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Electrochemical machining (ECM) and its recent development

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KEYWORDS

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Fuzzly logic (FL)

ABSTRACT

Electrochemical machining (ECM) is a process that utilized electrolysis process for the removal of the unwanted material and suitable for manufacturing difficult to cut electrically conductive material with complicated and intricate shapes. Depending on the ECM parameters, a wide range of surface roughness values can be obtained ranging from 0.2–12.5 μm Ra. Meanwhile wire electrochemical machining (WECM) is a variant of ECM where the part is formed with the relative motion between the wire electrode and the workpiece. WECM has the advantage of producing more complicated part, higher accuracy, better quality with less energy consumption for critical parts such as surgical blades. In addition, various recent developments to improve the output of the ECM are such as combining ECM with magnetic abrasive finishing (MAF) to decrease the machining time, and jet-ECM to overcome the formation of passivation layers.

1.0 INTRODUCTION

Nowadays, electrochemical machining (ECM) has become a viable method for machining components in numerous industrial applications, particularly in the manufacture of typical aero-engine components with complex structures fabricated from materials that are difficult to cut. This is because of several advantages, such as no tool wear, independence on the mechanical properties of the material, and high machining efficiency. Electrochemical machining (ECM) is a machining method that able to generate intricate shapes and geometries on various advanced engineering material by eroding materials from workpiece through electrochemical dissolution

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at atomic level (Das & Chakraborty 2020). ECM is a perfect technique to machine hard materials as it does not affect by the hardness of workpiece (Schubert et al., 2017). When compare with other machining method, ECM does not generate that much thermal energy among the tool and the workpiece (Sathiyamoorthy et al., 2015). There are other benefits of ECM such as no thermal stress, no relevant tool wear, able to generate complex shapes and shining surfaces without additional processes (Lohrengel et al., 2015).

Electrochemical machining (ECM) is a method of removing metal by an electrochemical process. ECM is also defined as reverse electroplating, in which material is removed instead of added (Valenti, 2001, Todd et al., 1999). It is normally used for mass production and is used for working extremely hard materials or materials that are difficult to machine using conventional methods. Its use is limited to electrically conductive materials. It is similar in concept to electrical discharge machining (EDM) in that a high current is passed between an electrode and the part, through an electrolytic material removal process having a negatively charged electrode (cathode), a conductive fluid (electrolyte), and a conductive workpiece (anode) however, in ECM there is no tool wear. The ECM cutting tool is guided along the desired path close to the work but without touching the piece. Unlike EDM, however, no sparks are created. High metal removal rates are possible with ECM, with no thermal or mechanical stresses being transferred to the part, and mirror surface finishes can be achieved. In the ECM process, a cathode is advanced into an anode. The pressurized electrolyte is injected at a set temperature to the area being cut. The feed rate is the same as the rate of liquefication of the material (Valenti et al., 2001). The gap between the tool and the workpiece varies within 80–800 micrometers. As electrons cross the gap, material from the workpiece is dissolved, as the tool forms the desired shape in the workpiece. The electrolytic fluid carries away the metal hydroxide formed in the process. ECM can cut small or odd-shaped angles, intricate contours or cavities for hard and exotic metals, such as titanium aluminides, high nickel, cobalt, and rhenium alloys. Both external and internal geometries can be machined. The ECM process is most widely used to produce complicated shapes such as turbine blades with good surface finish for difficult to machine materials. It is also widely and effectively used as a deburring process.

