Chapter 8
Electrochemical Micromachining (EMM): Fundamentals and Applications

V. Rathod, B. Doloi and B. Bhattacharyya

Abstract Product miniaturization is the principal driving force for 21st century's industries because of the escalating demands for compact, intelligent, robust, multi-functional, and low cost products in all fields. As demand of miniaturized products is exponentially increasing, the need to manufacture such products from advanced engineering materials becomes more apparent. Micromachining plays significant role in miniaturization, and consist of machining different microfeatures on products. Design of microtools, tool wear, surface quality, burr and heat removal are the main challenges in various micromachining methods. Electrochemical micromachining is one of the important techniques because of its special material removal mechanism, better precision and control, environmentally acceptable, and mainly it permits machining of any metallic materials irrespective of its hardness. For better understanding of EMM process, the basic concepts such as electrochemistry, Faraday's laws of electrolysis, electrical double layer, equivalent electrical circuit, and material removal mechanism have been discussed. Significant process parameters which affect the process performance, need of EMM setup development, various subsystems, along with the challenges in setup developments, and important techniques for improving the machining accuracy have been highlighted. Machining, finishing, and surface engineering applications of EMM, as well as recent advancement in EMM for micro and nanofabrication have also been discussed.

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8.1 Introduction

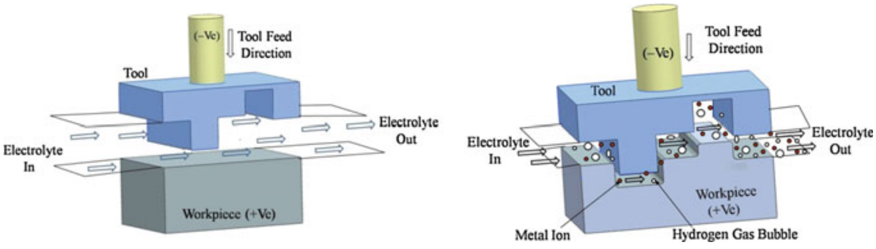
Material removal as a means of making things dates back to prehistoric times, when ancient man started to carve wood and chip stones to make the hunting and farming tools. Human beings shaped copper by casting for metal and jewelry work before 5000 BC. Invention of copper, bronze and then iron age revolutionized the ancient civilizations. Development of modern machine tools is closely related to the Industrial revolution. Introduction of hard, temperature resistant materials in various fields of application led to the development of various non-conventional machining processes. The non-traditional processes have been developed since World War II, in response to new and unusual manufacturing requirements such as machining of complex part geometries with close tolerances, without any surface damage that could not be realized by conventional methods. There are various non-traditional machining processes, most of which are unique in their range of applications. Electrochemical machining (ECM) is one of the important non-conventional machining processes used for machining of extremely hard alloys, which cannot be machined satisfactorily by conventional methods. The metal removal phenomenon of controlled anodic dissolution was known early in 20th century, but it was until the 1960s that ECM came into use as a practical machining method. In last decades, ECM has been developed, and anodic dissolution can be effectively utilized for high-precision ultrafine machining to generate macro-as well as micro features on work pieces, due to its advantages like no tool wear, ability to machine any metallic surfaces irrespective of its hardness, stress/burr free surfaces, high MRR and accuracy, and capability to machine irregular 3D shapes.

Miniaturization is the principal driving force for 21st century's developments because of the escalating demands for compact, intelligent, robust, multi-functional, and low cost industrial products. As the demand of micro and nano products is exponentially increasing, the need to manufacture micro and nano products from advanced engineering materials becomes more apparent. Advanced micro machining may consist of machining different micro features on micro or macro work pieces. Micro features such as micro holes, micro slots, microgrooves, thin walls etc. are to be machined on different surfaces of a product to fulfill its functional requirements. Design of microtools and micro fixtures, tool wear, lack of tool rigidity, poor surface finish, scrap and heat removal etc. are the main challenges, when these micro features are machined with traditional machining techniques.

8.2 Electrochemical Machining (ECM): Basic Process

The principle of ECM was discovered long back in the nineteenth century by Michael Faraday (1791–1867). Faraday established the laws of electrolysis in 1833, which is the foundation of both the better-known electro deposition and electro dissolution techniques. In 1929, the Russian researcher W. Gussef first developed a process to machine metal anodically through electrolytic process. The significant developments in ECM occurred in the 1950s, when ECM was investigated as a method for shaping high-strength alloys. In 1959, Anocut Engineering, Chicago established the anodic metal machining techniques for commercial applications. In 1960s and 1970s the technique was applied mainly for machining of large components made of advanced and difficult-to-cut metals particularly in the gas turbine, aircraft and aerospace industries for shaping, finishing, deburring, and milling operations. Although ECM was initially developed to machine the hard-to-machine alloys, any metal can also be machined, only from the 1990s ECM was employed in applications such as automotive, biomedical, and aerospace firms, which are its major user until now.

Manufacturing processes such as electroplating, electro polishing, and other allied processes that are well established in the manufacturing industries were initiated from the basic concept of Faraday's laws. The basic mechanism of metal removal in ECM is based upon the electrolysis, in which metals are liberated from anode workpiece surface atom by atom. ECM is an anodic dissolution process in which work piece as anode and shaped tool as cathode are placed very close to each other and immersed in an electrolyte tank. When potential is applied across the electrodes, the work piece material dissolves locally so that the shape of the generated work piece is approximately negative mirror image of the tool, as shown in Fig. 8.1. The electrolyte, which is generally a concentrated salt solution, is pumped at high velocities through the machining gap in order to remove the reaction products and to dissipate the heat generated. The smaller the machining gap between preshaped tool and workpiece surface, the greater will be the current flow and rate of metal removal from the anode. It also promotes rapid generation of metal hydroxide and gas bubbles in the small gap between the electrodes and becomes a barrier to the current flow and further machining. Hence, for the continuation of the dissolution process, these products of the machining process are to be removed by circulating electrolyte at a high velocity through the gap between the electrodes. The initial gap increases in size as metal ions are removed from the anode, which increases the electrical resistance across the gap and in turn reduces the current flow. To maintain the initial current flow and rate of metal removal, the



(a) Before machining (b) After machining

Fig. 8.1 Schematics of ECM process

gap between the electrodes should be maintained uniform by advancing the cathode toward the anode at the same rate at which the metal is being dissolved. As the cathode tool advances during machining operations the anode workpiece gradually attains a shape that is almost a replica of the cathode tool.

Controlled metallic dissolution with high accuracy is required to put the ECM technique in industry for practical applications. For this purpose the ECM setup needs electrical power source to supply the machining current to the electrodes, arrangement to circulate an electrolyte in the machining gap, and mechanical structure for regulating the tool movement towards the workpiece. In ECM, dissolution rate of anodic surface depends upon the machining current, machining time, atomic weight of the workpiece metal, and valency of the ion produced, whereas it does not depends on the hardness of material. Various process parameters such as applied voltage, machining current, electrolyte type, concentration, flow rate, and inter electrode gap (IEG) influences the major ECM machining criteria like metal removal rate, surface finish, and accuracy. The shape of the tool remains unchanged during machining, since only hydrogen gas is evolved at the cathode surface [1]. Significant technological development such as tool vibration, pulsed machining current, electrolyte microfiltration, CNC controller and application of computer aided design to predict cathode tool profiles, for improving machining accuracy and waste disposal make today's ECM technique a better choice than many other conventional as well as non-conventional machining techniques.

8.3 Electrochemical Micromachining (EMM): Focusing Area

Product miniaturization with integrated functions is the recent trend in manufacturing industries due to the multiple benefits of microproducts such as less space, light weight, less material and less energy consumption, and low cost of production etc. Microproducts has to perform multiple functions in adverse service conditions, which necessitates the micro components to be made from advanced engineering materials like super alloys, titanium, nickel, aluminum alloys, copper alloys, and stainless steel, which are hard and difficult to cut by conventional machining methods. With the development in MEMS, micro products are widely used in various fields namely electronics, aerospace, optical, biomedical, automotive, refrigeration and air conditioning etc. for fabrication of micro products like inertia sensor for air bag deployment systems in automobiles, read-write heads in computer storage systems, nozzles of ink jet printers, bio-medical filters, micro robots, micro reactors, micro pumps, micro fuel cells, and ultra precision machinery parts, etc. Different micromachining methods are available to machine the micro features on macro or micro sized components on advanced engineering materials, which can be selected based on the number of criteria's such as required machining accuracy, surface finish, type of workpiece material, production rate, and cost of production [2].

