composition was used to produce better surface quality and efficiency [95]. The optimal combination of electrolyte could create tiny craters produced owing to the material removal with uniform distribution as shown in Fig. 8. This can improves the surface quality of the machined specimens. The iron-coated and uncoated Inconel 718 work piece was investigated in electrochemical machining process using $NaNO_3$. The iron coated work piece has reduced stray current region and improved the machining accuracy and productivity [96]. The dissolution of cobalt was studied in electrochemical machining using alkaline and neutral electrolyte solution. The anodic dissolution was measured by ultra violet (UV)-spectroscopy. The $NaNO_3$ and NH_3 mixture of electrolyte was used in machining the cobalt material and it acted like a complex agent to improved dissolution mechanism at high current density [97]. An experimental study was described in Electrochemical Machining (ECM) for the machining of special stainless steel 00Cr12Ni9Mo4Cu2 using Grey relational analysis method. They optimized the selection of electrolyte to be used in the main experiment using Grey relational analysis method. They chose three electrolytes which are sodium chloride (NaCl), sodium chlorate ($NaClO_3$) and sodium nitrate ($NaNO_3$) respectively, of which he chose the composite of sodium nitrate ($NaNO_3$) and sodium chlorate ($NaClO_3$). When voltage is constant and feed rate of tool increases, the machining rate increases and the side gap and surface roughness value decreases [98].In the opposite condition the result is vice versa. The high-quality surface and accurate structure was obtained by microstructure analysis from workpiece machined with oxygenated aqueous NaCl electrolyte solution. A study was performed to determine the efficiency of current in electrochemical processing using an electrochemical current determination of SS304with copper wire electrode using three different electrolytes (NaCl, $NaNO_3$ and HCl). The difference between the electrolytes and the electric current is measured simultaneously as a function of time. The influence of the current density, electrolyte concentration and voltage on the dissolution efficiency was determined [99].

In addition to optimizing surface quality by optimizing fluid dynamics, it can also quickly remove electrolytic products and gas bubbles and clean the gap between the cutting tool and the machining surface. For instance, Kozak and Zybura-Skrabalak [100] found that boundary layer hydrodynamic instability influenced surface roughness. Gas bubbles in the machining area can also affect the machining accuracy of the ECM process [101, 102]. In their simulation of the electrochemically machined profile of the engine blade using COMSOL Multiphysics software, Klocke et al. [103] assumed the flow field to be two-phase at the inter-electrode gap. The electrical conductivity was corrected using the Bruggemann equation [104] after calculating the volume fraction of bubbles within the electrolyte. In addition, to understand the influences of bubbles generated in