2.0 WORKING PRINCIPLE OF ECM

In ECM, the workpiece material is removed by electrolysis (Anonymous, 2020). A tool, usually copper (-ve electrode), of the desired shape is kept at a fixed distance away from the electrically conductive workpiece (+ve electrode), which is immersed in a bath containing a fast-flowing electrolyte and connected to a power supply. The workpiece is then dissolved by an electrochemical reaction to the shape of the tool. The electrolyte also removes the ‘sludge’ produced at the workpiece surface. The value consistency of an inter electrode gap (IEG) in ECM depends on various factors, namely electrolyte temperature, the thickness of the passive layer produced and the efficiency of IEG residue removal. These factors play a vital role in promoting a constant current density at the IEG which results in obtaining a better material removal rate (MRR) and surface roughness (Sathiyamoorthy et al., 2015). The main disadvantage of the ECM is as it requires the need for electrical conductors for the electrode materials and the workpiece. The removal rate of material decreases linearly with applied voltage and decreases nonlinearly with the feed rate of the devices (Sathiyamoorthy et al., 2015). The working principle of ECM involves a high current is passed between an electrode and the component, through an electrolytic material removal method providing a negative charged electrode (cathode), a conductive fluid (electrolyte), and a conductive workpiece (anode). Figure 1 shows the schematic diagram of ECM process.

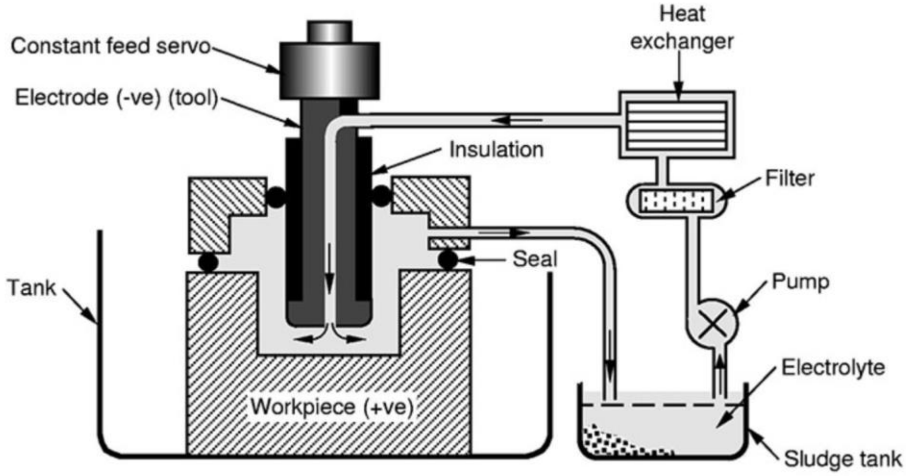

Figure 1. Principle of ECM. Adapted after Anonymous, (2010).

Optimum utilization of ECM requires consistent current density by selecting optimum parameters. Since the ECM process requires high initial investment, tooling and maintenance costs, the optimum choice of process parameters is required in order to achieve better results. Xu *et al.,* (2016) has studied the effect of electrolyte concentration and temperature on the dissolution voltage. Their study proves that electrolyte with greater concentration will have a lower dissolution voltage, allowing the ECM to be carried out at lower voltage. Same thing happened to electrolyte with higher temperature. They claimed that the temperature of electrolyte will influence the velocity of reactive ion exchange due to the kinetic and thermodynamic effect, thus causing a lower dissolution voltage for electrolyte with higher temperature. Sadegh, (2017) had implemented FL into ECM to control the feed rate and flow rate of electrolyte. In this study, a fuzzy logic controller (FLC) was built to make sure the ECM system will always remain at optimum situation. The author had tested the controller by forcing the ECM into short circuit situation. The controller is then turned on and brought the system back to optimum process condition.

There are several advantages of ECM, because it is a contactless machining method, suitable for difficult-to-cut materials, regardless of their hardness and strength. During the process, the shaped cathode tool does not wear because only hydrogen is released on the cathode. Moreover, high material removal rates can be achieved as well as high machining accuracy and good surface quality without the occurrence of deformation, micro cracks, residual stress, a recast layer, or heat affected zones. In addition, due to the cost of predevelopment of tools and fixtures as well as the investment required for unique machine tools, ECM is specifically used in large bath-size production to reduce cost (Xu & Wang, 2019). In addition, due to the cost of predevelopment of tools and fixtures as well as the investment required for unique machine tools, ECM is specifically used in large bath-size production to reduce cost (Xu & Wang, 2019). The advantages and disadvantages of ECM compare to other processes are summarized and shown in Table 1.