8.3.1 ECM and EMM

The term micromachining refers to the material removal of smaller dimensions ranging from 1 to 999 μm. When ECM is applied for machining of micro features in microscopic domain, it is called as Electrochemical Micromachining (EMM) [2]. EMM is an anodic dissolution process in which high frequency pulsed direct current with low voltage is applied between the metallic workpiece as anode and microtool as cathode, immersed in an electrolyte with few microns of inter-electrode gap. The anodic material dissolves into metallic ions by the electrochemical reactions generating hydrogen gas bubbles on the cathode surface. Micro features of the micro tool electrode such as shape, size and surface finish are directly transferred to the work surface, hence micro tool electrodes plays a vital role during machining of micro features by EMM. EMM is similar to the ECM in all respect, whereas these processes can be compared with each other on the basis of range of major machining characteristics as given in Table 8.1.

Table 8.1 Comparison between ECM and EMM [3]

Major machining characteristics	Electrochemical machining (ECM)	Electrochemical micromachining (EMM)
Voltage	10–30 V	1–12 V
Current density	20–200 A/cm^2	75–100 A/cm^2
Power supply	Continuous/pulsed	Pulsed
Electrolyte flow	10–60 m/s	<3 m/s
Electrolyte type	Natural salt solution	Natural or dilute acid/alkali
Electrolyte temperature	24–65 °C	37–50 °C
Electrolyte concentration	>20 g/l	<20 g/l
Size of the tool	Large to medium	Micro
Inter electrode gap	100–600 μm	5–50 μm
Operation type	Maskless	Mask/maskless
Machining rate	0.2–10 mm/min	5 μm/min
Side gap	>20 μm	<10 μm
Accuracy	±0.02–0.1 mm	±0.01 mm
Surface finish	Good, 0.1–1.5 μm	Excellent, 0.05–0.4 μm
Problems due to waste disposal/toxicity	Low	Low to moderate

8.3.2 Advantages and Limitations of EMM

The EMM process has numerous advantages and some limitations which can be categorized by product, material and machine advantages.

(a) Product Advantages
The EMM has the following advantages on the final product:

(i) Burrs free surfaces are machined by EMM.
(ii) In EMM, micro tool does not touch the workpiece surface, hence it does not cause thermal or physical strain in the product. Also, the upper layer of the workpiece surface is free from any deformations.
(iii) By designing a single tool cathode or adopting suitable microtool movement strategies, free formed 3-dimensional micro features can be processed in single step. Use of EMM techniques permits more freedom of design a micro product.
(iv) By adopting the advanced process monitoring capabilities, high dimensional accuracy and high surface quality ($R_a < 0.05$ μm) can be attained with EMM.

(b) Material Advantages

In EMM, the rate of anodic dissolution i.e. rate of machining depends only upon the atomic weight (A) and valency (z) of ions produced, the machining current passed through the electrodes, and the time (t) for which the current passes. The mechanical properties of metal such as hardness, and toughness, as well as thermal conductivity do not influence the material removal rate. The process has a complete freedom of machining the product before or after hardening step. Material removal rate is higher in comparison to the competing micromachining techniques and can be controlled by selecting appropriate process parameters.

(c) Machine Advantages
The EMM process has following advantages over other micro machining processes

(i) Initial investment on process design and micro tool fabrication is low. Also the, running cost and tooling costs are low.
(ii) The shape of the microtool remains unchanged during machining, since only the hydrogen gas is evolved at cathode microtool surface during electrolysis. Hence microtools of complicated shapes can be reused multiple times.
(iii) EMM is a process with high machining speed and relatively low cost.

(d) General Limitations

Although ECM process has following disadvantages:

(i) ECM was previously known as process that harms environment. After thorough developments in the treatment of electrolytes, the process has become less harmful to the environment. However, EMM also needs very less volume of electrolyte.
(ii) Each micro product and material requires new research. So, higher production numbers are essential for the cost effectiveness of the process.
(iii) Needs careful handling of micro tools with in situ fabrication.
(iv) EMM requires a relatively high knowledge base for operation.

8.3.3 Role of EMM in Micromachining

Micromachining is an application of specific techniques to produce micro features on macro or micro sized components with high precision and close geometrical tolerances. Micromachining technology will be an important technology in the future, since the miniaturization will continue as long as people require effective space utilization with more efficient and accurate products. Therefore attention needs to be given for further developments in traditional as well as non-traditional micro machining techniques to improve the machining precision. Machining of advanced engineering materials needs suitable micro machining techniques for the fabrication of precise and accurate micro features on products. Traditional micromachining techniques such as micro turning, micro grinding, and micro milling have dimensional limitations for the cutting tools and fixtures, high tool wear, and poor surface quality. Whereas, non-traditional micro machining methods like EDM and LBM are thermal based, and results tool wear and heat affected zone respectively. LIGA process is limited to the fabrication of 2D micro structures and chemical machining process cannot be controlled properly in micromachining domain [4]. Hence, EMM is the most suitable method for machining of micro features on difficult to cut metals because of its important benefits like better precision and control, good surface quality without affecting metallic properties of work piece irrespective of the hardness of the material, no residual stress, no heat affected zone, and no tool wear i.e. complex microtools can be used repeatedly for longer period of time [5].

8.4 Fundamentals of EMM

EMM is the application of basic ECM in microscopic domain for micromachining applications. Basically it is anodic dissolution process in which, workpiece as anode and microtool as cathode are submerged in an electrolyte with narrow inter-electrode gap, and low voltage pulsed direct current is applied in between the electrodes. The workpiece material dissolves into metallic ions by the electrochemical reactions according to Faraday's law of electrolysis. The dissolved material and other process by-products such as precipitates, sludge, hydrogen gas etc. are carried away from narrow machining zone by the electrolyte. The final shape, and size of the machined micro feature is approximately negative mirror image of the microtool electrode. Machining accuracy depends on different machining conditions in the narrow machining zone. Machining criteria like material removal rate, machined surface characteristics, and machining accuracy are influenced by the process parameters such as pulse amplitude i.e. applied voltage, pulse frequency, duty ratio, machining current, electrolyte type and its concentration, inter-electrode gap and tool feed rate etc. [6].

8.4.1 Electrochemistry of EMM

The chemical process which occurs when an electric current is passed between the two conductors immersed into electrolytic liquid solution is known as 'Electrolysis'. The metallic conductors immersed in liquid solution are termed as 'electrodes'. The electrode with positive polarity is called as 'anode' and the electrode with negative polarity is called as 'cathode'. Electrodes conduct electrical current by the movement of electrons. The liquid solution in which electrodes are immersed, and also conducts electricity through it is known as 'electrolyte'. The system of electrodes and electrolytes is called as 'electrochemical cell'. The reactions which occur at anode and cathode are called as 'anodic reaction' and 'cathodic reaction' respectively. Electrolytes carry electrical current by the movement of atoms or group of atoms, which have either lost or gained electrons, thus acquiring either positive or negative charge. Such atoms are called as 'ions'. Ions which carry positive charges and moves through an electrolyte towards cathode are known as 'cations'. Similarly, the negatively charged ions which move towards the anode are known as 'anions' [7].