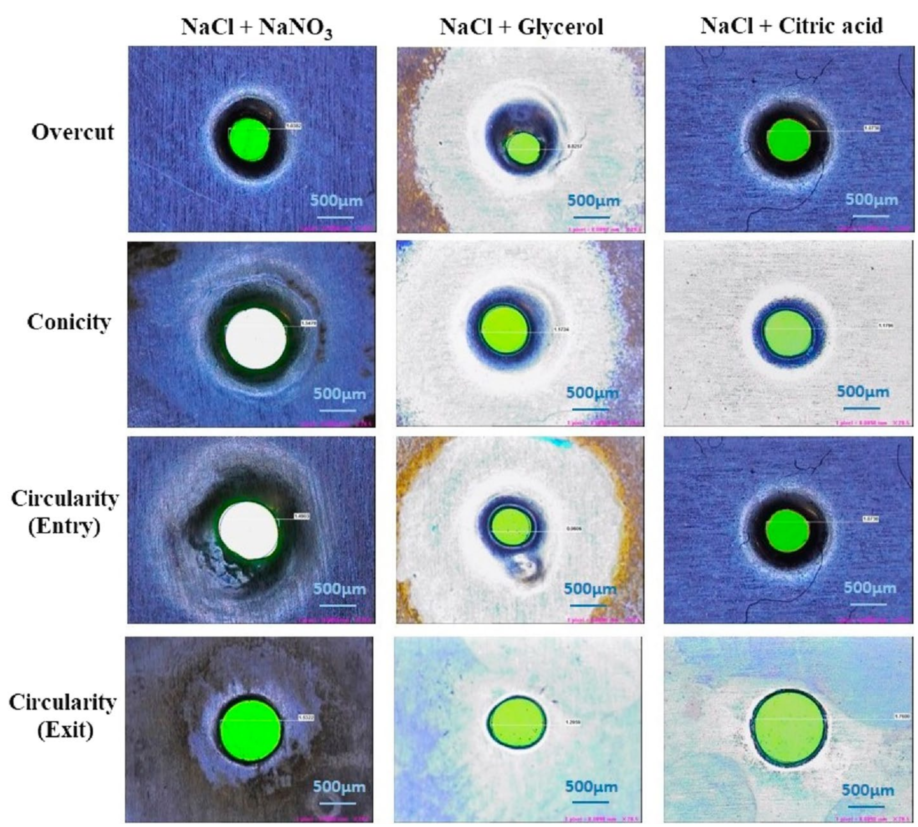


Fig. 8 Effect of electrolyte on the quality of holes frilling during ECM process of titanium Grade 5 [15]

the machining gap on the stability and accuracy of ECM, gap phenomena were observed directly using a transparent electrode [105, 106]. Many methods have been proposed to reduce the effect of hydrogen bubbles on ECM by improving hydrogen bubble detachment from tool surfaces. The direction of the electrolyte flow affected the suction of air and the collapse of bubbles [107]. An uneven pressure or flow rate improves the surface quality of trepanning ECM and compensates for the pressure loss of the electrolyte [108]. As a result, the distributions of air and electrolyte will become more uniform [109]. Figure 9 shows 3 stages of bubble formation in ECM process. Turbulent flow Wire electrodes can be fabricated with microstructures on the surface, and ribbed wire electrodes can be vibrated at high amplitudes in wire ECM [110, 111].

Using a rotary Axisymmetric curvilinear shape element, a numerical and experimental study was performed to investigate physical phenomena that occur during rotary ECM [112]. Using a quasi-three-dimensional ECM model can enhance the analysis of physical phenomena in the inter electrode gap. Mathematical ECM models are based on applying the equation of the evolution of workpiece shape and a system of partial differential equations that describe a flow of electrolytes in the inter electrode gap based on the principles of mass conservation, momentum, and energy conservation. Electrolyte flow in the inter electrode gap was found to be an important factor [113], with values such as $2300 < Re < 50{,}000$. However, there is a limited investigation of the Marangoni effect that takes place in lower Reynolds number flow fields. The Marangoni flow along the free surface transports heat and micro/nanoparticles. Electrolytic gas bubbles generated on electrodes can also change the surface tension when combined with the Marangoni effect, localized ohmic heating, and shear stress conditions [114, 115].

Another way to control the surface quality in the case of Jet-ECM is the tool design, the jet angle and the number of passes [116]. A standard cathode tool produces unsatisfactory surface quality in macro-electrochemical jet milling due to low current density and inefficient mass transfer. With the help of an insulated nozzle tip and an inclination angle, Zhang et al. [117], proposes a new cathode tool with enhanced mass transfer and confinement of the low current density region. According to experimental results of the proposed tool (tool C) produces a relatively smooth surface with a surface roughness that is approximately six times lower than that produced by the standard tool. Moreover, tool C removes material at a rate approximately 1.6 times greater than tool vertical. In addition, a mirror-like surface with a clear reflection and a surface roughness (R_a) of 0.12 µm was successfully manufactured. Although, using a rectangular tool tip density distribution exhibits a peak before dropping to zero. Liu et al. [118] numerical simulations and experiments confirmed Mitchell-Smith et al. [119] observation that an inclined nozzle increases the slope of the current density