Table 1: Advantages and disadvantages of ECM compare to other processes.

ECM		Abrasive water jet (AWJ)		Milling process	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**	**Advantages**	**Disadvantages**
ECM is well suited for the machining of complex two-dimensional shapes.	Initial tooling can be timely and costly	Suitable of removal of deposits (oxides, coating, etc.) on surface.	Not suitable for soft and ductile materials.	The metal is removed at a faster rate as the cutter has got multiple cutting edges and rotates at a higher speed.	The cost of the milling machine is high.
Delicate parts may be made	Environmentally harmful by-products	Wide range of surface finish can be obtained.	Abrasive is not reusable.	It is possible to perform machining by mounting more than one cutter at a time.	As milling cutters cost high, the investment for procuring tools is more.
Difficult-to-machine geometries	Complicated tool design.	Process is independent of electrical or thermal properties.	Abrasive collection and disposable are problematic.	The table of the machine can be moved to an accuracy of 0.02mm.	
Poorly machinable materials may be processes	Large power consumption	No thermal damage.	Limited nozzle life.	It is very useful since various cutters and precise tools can be machined.	
Little or no tool wear		Suitable for nonconductive brittle materials.		Special attachments can be mounted on the machine to perform operations that are performed in other machine tools.	
		Low capital investment.			

3.0 RECENT DEVELOPMENT TECHNIQUES OF ECM

Despite the investigation of effect of cutting condition or parameters on the results of ECM, other efforts have been done to improve the diversification of ECM to cope with the latest needs from the industry.

During ECM, hydrogen gas is generated in the form of gas bubble while some by-product will also form at IEG. This will reduce the conductivity of electrolyte and affect the MRR (Fang et al., 2017). Fang et al., (2017) have implemented large amplitude vibrations in wire ECM to encourage the bubble removal and electrolyte renewal. Wire ECM is ECM that uses metallic wire as tool to carry out machining. In this study, through simulations and experiments, the authors found out that vibrating tool will help gas to escape. As result, a large-amplitude vibration of ribbed wire electrode will encourage the bubble removal process and improve the MRR and matching efficiency. WECM is a variant of ECM. It uses a metal wire as the tool cathode and removes material by anodic electrochemical dissolution, and the part is formed with the relative motion between the wire electrode and the workpiece. It has great advantages and well surface integrity such as no dependence on mechanical properties of the material being machined, no tool wear, no residual stress, no recast layers and heat-affected zones (Zeng et al., 2012). Hence, it is a potential method for processing parts with ruled surfaces which is hard to machine like the fir-tree slots in a turbine disc (Klocke et al., 2018a).

ECM concept of electrolysis was also utilized in tribology areas. Capitanu et al., (2019) elaborated on the fretting of CoCrMo and Ti6Al4V alloys in modular prostheses, in which an in-situ electrochemical ball on plate tribometer was instrumented to characterize tribocorrosion damage due to the contact of the two material couplings. In addition, Mukhopadhyay et al., (2016) investigate the tribological behavior of Ni-P-W coating under dry and lubricated condition with the coating is deposited onto mild steel (AISI 1040) specimens by the electroless method using a sodium hypophosphite based alkaline bath.

In WECM, the machining gap is usually tens of microns down to only a few microns, making it very difficult to rapid remove electrolytic products entirely from such a small gap. Much research has been conducted to improve the outcome of WECM on thick workpieces, and they can be divided into two categories according to the electrolyte flow status. In the first category, the workpiece is immersed in electrolyte, and the electrolyte in machining gap flows following the electrode movement (Fang et al., 2017; Kalaimathi et al., 2017; Xianghe et al., 2017). The second category is axial electrolyte flushing (Klocke et al., 2018 b). The electrolyte with a certain pressure is ejected from the nozzle, and flows into the machining gap along the electrode, which brings the electrolyte products out of the machining gap from top to bottom. High-speed flushing is the most commonly used method to promote electrolyte renewal and replenishment.