When small electric current (DC) is applied across the workpiece as anode and the microtool as cathode, submerged in an electrolyte with very small inter-electrode gap, the transfer of electrons between ions and electrodes completes the electric circuit. Since the electrons cannot flow through the electrolyte, the electric current is maintained by the removal of electrons from the atomic structure of the workpiece, i.e. the current is carried by the ions. The metal material dissolves atom by atom from anodic surface and enters into the electrolyte as positive ions. The positively charged ions move through the electrolyte towards the cathode and the negatively charged ions travel towards the anode as shown in Fig. 8.2. The movement of ions is accompanied by the flow of electrons in the opposite sense outside cell and both the actions are a consequence of the applied potential difference. The least strongly bounded electrons are found at the surface of the

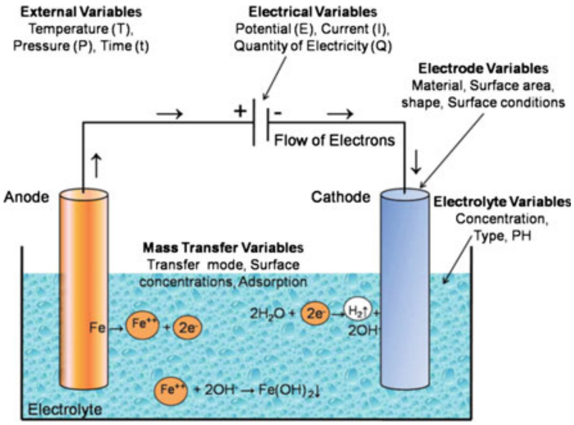


Fig. 8.2 Principle of anodic dissolution of metal

workpiece and flow into the electrolyte circuit. These electrons dissociate themselves from the workpiece and flow into the electric circuit.

In electrochemical machining, dissolved metal appears as precipitated solid of metal hydroxides. Chemical reactions occur at the cathode, and anode in the electrolyte. At cathode i.e. microtool, the reaction having the smallest oxidation potential takes place, and at anode i.e. the workpiece, the reaction having the largest oxidation potential occurs first. Hence, the factors such as (i) nature of metal being machined, (ii) type of electrolyte, (iii) current density and, (iv) temperature of electrolyte influences the oxidation potential and thus determine the kind of reaction that will occur. Different variables as shown in Fig. 8.2, also affects the rate of electrochemical reaction. The material removal in electrochemical reactions are governed by (i) electrical variables such as an applied potential, and quantity of electricity passed i.e. machining current passed for machining time, (ii) electrolyte variables like type of electrolyte, its concentration, pH, and temperature of electrolyte, (iii) mass transfer variables i.e. different modes of mass transfer such as diffusion, convection, surface concentrations and adsorption, (iv) electrode variables namely electrode material, surface area, surface conditions and geometry of electrode, (v) External variables such as room temp., pressure and machining time.

The electrochemical reactions taking place at cathode and anode during machining are as follows [8].

8.4.1.1 Cathode Reactions

Two possible reactions occurring at cathode are:

(i) Evolution of hydrogen gas,
(ii) Neutralization of positively charged metal ions.

The reactions causing the evolution of hydrogen gas at the cathode are:

$$2H^{+} + 2e^{-} \rightarrow H_2 \uparrow \text{ (for acidic electrolyte)} \tag{8.1}$$

$$2H_2O + 2e^{-} \rightarrow H_2 \uparrow \text{ (for alkaline electrolyte)} \tag{8.2}$$

The neutralization of positively charged metal ion is caused by the reaction:

$$M^{+} + e^{-} \rightarrow M \text{ (Metal)} \tag{8.3}$$

For example, when the workpiece is iron, the cathode reactions are:

$$Fe - 2e \rightarrow 2Fe^{2+} \tag{8.4}$$

$$2Fe^{2+} + 2OH^{-} \rightarrow Fe\ (OH)_2 \tag{8.5}$$

Metal ions form the metal hydroxides when neutral electrolytes are used. They appear as solid precipitates since these are insoluble in water. These precipitates do not affect the electrochemical reaction.

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2 \uparrow \tag{8.6}$$

Ferrous oxide may further react with water and oxygen to form ferric hydroxide such as:

$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3 \downarrow \tag{8.7}$$

8.4.1.2 Anode Reactions

At anode also two possible reactions are occurring

(i) Evolution of oxygen or halogen gas,
(ii) Dissolution of metal ions.

The reactions leading to the evolution of oxygen gas are as follows:

$$2H_2O \rightarrow O_2 \uparrow + 2H^{+} + 2e^{-} \text{ (for acidic electrolyte)} \tag{8.8}$$

$$4(OH)^{-} \rightarrow 2H_2O + O_2 \uparrow + 4e^{-} \text{ (for alkaline electrolyte)} \tag{8.9}$$

The reaction leading to the dissolution of the metal

$$M \rightarrow M^{+} + e^{-} \tag{8.10}$$

$$\mathrm{M^+ + (OH)^- \rightarrow M(OH)} \tag{8.11}$$

The overall reactions occurring during ECM of iron can be given as:

$$\text{Anode: } \mathrm{Fe \rightarrow Fe^{++} + 2e^-} \tag{8.12}$$

$$\text{Cathode: } \mathrm{2H_2O + 2e^- \rightarrow 2(OH)^- + H_2 \uparrow} \tag{8.13}$$

It has been observed that, the metal dissolution is the main or the only reaction that occurs at the anode, and the electrolyte acts as carrier of current only. The current efficiency, which is the ratio of the amount of dissolved metal to the amount that should be dissolved according to Faraday's law for the known current and time, is often lower than 100%. This is because apart from the dissolution of the metal, other anode reactions can occur, such as the oxidation of water, with the release of oxygen gas:

$$\mathrm{2H_2O \rightarrow 4H^+ + O_2 \uparrow\ +\ 4e} \tag{8.14}$$

The extent to which this reaction lowers the current efficiency depends greatly on the material of the workpiece, the electrolyte and the current density. Besides the oxidation of water further oxidation of metal ions can also occur at the anode.

8.4.2 Faraday's Law of Electrolysis

Michael Faraday introduced two fundamental laws of electrolysis in 1934, which governed the phenomenon of electrolysis. The most common statements of Faraday's law resemble as the following:

(i) The mass of any substance deposited or dissolved at an electrode during electrolysis is directly proportional to the amount of electricity passed through electrode. Quantity of electricity refers to the electrical charge, and typically measured in coulombs.
(ii) The amounts of different substances deposited or dissolved by the same quantity of electricity at an electrode is directly proportional to chemical equivalent weights.

Mathematically these two laws can be combined to give mass (m) removed from electrode or deposited upon the electrode, as:

$$m = \left(\frac{Q}{F}\right)\left(\frac{M}{z}\right) \tag{8.15}$$

where, *'Q'* is the total electric charge passed through the metallic material, *'F'* is Faraday's constant (96.485 C/mol), *'M'* is the atomic weight of the substance, *'z'* is the valancy number of the substance (electrons transferred per ion), and *(M/z)* is the chemical equivalent weight of the substance altered. As per Faraday's first and second law, Q, M, F, and z are the constants hence larger value of Q, as well as chemical equivalent weight of metal implies higher mass of material removal.

For constant current electrolysis, total electric charge passed through the metallic material can be given as:

$$Q = I.t \tag{8.16}$$

where, 'I' is the current passed through the electrodes for time 't'Therefore, amount mass removed (m) can be given as

$$m = \left(\frac{I.t}{F}\right)\left(\frac{M}{z}\right) \tag{8.17}$$

When the product $(I.t)$ is unity i.e. one coulomb charge is passed through the electrodes, the mass of material removed $(M/z.F)$ is known as 'electrochemical equivalent of the metal'. From above equations, it can be concluded that rate of anodic dissolution depends upon atomic weight, valency of the ions produced, the current, and the time for which the current is passed. The metallic dissolution rate is not influenced by the hardness or any other mechanical properties of metal. During the electrochemical reaction only hydrogen gas is evolved at the cathode surface, hence the shape of cathode tool remains unchanged i.e. no tool wear takes place. This feature is very much useful during machining of complex micro features with micron sized tools in EMM applications.