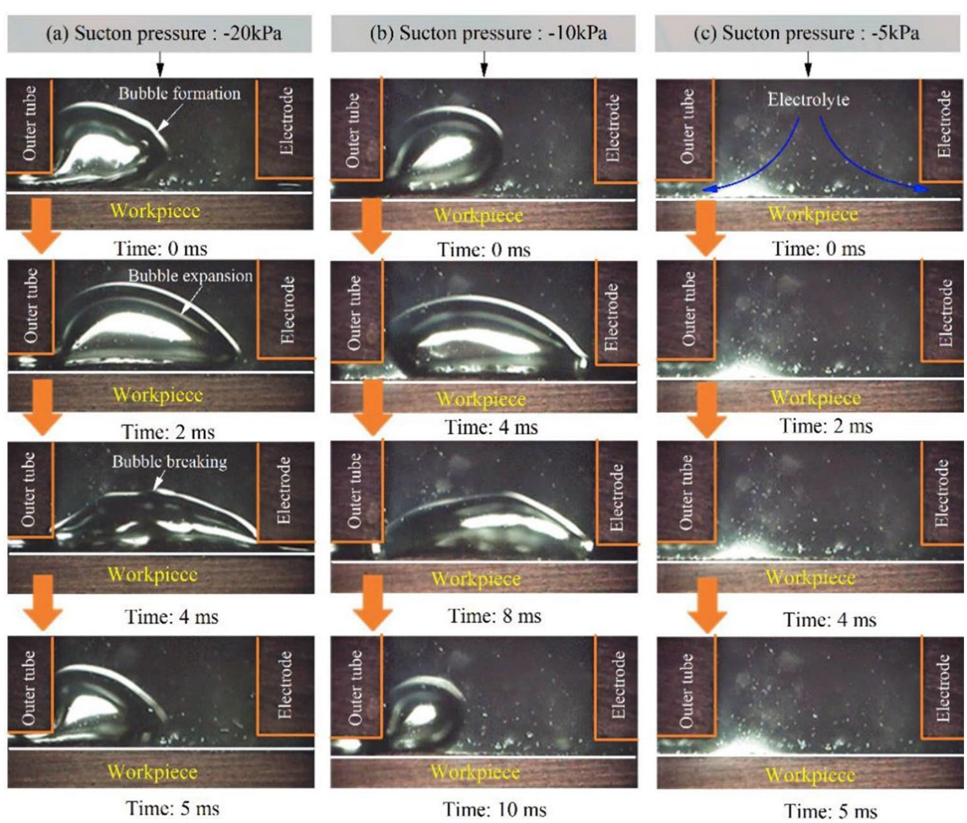


Fig. 9 Influence of pressure in the bubble formation [107]