Although the above methods do accelerate the electrolyte renewal and the products removal, but the flow path is very long, meaning that fresh electrolyte has relatively to travel far to reach the reaction area. Hence, research is carried out to create a relatively short flow path (Xu et al., 2020). A pulsating radial electrolyte supply in WECM is proposed to improve the machining capability for thick workpiece. The tool is a tube electrode with a line of micro-holes on cylindrical surface. The processing of micro-holes in the tube electrode using a rotating helical electrode is is shown in Figure 2. It was shown experimentally that using a tube electrode with holes of varying diameters as a tool electrode provides better process capacity for pulsating radial electrolyte supply in WECM.

Machining accuracy, efficiency, and quality in WECM are influenced by different electrolytic factors, power factors, vibration amplitude and frequency of tool or workpiece, workpiece thickness and feed rate of tool or workpiece. Amongst various tool materials, tungsten is most widely used due to its high tensile strength and excellent chemical stability. Ribbed wire, textured wire, helical tools, cutting edge tools, and fluted tools have been used for enhancing flushing in WECM.

In 2019, Baoji et al., carried out a study on magnetic field-assisted ECM drilling. The ECM was assisted with magnetic field that suppresses anodic dissolution and magnetic field that promotes anodic dissolution. Results show that ECM localization was enhanced under magnetic field that suppresses anodic dissolution while not benefited under magnetic field that promotes anodic dissolution.

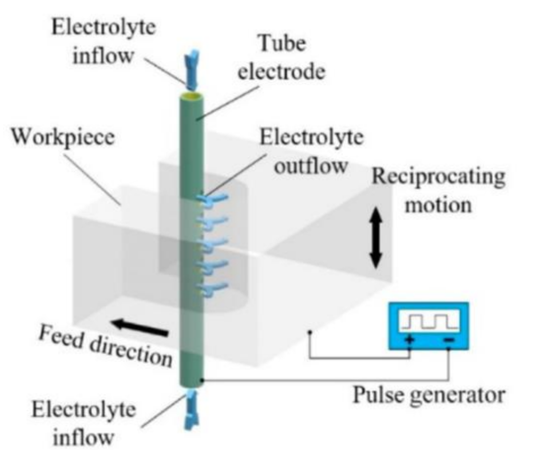

Figure 2: Schematic diagram of WECM process of processing of micro-holes in the tube electrode using a rotating helical electrode (Xu et al., 2020).

A study was carried out by Ridha et al., (2015) to combine the use of magnetic abrasive finishing (MAF) and ECM to decrease the machining time. Comparison of machining time between conventional MAF and combination of MAF and ECM was done. As result, the combination of MAF and ECM was able to achieve similar surface roughness as conventional MAF by using 60% to 70% of time used by conventional MAF.

A study was done to implement the use of ultrasonic in jet-ECM to overcome the formation of passivation layers (Clare & Mitchell-Smith, 2016). Jet-ECM is ECM with electrolyte injected to ease the removal of removed material from the workpiece. During the ECM of certain material, such as Titanium, passivation layers might form around the workpiece in the form of oxides. These layers will suppress material removal and reduce surface finish of the workpiece. In this study, ultrasonic was found to be able to reduce the formation of passivating layers by 23% at selected frequency, and the Ra was reduced by 31%.