8.4.3 Electrical Double Layer

When the metallic electrode is placed in electrolyte, an equilibrium potential difference is established between the metal electrode and electrolyte solution. This potential difference arises due to the transfer of metallic ions into the electrolyte from the metal electrode, and the simultaneous discharge of ions from the electrolyte at the electrode surface. Equilibrium is established when the electrons left in the metal contribute to the formation of a layer of ions whose charge is equal and opposite to that of the cations in solution at the interface. The negative charges of electrons just inside the metal electrode and positive charges of cations just outside the electrode surface in the electrolyte solution forms an array of positive and negative charges, as shown in Fig. 8.3, and is known as 'electrical double layer' [9]. The solution side of the double layer consists of several layers. The inner layer, which is closest to the electrode consist of solvent and other ions, known as specifically adsorbed ions. This inner layer is compact, called as Helmholtz layer, and locus of the electrical centers of this inner layer is called 'Inner Helmholtz plane (IHP)'. The locus of the centers of the nearest solvated ion is called as 'Outer Helmholtz plane (OHP)'. The interaction of solvated ion with metal electrode

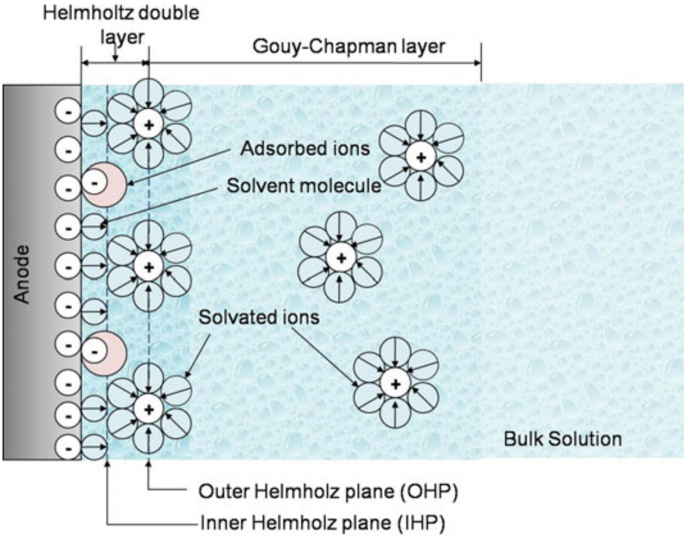


Fig. 8.3 Schematics of electrical double layer

involves only electro-static force and independent of the chemical properties of the ions. These ions are called as non-specifically adsorbed ions. These ions are distributed in three dimensional region called as diffusion layer or Gouy-Chapman layer and its thickness depends on ionic concentration in the electrolyte. The bulk electrolyte with its usual properties is located outside the Gouy-Chapman layer. The structure of the double layer affects the rate of electrode reactions. The transfer of ions will cease, when the energy required for an ion to dissolve is less than the work necessary to pass it across the double layer. The excess charge stored on both sides of the double layer depends on the electrode potential and acts like the charged plates of capacitor separated by very small distance. Therefore, double layers at the electrode-electrolyte interface can be represented by a capacitor in equivalent circuits and the interfacial capacity can be described as two capacitors in series. The resulting potential drop across the interface due to this capacitance is termed as 'double-layer potential'.

8.4.4 Equivalent Electrical Circuit

In EMM, workpiece as anode and microtool as cathode are immersed in electrolyte with very small inter-electrode gap and connected to the DC power source. The inter-electrode gap filled up with electrolyte, acts as resistance to the flow of

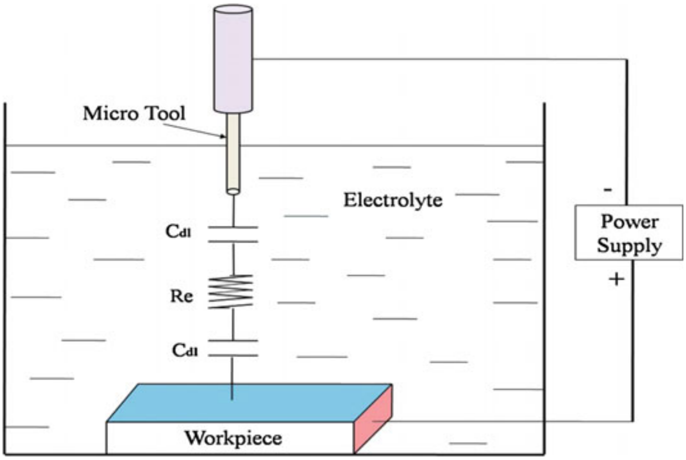


Fig. 8.4 Equivalent electrical circuit of EMM

current, and the double layers which form at electrode-electrolyte interfaces which act as capacitors.

Hence the electrodes i.e. anode and cathode, immersed in the electrolyte can be represented by the basic analogous equivalent R-C circuit as shown in Fig. 8.4, which consist of two capacitors (C_{dl}) representing double layers at both the electrode-electrolyte interfaces and resistance of the electrolyte (R_e) in between two electrodes.

At metal-electrolyte interface, the metal molecule dissolves into the elecrolyte. In the forward reaction, electrons enter the metal and metal ions diffuse into the electrolyte, called as 'charge transfer'. Whereas in backward reaction, metal ions are discharged to metal, and thus equilibrium condition is reached. For the dissolution of anodic metal, the reaction must be in the forward direction only i.e. irreversible. The resistance involved in irreversible reaction is called 'charge transfer resistance'. The electrolyte flow velocity is negligible or stagnant electrolyte is preferable in the case of EMM. So there is not sufficient transfer of mass from one electrode to the other electrode due to convection. This gives rise to another diffusion component called Warburg Impedance (R_w). Faradic reaction consists of an active charge transfer resistance (R_{ct}) and Warburg resistance. In EMM, the equivalent electrolyte resistance can be represented by considering the effect of flow of current from the lateral and longitudinal surfaces of the microtool to the workpiece. The inter-electrode gap in case of EMM is very small, hence current flow path is small across the front end of the microtool, and this electrolyte resistance is represented by R_{bottom}. Path of current flow from longitudinal surface of the microtool to the workpiece surface is much longer and this electrolyte resistance is represented by R_{side}. Therefore by considering the flow of a current along lateral and longitudinal surfaces of the microtool, their respective electrolyte

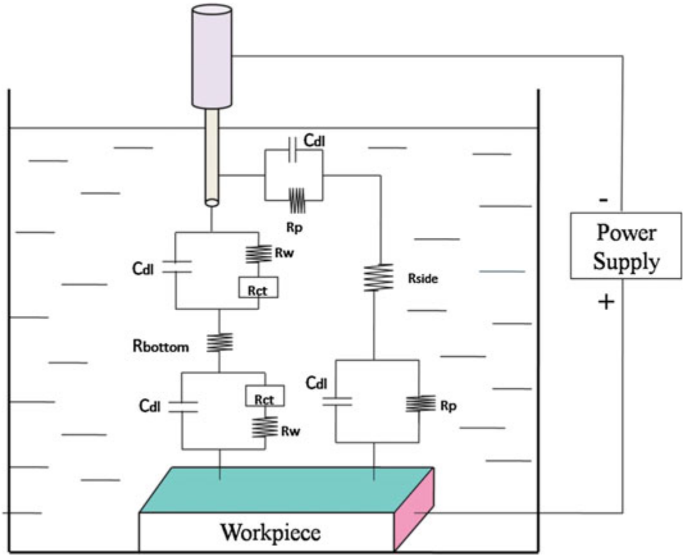


Fig. 8.5 Modified equivalent electrical circuit of EMM

resistances, and polarized resistance (R_p), the equivalent circuit of EMM can be modified as shown in Fig. 8.5 [10].

8.5 Material Removal Mechanism in EMM

In EMM, ultra short pulses of very low voltage amplitude are applied between the electrodes which are separated by very narrow machining gap. At narrow machining zone, in addition to the electrolyte resistance, other resistances which are not so prominent in conventional ECM have much more influence in EMM. Hence, all of these resistances at machining zone need to be considered in electrical circuit model of EMM. The inter-electrode gap electrolyte resistance in EMM is given as:

$$R = \frac{\rho_s . h}{A} \tag{8.18}$$

where, 'ρ_s' is specific resistance or resistivity of electrolyte, 'A' is active micro electrode surface area which is taking part in machining, and 'h' is inter-electrode gap. Faraday's two laws of electrolysis can be combined to predict the volume of material removed during electrochemical micromachining as:

$$V_m = \frac{\eta.M.I.t}{z.F.\rho_w} \tag{8.19}$$

where, *'M'* is the atomic weight of the material dissolved, *'I'* is the amount of current passed through the electrode, for machining time *'t'*, 'ρ_w' is the density of workpiece material, and 'η' is the dissolution efficiency or current efficiency. The current efficiency is defined as the ratio of the actual amount of metal dissolved to the theoretical amount as predicted by Faraday's laws. The material removal rate or unit removal in electrochemical reaction basically depends on the following factors [11]:

(i) Anodic reaction and current efficiency,
(ii) Mass transport and controlled anodic dissolution, and
(iii) Current distribution and shape evolution.