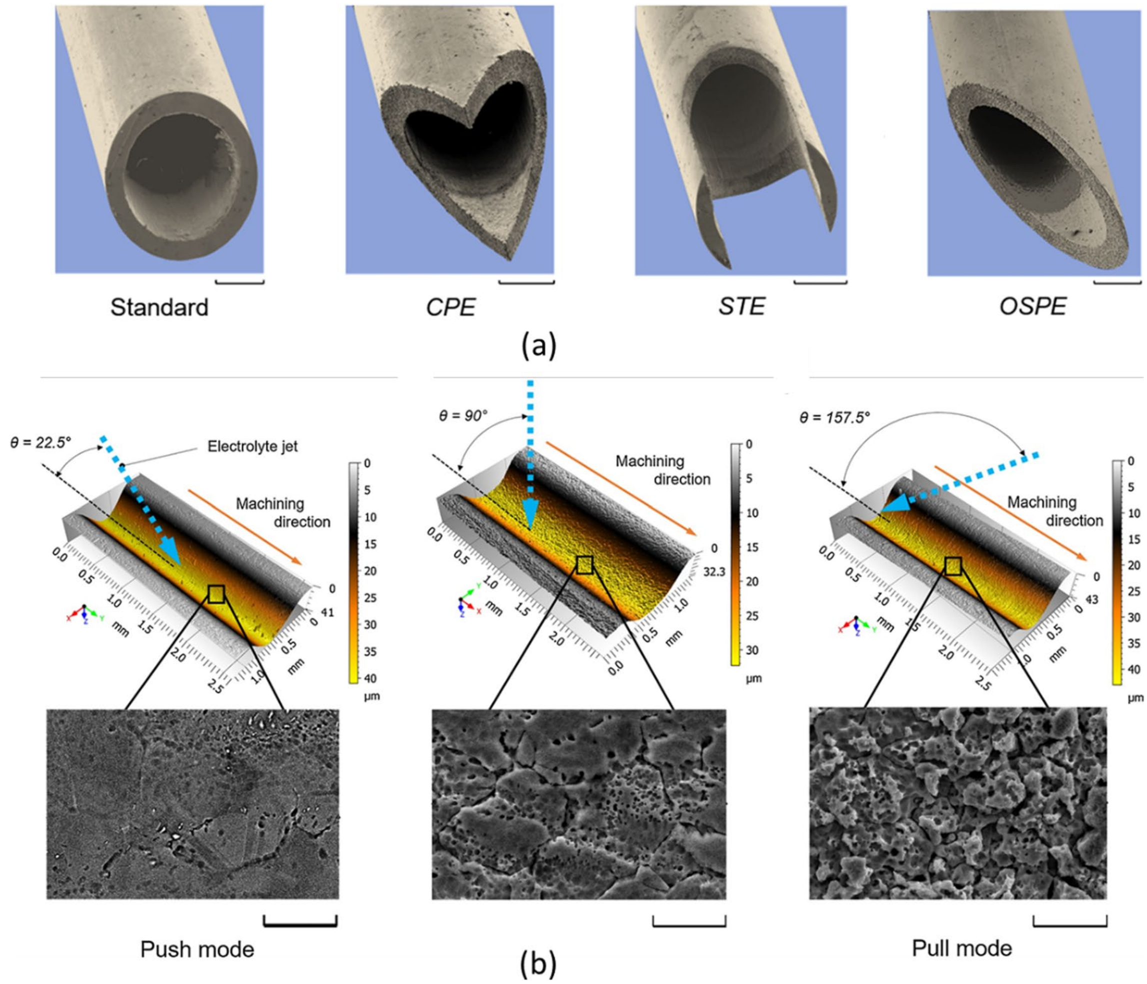


Fig. 10 SEM images **a** standard and modified nozzles machined by WEDM [116], and **b** SEM surface topography of a machined surface using different machine angles [119]

at the trail edge. Figure 10 shows (a) SEM images of modified tool tips using WEDM, and (b) shoes the influence of the Jet angle and machining direction on surface finish. It is obvious that the surface roughness is lower in case of the push mode (Fig. 10(b)) compared to the pull operation mode.

5 Optimization of ECMM process parameters

The optimization of process parameters can enhance the performance measures of any machining process as shown [120]. The empirical modeling of process factors can modify the surface morphology in any machining process. Table 3. shows the effect of optimization algorithms in ECM process. The effect of working parameters such as electrolyte concentration, frequency, current and voltage was studied on response parameters such as machining time for machining B_4C DRMM Al 6063 composite specimen using electrochemical micromachining process with Taguchi L_9 orthogonal array and optimized by Taguchi-fuzzy logic technique. The pulse frequency and voltage parameters are the most significant factors for machining B_4C reinforced Al composite anode. Finally, the results for both Taguchi and fuzzy logic method have obtained same values with zero tolerance [121]. The electrochemical machining (ECM) was reported for the cutting of aluminium and mild steel using Taguchi optimization technique [122]. The following input parameters were chosen for optimization: voltage and tool feed rate. Their study reveals that the voltage is the main parameter to be taken care of when it comes to material removal rate (MRR) for both materials and the current becomes the most significant factor to be reckoned with when it comes to surface roughness (R_a) for both materials [123, 124].