4.0 APPLICATION ECM AND RELATED PROCESSES

Typical application of ECM such as for producing hole (circular and non-circular) production, profiling and contouring of components, engine casting features, turbine blade shaping, dies for forging, gun barrel rifling, honeycomb structures and irregular shapes, and burr free parts. This process allows for complex shapes to be obtained without distortion, cracks, burrs, white layer, heat-affected zone or residual stress. This technique can also provide a long service life of the non-existent electrode or tool wear (Mohan and Vinod, 2010), with high material removal rate and good surface quality. In general, typical application of ECM are (Raj et al., 2019):

(a) Machining of cavities in forging dies, drilling deeper holes and irregular shaped holes which cannot be obtained by conventional machining methods.
(b) Machining of complex profiles like turbine wheels, turbine and jet blades.
(c) Die sinking: Electro Chemical Machining is often used as an alternative to the cavity type electric discharge machining (EDM).

(d) Fabrication of thin-walled parts: Electrochemical machining does not produce surface stress in the work piece therefore even very brittle and easily deformed materials may be machined in thin-walled shapes.
(e) Grinding of a work piece by a rotating wheel, which performs grinding operation through an electrolyte. The wheel is conductive and catholically connected. Non-conductive hard particles are set on the wheel surface. The particles provide a constant gap through which an electrolyte is continuously fed. Hard and brittle materials are ground by the method.
(f) Rough corners or edges can be turned into very smooth parts and the process is known as deburring.

Surface roughness values obtained ranging 0.2–12.5 µm Ra. Dependent on current density and material being machined. According to De-Silva and Altena, (2002) the recovery of the gap conditions during pulse-off times was enables with pulsed ECM which improved dissolution efficiency. Resulted in smaller inter-electrode gaps (<150µm), without the· risk of electrolyte boiling, therefore yield improved dimensional accuracy of the order of 0.05 mm. Furthermore, they developed graphical models to visualize quickly the dimensional accuracy better than 5 µm and surface finish better than 0.03µm Ra.

At present, WECM is still a lab-based study. However, more application-based research can be carried out for the fabrication of critical components such as surgical blades, micro-pin-fin heat exchangers, tooth implant screw threads, small crankshaft, etc. with low energy consumption, high surface finish, and no surface defects (Sharma et al., 2020). As there is no burr formation in electrochemical dissolution, WECM can be used to generate sharp cutting edges on surgical tools (Figure 3). The process can also be used for generating periodic patterns on thin-walled tubes and their selective thinning WECM can prove to be an inexpensive way of micro-turning as diamond-tip tool inserts, generally used in micro turning, are relatively expensive. Another application of WECM in turning can be in machining micro threads on dental implants (Figure 4). Since wire with very small diameter can be used in the process, this process is suitable for internal finishing of tubes with small internal diameter. The process can also be used for making internal gears and internal fins for heat pipes. Electrostatic comb-drive actuators (Figure 5) used in micro-electromechanical system (MEMS) can be machined using WECM to replace the conventional lithography method which is time consuming.

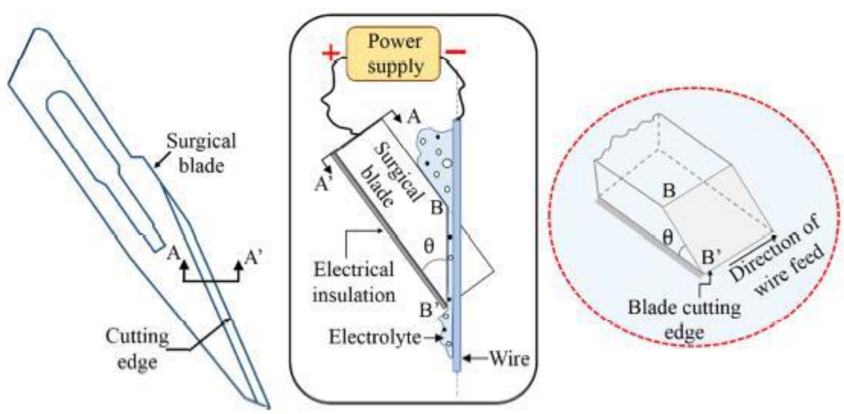

Figure 3: Schematic diagram of preparing sharp cutting edge of surgical instruments (Sharma et al., 2020).