(i) Anodic reaction and current efficiency

Based upon the various machining conditions and electrode-electrolyte combinations, different anodic reactions take place. Rate of these reactions depends upon the ability of the electrochemical cell to remove the reaction products as soon as they are formed, and supply of fresh electrolyte at machining zone. All of these factors influence the machining performance namely dissolution rate, shape control and surface finish of the workpiece. The current efficiency (η) of the metal dissolution is related to the weight loss (∇w), which is given as:

$$\eta = \frac{\nabla w.z.F}{I.t.M} \tag{8.20}$$

where, *'z'* is the valency of metal dissolved, *'F'* is Faraday's constant, *'I'* is machining current, *'t'* is machining time, and *'M'* is atomic weight of the metal.

Current efficiency for metal dissolution is the function of current density and local flow conditions, and varies as a function of distance from the tool. Though current efficiency is a commonly used factor in ECM, a more accurate evaluation of the process requires an estimate of electrical power efficiency. Power efficiency is the ratio between output power and input power of a device. Conductivity of electrolyte increases with the increase of temperature. Hence, for the same operating condition power requirements decreases and power efficiency increases.

(ii) Mass transport and controlled anodic dissolution

Electrolyte with negligible flow velocity or almost stagnant electrolyte is utilized in the case of EMM. Therefore, mass transport plays significant role in shaping and surface finishing of anode in dissolution process. Rate of electrochemical reactions at electrode surfaces are mainly influenced by the current passing through the electrodes, and also depends on mass transport, various surface effects, and kinetic variables. Current distribution and machining accuracy may get affected by mass transport conditions. The simplest electrode reactions are those in which the rates of all associated chemical reactions are faster as compared to those of the mass-transfer processes.

The mass transfer is the movement of material from one location to another, in electrolytic solution, and is achieved through the different modes as follows:

(a) Migration is the movement of a charged body under the influence of an electric field (electrical potential gradient).
(b) Diffusion is the movement of a species under the influence of a gradient of chemical potential (i.e. a concentration gradient).
(c) Convection is related to hydrodynamic transport. Generally fluid flow occurs because of natural convection i.e. convection caused by density gradients, and forced convection, and may be characterized by stagnant regions, laminar flow, and turbulent flow.

In EMM, smooth surface finish can be achieved only at limiting current density. An increase in current density leads to increase in the rate of metal dissolution at the anode. If the current density is too high, it may cause heating effect due to rise in temperature and it finally results improper surface finish and accuracy. The limiting current density is controlled by convective mass transfer, the anodic limiting current density 'J' is given by

$$J = \frac{v.F.D.C_{sat}}{\delta} \tag{8.21}$$

where, 'D' is the effective diffusion coefficient that takes into account the contribution from transfer by migration, 'C_{sat}' is surface concentration, and 'δ' is diffusion layer thickness.

(iii) Current distribution and shape evolution

The nature of current distribution pattern also influences the shape generation and degree of leveling in EMM. In through mask EMM, three different scales must be considered with respect to current distribution, i.e. workpiece scale or cell scale, pattern scale and feature scale. At the workpiece/cell scale, geometry of the workpiece and tool can be controlled by the current distribution. On the pattern scale, current distribution is achieved by carrying out dissolution under mass transport control. Current distribution also depends on the spacing of the features and on their geometry. On the feature scale, shape is evaluated through the current distribution. The current distribution at the anode depends on the geometry, anode reaction kinetics, electrolyte conductivity and hydrodynamic conditions.

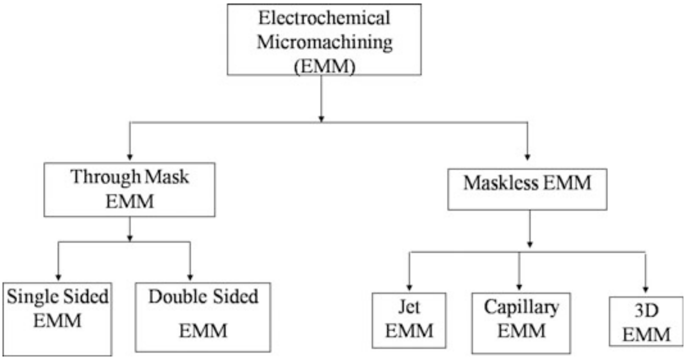


Fig. 8.6 Types of EMM

8.6 Different Types of EMM

Two-dimensional as well as three-dimensional micro features of different shapes, sizes, and surface qualities can be machined on micro or macro products by electrochemical micro-machining (EMM). In EMM controlled metallic dissolution can be achieved in microscopic domain utilizing high-frequency pulse power supply, and by the precise movement of microtool and workpiece. Flexibility in anodic material dissolution by applying the principle of electro-chemical technique is one of the main criteria to be considered during selection of the type of EMM. Depending upon the basis of the degree of localization effect of the material removal mechanism, EMM can be broadly classified into two groups as shown in Fig. 8.6.

8.6.1 Through-Mask EMM

Material removal is restricted by positioning a photoresist pattern i.e. masks on the metal surface thus, dissolution is allowed from the desired portions of the metal surface only. Through-mask EMM is more suitable for shaping and finishing of 2D micro features, as well as for fabrication of micro patterns. The photoresist is applied on metallic workpiece in required pattern, and made as anode in an electrochemical cell, so that metal surface is removed by anodic metal dissolution from the exposed surfaces only. In through-mask EMM, metal dissolution takes place at the workpiece surface that lies at the bottom of the cavity created by the photoresist mask [12]. Figure 8.7 shows the schematics for the shape evolution during through-mask EMM. Through-mask EMM process involves the careful implementation of various steps that include production of the master artwork, surface preparation, choice of suitable photoresist, and imaging. The metal removal is isotropic in nature, and hence leads to undercutting below the mask. During the designing of a photoresist mask, it is essential to have a knowledge of the metal removal rate and the undercutting of the photoresist in through-mask EMM at different electrolytes and metal combinations. The undercut and shape of the evolving surface are governed by aspect ratio, spacing to opening ratio, and film thickness ratio, etc. [13].

Through-mask EMM can be of two types (i) dissolution of the metal substrate from a single side, and (ii) simultaneous dissolution of material from both the sides. Micro nozzles can be fabricated on a thin metal foil by one-sided through-Mask EMM. Fabrication of nozzle plates by EMM involves cleaning of the metallic foil and application of photoresist on both sides of the foil. The photoresist on one side is exposed and developed to generate the initial pattern, consisting of an array of circular openings. A controlled one-sided through-Mask EMM process is employed to fabricate flat-bottomed V shaped nozzles on the sample as shown in Fig. 8.8. The taper angle of the micronozzle i.e. the ratio of the undercut (r) to thickness of metal film (b) can be controlled by regulating the EMM parameters [14]. By controlling EMM parameters, nozzles of desired shapes can be fabricated. The final nozzle shape is determined by several factors that include undercutting, etching factor,

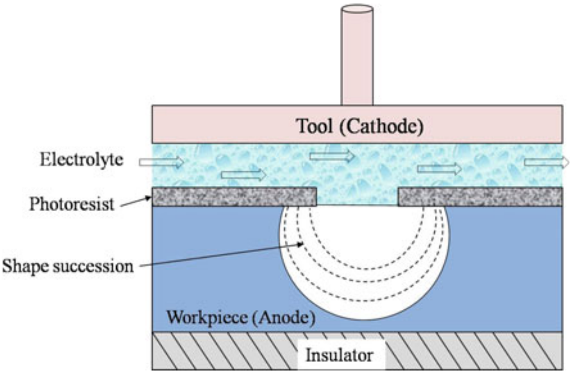


Fig. 8.7 Schematics for shape evolution during through-mask EMM

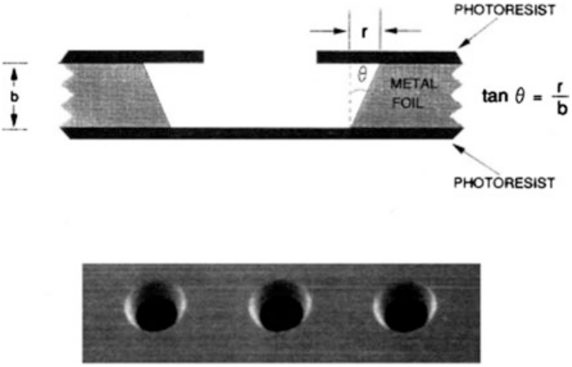


Fig. 8.8 Micronozzles fabricated by single sided through-mask EMM [11]

dissolution time, and dissolution conditions. Pulsed power supply is found to be effective in achieving dimensional uniformity of an array of nozzles during one-sided through-Mask EMM.