The literature review was conducted on modern machining process like abrasive jet machining, laser beam machining, electric discharge machining, ultrasonic machining,

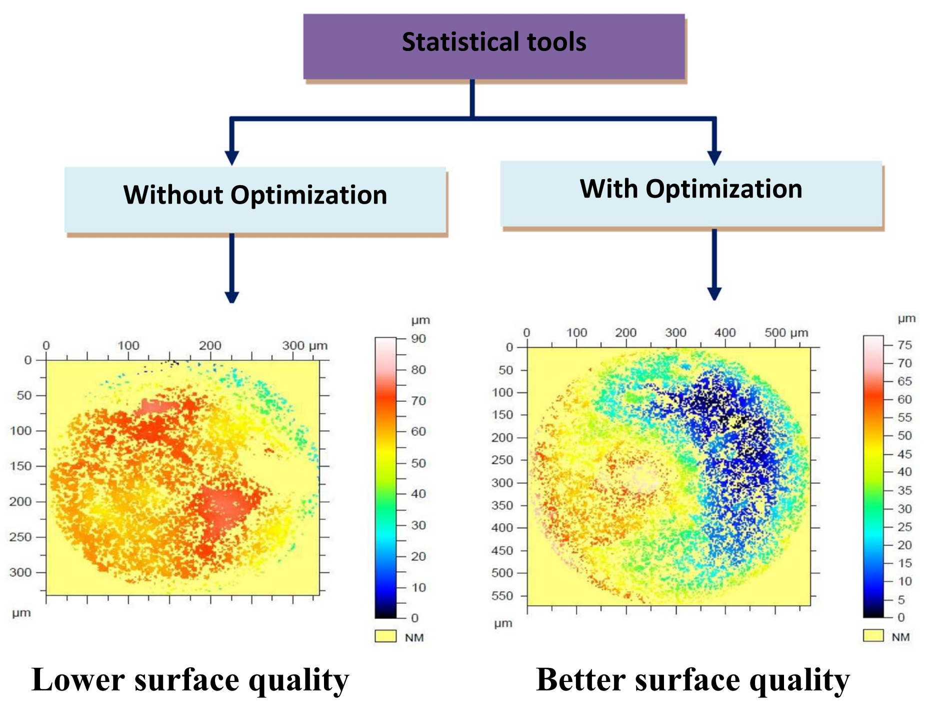
Table 3 Optimization algorithms in ECMM process

Process	Materials	Optimization	Inference
ECM	Al 6063 composite	Taguchi-fuzzy logic	Frequency and current are significant parameters [121]
	Aluminium and mild steel	Taguchi method	Current value determines surface roughness [122]
	Metallic materials	RSM, genetic algorithms(GA), ANN	Voltage determines material removal [123]
	EN-31 steel	Taguchi-Grey	Better prediction is observed [125]
	Mild steel and Aluminium alloy	Taguchi	Electrolyte flow rate and current could be the most significant parameters [126]
	Hastelloy C-276 and Ni base superalloy		ECM efficiency is improved by optimal process parameters combination [127]

electrochemical machining, nano finishing, micro machining and hybrid process optimization using various techniques such as RSM, GA, ANN, teaching learning based optimization (TLBO), simulated annealing (SA), and particle swarm optimization (PSO) [125]. The proper optimal combination of the process parameters can enhance the surface quality of machined specimens in ECMM process as shown in Fig. 11. The blue region indicates the lower surface roughness region. It was observed that the optimization approach can improve the surface quality and machining accuracy due to its controlled energy in ECMM process. Normally the surface quality of machined surface is determined using the average surface roughness value only. Since the right side specimen is having higher distribution of lower surface roughness, the lower average R_a was observed as compared with left side specimen to produce better surface quality. It was also observed that the better machined dimensional accuracy could be produced with optimization approaches.

The optimization of the process parameters was performed in Electrochemical Micro Machining (ECMM) process for the machining of EN-31 steel using Taguchi methodology and Grey relational analysis [126]. The three input parameters was chosen such as electrolyte concentration, feed rate and applied voltage. The output parameters were optimized namely material removal rate, cylindricity error, surface roughness and overcut. It was found that feed rate as the most influencing parameter to affect the machining performance like MRR, cylindricity error, surface roughness and overcut. The higher MRR and lesser cylindricity error, surface roughness, overcut was achieved in this combination of parameters like feed rate of 0.32 mm/min, electrolyte concentration of 15% and voltage of 20 V. The

Fig. 11 Effect of optimization on surface quality in ECM process



parameters material removal rate and surface finish was optimized on varying working parameters such as inter electrode gap, voltage, electrolyte concentration and tool feed rate of machining EN31 tool steel in electrochemical machining using Taguchi-Grey approach with L_{27} orthogonal array. The surface morphology was studied by scanning electron microscopy image.