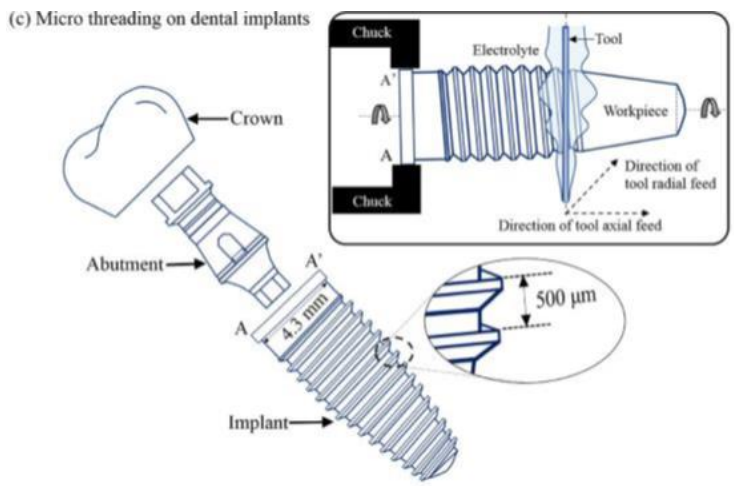

Figure 4: Schematic diagram of micro threading on dental implants (Sharma et al., 2020).

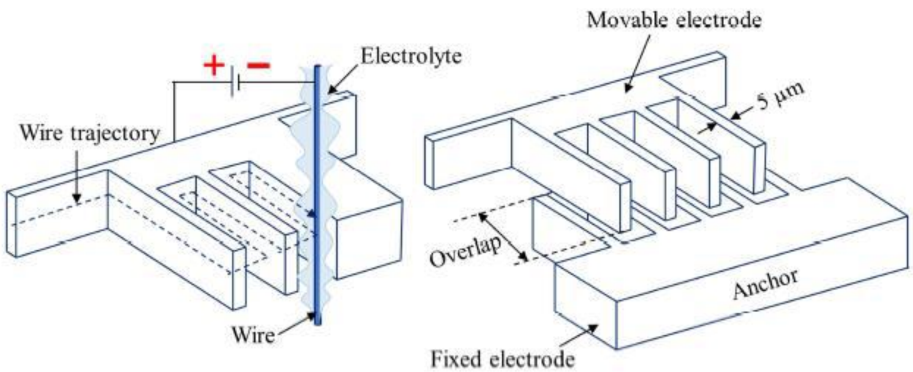

Figure 5: Schematic diagram of machining of comb-drive actuator used in MEMS (Sharma et al., 2020).

In addition to the above application, WECM is also used to remove the recast layer and reduce the WEDM surface roughness, which was proposed by Wu et al., (2019). This method was called as WEDCM.

According to Wu et al., (2019), two factors, which have a great influence on the surface roughness, namely the feed rate of the wire electrode and the movement distance of the workpiece, were analysed and found that the recast layer and craters on the WEDM surface can be dissolved owing to the anodic dissolution of WECM, and the surface quality can be improved. Study done by Zhu et al., (2020) found the roughness of the slit side wall is mainly determined by secondary velocity. The roughness increases fast with secondary velocity and a smoother surface can be obtained when the initial velocity is close to the secondary velocity. The best surface roughness is 0.110 µm. Ra of between 0.1-0.4 µm were achieved of slit side walls using different initial and secondary velocities of 50 and 50 $\mu m \cdot s^{-1}$, 50 and 500 $\mu m \cdot s^{-1}$, 25 and 50 $\mu m \cdot s^{-1}$, 10 and 50 $\mu m \cdot s^{-1}$.

Electro-chemical machining is also one of the techniques commonly applied for surface texture fabrication (Mahayuddin et al. 2020). Benefit of surface texturing has been explained in detailed by Ahmad et al. (2020) and Ab. Latiff et al. (2019).