Through-mask EMM offers better control and flexibility for micro fabrication, as compared to chemical etching process. Higher machining rate and the use of less corrosive electrolyte are some of the advantages of through-mask EMM. Moreover, a wide range of materials, including high strength corrosion resistance alloys, can be machined by this technique. However, a limitation of through-mask EMM is the low aspect ratio of the produced micro features, due to the isotropic etching behavior.

8.6.2 Maskless EMM

Material removal from the workpiece surface is not limited by photoresist masking but is controlled by localized material dissolution mechanism. Highly localized selective metal dissolution from workpiece surface can generate the desired pattern or shape in 2D or 3D scale [15]. Anodic dissolution in maskless EMM is controlled by the current density, which depends on various predominant machining parameters. Inter electrode gap between the workpiece surface and tool is maintained at a very low value such that stray current effect is minimized. Passivating electrolyte is suitable for maskless EMM due to its ability to form transpassive oxide films and evolve oxygen in the stray current zone. To achieve highly localized anodic dissolutions, maskless EMM requires machining setup for precise movement of the tool as well as workpiece. During micromachining, to maintain and monitor the narrow IEG, the EMM setup needs highly sensitive sensing and controlling devices that should work on close loop control strategies. Circulation of fresh electrolyte at narrow machining zone is one of the important challenges in maskless EMM. Selection of a suitable electrolyte during micromachining of different materials is another essential task that influences the controlled metal removal process at different metal–electrolyte combinations. Another significant problem is the removal of machining by-products such as sludge, gas bubbles, and heat generated at fine IEG. For effective localization of metal removal, maskless EMM demands a higher frequency pulsed power supply.

Maskless EMM is competent to machine a high aspect ratio micro feature, which is one of the main limitations of through-mask EMM process. One of the main advantages of maskless EMM is the machining of 3D micro features. Different types of micro features can be fabricated by maskless EMM by exploiting its flexibility of material removal mechanism. It can be utilized to generate microstructures starting from a very low depth to very high aspect ratio, including surface structuring, micro patterns, deep micro holes, as well as 3D micro features. Depending on the depth of machining and geometrical complexity of the micro features, different techniques of maskless EMM may be selected. Maskless EMM can be classified into three categories, for example, Jet EMM, micro drilling, and

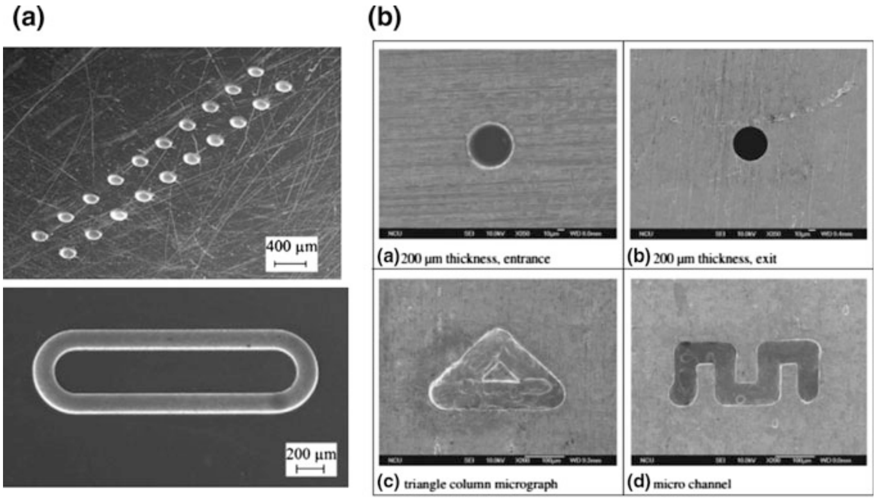


Fig. 8.9 Microholes and micro patterns machined by **a** jet EMM [15], **b** micro drilling, and 3D EMM [16]

3D EMM. Figure 8.9a shows micro hole array and micro pattern machined by jet EMM on stainless steel foil of 250 µm thickness with a nozzle diameter of 100 µm, voltage 56 V, 5 M $NaNO_3$ as an electrolyte, with at a feed speed of 300 µm/s. The cavity has a geometries consisting of lines having length of 1500 µm and semi-circles with a radius of 250 µm, depth of about 180 µm and width of approximately 190 µm. Figure 8.9b shows the micro hole and micro patterns machined on nickel at 1 MHz pulse frequency, 5% NaCl + 0.3 M HCl electrolyte concentration, 3 V applied voltage, 30 ns pulse duration, 50 µm tool diameter [16].

8.7 Important Process Parameters of EMM

Basic mechanism of material removal in EMM is based on anodic dissolution, in which metals are liberated from workpiece surface atom by atom. Various process parameters, namely applied voltage, machining current, electrolyte type, concentration, flow rate, inter-electrode gap (IEG), etc., influence major machining criteria of EMM such as metal removal rate, surface finish, profile accuracy, etc. [17]. In order to achieve the effective and high precision of machining in microscopic domain the process parameters needs to be controlled optimally [18, 19]. The machining accuracy and process performance can be improved by selecting and regulating the appropriate process parameters at narrow machining zone.

Figure 8.10 shows a fishbone diagram, also called as Ishikawa diagram or cause and effect diagram, indicating the influential EMM process parameters. Some of the

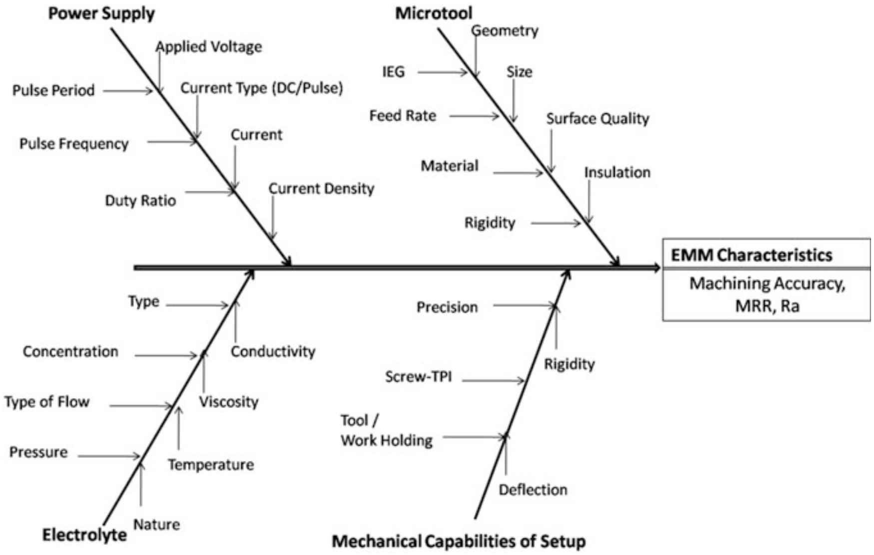


Fig. 8.10 Cause and effect diagram for EMM

predominant process parameters, which have major influences on EMM criteria are identified as follows:

(i) Nature of power supply i.e. DC or pulsed DC, its amplitude, and pulse frequency etc.
(ii) Microtool parameters like shape, size, surface quality, IEG, tool feed rate.
(iii) Electrolyte parameters such as type of electrolyte, its concentration, temperature, flow rate, and density.
(iv) Mechanical capabilities of machining setup such as resolution, rigidity, damp proof structure etc.