The optimization of process parameters such as tool feed rate, electrolyte flow rate, current and voltage was discussed on output parameters such as surface finish and material removal rate with machining mild steel and aluminium alloy material in electrochemical machining process using S/N ratio [126]. The electrolyte flow rate and current could be the most significant parameters for mild steel and aluminium alloy as a workpiece material. The influence of process parameters was investigated on material removal rate in electrochemical machining process of hastelloy C-276 and Ni-base superalloy. Three parameters were selected which mainly influence the material removal rate and surface roughness namely tool feed rate, voltage and electrolyte flow rate, and remaining parameters were constant [127]. The optimization of parameters was performed by Taguchi methodology. The signal-to-noise method was used to find the best combination of parameters. The shorter voltage, feed rate and electrolyte flow rate should be high for higher material removal rate and machining accuracy. The voltage parameter has the major significant factor on surface finish and the practical and theoretical values were compared and analyzed. To determine the optimal Jet-ECM process parameters for producing the best performance measures for the material removal rate (MRR) and nickel presence (NP) in the sludge, meta-heuristic algorithms (i.e., the moth-flame algorithm, grey wolf optimization (GWO), and particle swarm optimization (PSO)) were applied. All the process variables significantly affected the performance of this ECM experiment based on its surface, main, and interaction plots. The controlling of the process parameters in any machining process is possible, the significance of the process factors on process mechanism need to be known through optimization algorithms [128–131]. The prediction modeling of the process factors in any process can also modify the performance measures through various algorithms such GRA, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [132–134]. Hence it is essential to implement such algorithms in ECM process [135, 136].

6 Possible recent trends in ECM process

The main demerit of ECM process is inability of machining non-electrical conductive materials. Many research work attentions are needed to implement hybrid and enhanced process mechanism to machine such materials also. Electro Chemical Discharge Machining (ECDM) is a new type of machining method that combines the features of EDM and ECM [137]. It is used to machine both conducting and non-conducting industrial materials. It is also possible to machine polymer materials also using such technique [138]. However it is essential to apply more research focus in such techniques. The application of the electrolyte-air injection can enhance the flushing process in ECDM process to effectively improve quality measures [139]. Still lot of attentions are needed to enhance servo tool feed control mechanism in ECM, EDM and ECDM process [140, 141]. The implementation of flexible contact force feedback control assisted scanning process has increased the surface quality of machined specimen in ECDM process [142]. The utilization of heat-treated and additive manufactured tool electrode is also interesting research area for the new ECM technologists [143, 144]. There are many control algorithms such as Real-Time Extremum-Seeking Controller, adaptive servo tool standoff distance control, machining bed movement control have already implemented in many machining processes [145, 146]. There are only few attempted have been made on adopting such approaches in ECM process [147]. The pulse applied across the machining zone can modify the performance measures in ECM and EDM process [148, 149]. The reduction of fume gasses and analysis of machined specimen to implement green manufacturing should also be initiated in such unconventional machining processes [150, 151]. The research works and research focus can also be initiated in such fields.

7 Conclusions

In the present study, a detailed literature survey was performed to analyze the influence of various process parameters on performance measures in Electro chemical machining process. The effects of various factors on material removal, overcut and surface topography were investigated under different perspectives such materials, electrolyte and machining parameters. From the detailed literatures, the following conclusions were drawn.

- Still a lot of research works have been required to find the suitable electrolytes and their combination during the machining process.
- A considerable research focus can be provided for controlling of machining mechanism in ECM process.
- The performance measures of the machining process can be improved by adopting different and suitable optimization algorithms.
- The investigation on analyzing the effect of additive tool with both ECM process and Electro Chemical Discharge Machining (ECDM) in future.

- The influence of eco-friendly electrolytes can also be investigated in ECM process.

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Author contributions All authors are involved in conducting experiments, analysis, data interpretation, finding and manuscript preparation.

Data availability Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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