5.0 APPLICATION OF FUZZY LOGIC (FL) IN ECM

According to Mohd Adnan et al., (2013), fuzzy logic (FL) is capable to converse, reason and make rational decisions in an environment of imperfect information. FL involves fuzzifier process, rules, membership function, and defuzzification. Fuzzier process is the process of transforming fuzzy set data into suitable linguistic values by the definition of linguistic variables the types of membership function (MF), which defines the way of input being mapped to a membership value. Fuzzy rules are set of linguistic statements which establish the relationship between the input and the output in a fuzzy system. Fuzzy rule is obtained based on experimental work and knowledge. Defuzzification will be used to generate a non-fuzzy decision.

FL has been widely used in machining due to their similar features in input and output (Mohd et al., 2013). FL is said to be able to implement in machining as the input of FL in machining can be indicated as different types of machining parameter while output of FL can represent the machining performance. FL has been used for various purpose in machining. Some researchers have used FL to determine the output of machining (Balasubramanian et al., 2016; Hossain et al., 2016; Mohamad et al., 2010). Besides, some of the researchers implemented FL into machining to investigate the applicable of controlling the machining performance through FL (Sadegh, 2017; Labib et al., 2011). There were also researchers tried to implement FL to obtain the optimum machining parameters (Chakraborty et al., 2018; Teimouri & Sohrabpoor, 2013).

A study was done using the adaptive neuro-fuzzy inference systems (ANFIS) and the cuckoo optimization algorithm (COA) to predict the influences of machining parameters in ECM and the optimum parameters for certain MRR and Ra (Teimouri & Sohrabpoor, 2013). ANFIS is a hybrid predictive approach that uses both meanings of neural network and fuzzy logic for modeling complex processes in which many inputs are contributed, and the amount of experimental data are small. According to the authors, the results obtained had a high prediction accuracy. Optimization of ECM was also done using ANFIS, COA, and principal component analysis (PCA) (Sohrabpoor et al., 2016). ANFIS was used to construct the objective function while PCA was used to determine the weight factor of the objective function. COA was then being used to perform the multi-objective optimization.

A study was done for optimization of ECM process parameter using hybrid fuzzy-Artificial Bee Colony algorithm (Fuzzy-ABC) (Solaiyappana *et al.,* 2014). In this study, fuzzy logic was integrated with artificial bee colony algorithm (ABC) to predict the optimum parameters that satisfy the real requirement of ECM. ABC is implemented by converting the considered optimization problem to the problem of finding the best parameter vector that will minimize an objective function. Then, the algorithm randomly discovers a population of initial solution vectors and then iteratively improve them by moving towards better solutions by means of a neighbor search mechanism while abandoning poor solutions. When compared with other algorithm, ABC is a new evolutionary computational technique that provides better results.

In 2018, a study was done to integrate Grey Relational Analysis (GRA) with FL for parametric optimization (Chakraborty *et al.,* 2018). In this study, the authors had integrated GRA with FL to determine the optimal parametric combinations of abrasive water-jet machining, ultrasonic machining, and ECM. GRA is potential to deal with incomplete and uncertain data. In GRA, the uncertain relations between one main factor and all other factors in a system are analyzed. It measures the absolute value of the data difference between sequences and can predict the approximate grade of correlation between the sequences. When there is lacking data, it helps to compensate for the shortcomings in statistical regression.

6.0 CONCLUSION

The working principle and application of ECM and related processes are presented. Complicated shapes parts with high material removal rate and good surface quality can be achieved using ECM process. The development of a new technology WECM is the process for the future. It is a promising technique for micromachining for fabrication of critical components with the thermal and mechanical properties of parent material is not altered after the machining process. In the recent development, WECM is used for the machining of cylindrical workpieces which suitable for turning a very thin-walled tubes, which is difficult to perform using a conventional machining method. The ECM performance can be improved by combining with other processes such as MAF and Jet-ECM. The recent developments of FL by integrating different algorithm into FL also show a promising future of ECM as most of the results are accurate and reliable after being tested.

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