8.7.1 Nature of Power Supply

Electrical power is the driving force for the flow of charged particles inside the electrolyte, which is essential for continuation of electrochemical reaction. The applied power supply may be direct current or pulse direct current. With direct current supply workpiece material dissolves continuously. It may give very high concentration of reaction products, which can only be partly removed by the electrolyte, especially if the inter-electrode gap is very narrow. The increasing contamination can cause a deposit to form on the microtool surface, so that the workpiece material no longer dissolves uniformly. Furthermore, changes in the electrolyte composition rise in electrolyte temperature, and increase in electrical resistivity can also affect the machining accuracy. These problems can be largely minimized by applying the pulsed direct current instead of continuous one [20]. Pulse duration and the intervals between the pulses are properly matched to the current density, so that the machining gap can be completely swept clean during machining resulting in a continuous EMM process. The pulse off-time should be long enough to ensure a complete flushing of the electrolyte in narrow machining gap. The current efficiency is much more dependent on the current density when pulsed current is used than the use of continuous current. With continuous supply, the efficiency decreases gradually when the current density is reduced, where as with pulsed supply the decrease is much more rapid. A steep fall in efficiency with decreasing current density improves the machining accuracy. This improvement depends upon the pulse duration and to somewhat lesser extent on the interval. By using pulsating current one can apply extremely high instantaneous current densities to the workpiece without the need for an elaborate electrolyte pumping system and rigid machine frame. This is possible since each current pulse is followed by a relaxation time of zero current, which allows removal of reaction by-products and heat from the inter electrode gap. Compared to direct current dissolution where only average current can be chosen, pulsating current has three parameters, i.e. pulse on-time, pulse off-time, and peak current density which can be varied independently in order to achieve a desired machining rate. By proper selection of these parameters, it is possible to minimize variations of electrolyte conductivity in the machining region and to achieve high instantaneous mass transport even at low electrolyte flow rates. On the other hand, the average current density in pulse EMM is lower than the direct ECM. Pulsating current is therefore, particularly suitable for high precision micromachining of delicate micro features where high electrolyte flow velocity cannot be tolerated. Shorter pulse period is preferable for achieving higher accuracy. Anodic dissolution becomes more localized, the throwing power is more restricted and the machining accuracy is improved with the application of shorter pulses.

8.7.2 Microtools for EMM

In electrochemical micromachining, the machined micro features are the mirror image of the microtool, and somewhat greater than the microtool size called an oversize or overcut. Hence, in machining of micro features by EMM, shape and size of the microtool plays an important role, as the geometry of machined feature is dependent on the geometry of microtool. The design of microtool depends upon microtool geometry, as well as suitable microtool material. The development of microtools for micro manufacturing is still a challenging task, and mainly deals with (i) selection of suitable microtool material, (ii) determination of the accurate microtool geometry, and (iii) fabrication of the microtools for actual machining. Microtool handling is also an important issue to be considered, especially when the microtool are fabricated by one machining method and to be used by another machining method for actual micro machining applications. Some of the important issues related to the micro tool are as discussed below:

(a) Microtool material

EMM demands micron sized tools to be used in working conditions like extremely corrosive environment, at elevated temperature due to Joules effect. Hence, microtool materials should have properties like high electrical and thermal conductivity, good wear and corrosion resistance, mechanical strength i.e. stiffness to withstand the pressure of electrolyte, and be easily machinable. Considering these requirements of the microtool materials, the microtools are generally made of chemically inert materials. The best choice of the materials limits to tungsten, platinum, titanium, and some super alloys. Other metals, such as gold, nickel, copper, silver, molybdenum, and steel are also used as electrode materials in connection with specific applications. Among a wide choice of metals available, tungsten and its alloy, platinum and its alloy, and titanium are most widely used as metallic electrodes. Such electrodes offer a very favorable electron-transfer kinetics, large anodic potential range and low hydrogen overvoltage. Platinum wire is a soft metal but alloying with iridium and rhodium increase its hardness. Tungsten is widely used as tool material because of its important properties like high rigidity, toughness and resistance to chemicals [21].

Tungsten carbide (WC) with cobalt binder is also used as tool material. Titanium and its alloys have also been used in electrochemical micromachining due to the high strength, high melting point and has proven suitable for harsh environment where the corrosion resistance plays a major role. Tungsten wires are commercially available in a long pieces and cutting-off the tungsten wire with wire cutter or micro grinder may leave burrs or micro-cracks. Therefore, the cut ends should be grind and clean in order to get a good microtool tip shape. No single material has been proven to be superior over all others, no single material can satisfy all the microtool design purposes, since each material has its benefits and limitations.

(b) Microtool shape, size, and surface finish

In EMM, geometry i.e. shape of the microtool plays an important role in machining accuracy, as well as machining performance. Microtool size is also an important parameter to be considered in EMM, which helps to improve the machining accuracy, as well as machining performance [22]. Microtools of higher diameter increases the effective surface area of microtool, increasing machining current and tool polarization area, and finally generates micro features of higher overcuts. Use of micron sized tool, not only generates accurate micro features but also takes less time to machine the micro features [23]. Microtools with different end shapes have already proven their effectiveness in micromachining applications. Cylindrical microtools with flat end, conical end, reverse conical end, spherical end, and disc shaped microtools, can be developed by different methods and utilized in EMM [24]. Use of disc shaped microtool generates straight walled micro features of higher depths, with minimum stray current effects. Surface quality of the microtool also plays an important role during machining of micro features by EMM.

The minor defects on the surface of microtool, directly affects the surface quality of machined micro features [25]. This can be observed on features machined with a microtool having a surface not finished to a high degree of surface smoothness. The presence of nicks, notches, scratches, lines, burrs, or other similar type of surface defects will be reproduced as the mirror image on the work surface. Therefore, special care must be taken to maintain the surface of the microtool very smooth.

(c) Microtool insulation

While machining micro features of high aspect ratio by EMM, workpiece material dissolves from the front end, as well as the lateral surface of the microtool. This results a micro features whose entry side is wider than exit side i.e. taper along the depth and also poor surface quality due to stray current effects [26]. Therefore sidewalls of the microtools are insulated to minimize the stray current effects and taper formation along the walls of the micro features.

(d) Microtool feed rate

In EMM, material dissolution depends upon machining time also. Tool feed rate regulates the time for which microtool is available at particular position during machining of micro features, hence microtool feed rate is one of the important process parameter in EMM. The micro tool feed rate should be always less than material removal rate to avoid short circuit during machining, since short circuit can seriously damage both the microtool and delicate surface of workpiece. The maximum value for the microtool feed rate for a particular machining condition can be determined depending on the occurrence of sparks or short-circuits between microtool and the workpiece during machining operation.

8.7.3 Electrolytes for EMM

Electrically conductive solution which carries electricity through ions is termed as electrolyte. The electrolyte not only completes the electric circuit between the tool and workpiece, but also allows the desired machining reactions to occur. The conductivity of an electrolyte solution depends on the concentration of the ions and behaves differently for concentrated and dilute electrolytes. The electrochemical processes take place at the interface of electrode-electrolyte solution, usually bulk solution. In electrochemical cell, the electrode potential is used to dissolve workpiece materials. The mass transfer inside the electrochemical cell i.e. the dissolution of material depends on the hydrodynamic conditions for a given metal-electrolyte combination, and the dissolved mass transfer occurs in three different modes namely diffusion, convection, and migration. In electrochemical micromachining processes, the migration mode dominates the process mostly when very low concentration electrolytes are used, and the use of electrolyte circulation system is very limited. Electrolyte selection is an important task in EMM [27], and following points needs to be considered before electrolyte selection for specific application.

(a) Types of electrolytes

An electrolyte contains free ionic species that make it electrically conductive. Depending upon pH value electrolytes can be classified into three categories namely acidic, neutral, and alkaline. pH is the negative logarithm of hydrogen ions concentration in the solution. If the electrolyte solution has pH value equal to 7 then it is neutral solution. If the electrolyte solution has pH value less than 7 then the solution is acidic, and if the pH value exceeds 7, then electrolyte solution is alkaline. Neutral electrolytes such as NaCl, $NaNO_3$ are commonly used in EMM. However, for microhole drilling acidic electrolytes are preferred. Electrolytes can also be classified based on the degree of dissociation and nature of passivation factor. The term degree of dissociation of an electrolyte is the fraction of solute which is dissociated into ions that are free to carry current at a given concentration. Electrolytes are also classified as strong electrolyte and weak electrolyte based on degree of dissociation of solute. Strong electrolytes dissociates greatly for concentration ranging from very low to high values, whereas, for weak electrolytes dissociation of an electrolyte tends to unity at very low, limiting concentration, and reduces to about zero at high concentration. Strong electrolytes such as NaCl are generally preferred for anodic dissolution. Whereas the electrolytes based on passivation are classified into two categories: passivating electrolytes containing oxidizing anions, i.e., sodium nitrate, sodium chlorate, and nonpassivating electrolytes containing relatively aggressive anions such as sodium chloride. Passivating electrolytes are known to give better machining precision. The pH value of electrolyte solution is chosen to ensure the good dissolution of the workpiece material during EMM process without affecting the microtool. In some applications acidic electrolytes are preferable for EMM because it produces soluble reaction products which can be removed easily from narrow inter-electrode gap without affecting the micro features of microtool. Although the precipitate has no direct effect on the process, it definitely increases the possibility of damage of microtool from short circuit. Hence it is advisable to use fresh and clean electrolyte for micromachining instead of re-circulation. For electrochemical micromachining of various metallic materials different electrolytes or mixed electrolytes are suitable. For machining of aluminum and aluminum alloys, NaCl or $NaNO_3$ is suitable; for copper, copper alloys, and tungsten, NaOH can be used; for titanium and titanium alloys, electrolytes such as NaBr, NaCl or mixture of NaCl and $NaNO_3$ is suitable, for Stainless steel, electrolyte such as H_2So_4, NaCl and $NaNO_3$ can be used; and for machining of tungsten carbide, mixture of NaCl, NaNOH and triethanolamine can be used [10]. Machining accuracy can be improved by using additives such as $NaHSO_4$ in the electrolyte. Also to prevent to prevent formation of metal hydroxide precipitates, complexing agents such as citric acid are added in the electrolyte.

(b) Electrolyte properties

The electrolyte at narrow inter-electrode gap facilitates the electrochemical reaction. Therefore the electrolyte solution should:

(i) Ensure a uniform and high speed anodic dissolution,
(ii) Avoid the formation of a passive film on the anodic surface,
(iii) Not deposit on the cathode surface,
(iv) Have a high electrical conductivity and low viscosity to reduce the power used,
(v) To have good flow conditions in the narrow inter-electrode gap,
(vi) Be safe, nontoxic, and less erosive to the machine body,
(vii) Maintain its stable ingredients and PH value during machining,
(viii) Have minimum variation in its conductivity and viscosity due to temperature rise during machining,
(ix) Be less expensive and easily available,
(x) Possess less throwing power apart from basic properties like good chemical stability, high electrical conductivity, low viscosity, non-corrosive and inexpensive to increase the machining accuracy.

Apart from facilitating for electrochemical reactions, electrolytes have to perform various functions such as:

(i) Create an environment for anodic dissolution of workpiece material,
(ii) Conduct the machining current,
(iii) Remove the process by-products formed during machining,
(iv) Carry away the heat generated at narrow inter-electrode gap, during machining to maintain the constant temperature.

(c) Working life of electrolytes

The composition of the electrolyte begins to change with the progress of time during electrochemical machining. The major changes that may occur and their effects are enumerated as follows:

(i) Loss of hydrogen, which may cause a reduction in electrical conductivity of the electrolyte and increase its pH value.
(ii) Loss of water, either by evaporation or carried off by evolved hydrogen gas, which may increase the concentration of the solution and thus may affect its electrical conductivity and its viscosity.
(iii) Formation of precipitate, which will reduce the concentration of the electrolyte and may affect its electrical conductivity,
(iv) Metal ions from the anode may pass into the solution and may be deposited on the cathode.

The aforesaid changes mean that the electrolyte has got finite life and in practice the life may be limited because of the following reasons:

(i) The need to maintain a reasonably constant electrical conductivity so as to facilitate the control over the process and to ensure the machining accuracy.
(ii) The need to prevent plating out of dissolved material on the microtool surface to ensure the machining accuracy.
(iii) The need to avoid formation and accumulation of excessive quantities of precipitate and sludge at narrow machining zone.

The first of the aforesaid consideration applies to all type of electrolytes, the second consideration applies mainly to acidic electrolytes and the third one applies mainly to neutral type of electrolytes.

(d) Electrolyte concentration, temperature and flow

(i) Electrolyte concentration

The electrolytes in electrochemical cell carry electrical current by the movement of ions and the number of ions available for electrochemical reaction increases with increases in concentration. Therefore increased concentration of an electrolyte offers low resistance to flow of current resulting increased electrical conductivity. The magnitude of conductivity is determined by the type and number of ions present in the electrolyte. Hence, to compare the conductivities of the different electrolytes, the term electrolyte concentration is generally used, which can be applied to all electrolytes. Electrolyte concentrations are measured as weight of the solute per unit (w/w) or weight per unit volume (w/v) of solution, or the volume of the solute per unit volume (v/v) of the solution. Molecular weight in grams i.e. gram-molecules, or moles of solute per liter of solution (M), is generally used to measure the concentration of the electrolytes. Electrical current is carried out by the movement of ions in electrochemical cell. The rate of ionic movement is termed as the ionic mobility. Increase in electrolyte concentration increases machining current due to reduced electrolyte resistance, however further increase in electrolyte concentration reduces the electrical conductivity due to reduced ion mobility. Also increased density of electrolyte at very high electrolyte concentration makes it difficult to remove the process by-products from narrow machining zone. Therefore dilute electrolytes are preferred in electrochemical micromachining of micro features [28].

(ii) Electrolyte temperature

During electrochemical micromachining of micro features, electrolyte concentration and temperatures are expected to be constant throughout the process for machining the micro structures with uniform features. Temperature of electrolyte at narrow inter-electrode gap increases due to Joule’s heating effect. Electrical conductivity of an electrolyte increases with increase in temperature because of increase in mobility of ions at increased temperature. Finally, increase in machining current because of reduced electrolyte resistance may result micro features with varied characteristics like increased surface roughness, reduced machining accuracy, and higher MRR.

Therefore, maintaining constant temperature of electrolyte during machining of micro features has its own importance.

(iii) Electrolyte flow

Machining of precise micro features by EMM demands micron sized tools with few micron of inter-electrode gap during machining. As per the requirements of the EMM process, fresh electrolyte needs to be supplied continuously at narrow inter-electrode gap by flushing out used electrolyte, for effective machining of micro features. Size of the microtools and IEG of few microns limits the movement i.e. flow rate of an electrolyte during machining. Higher flow rate of an electrolyte may vibrate the microtool in turn results in reduction of machining accuracy or result short circuit due physical contact with workpiece. Therefore, generally steady electrolytes are used in machining of micro features by EMM, since very small amount of material is removed precisely during micro machining [29].

8.7.4 *Mechanical Capabilities of Setup*

Mechanical capabilities of machining setup also play an important role in machining of accurate micro features. Resolution of linear stages representing X, Y and Z axes directly affects the machining accuracy of machined features. Arrangement for rotating the microtool, as well as an attachment of microtool vibration system enhances the supply of fresh electrolyte at machining zone, as well as helps to remove the machining by-products from narrow machining gap, and improves the machining accuracy of EMM [30]. Hall current sensor for detecting the short circuit is very much useful in detecting the physical contact of the microtool with workpiece surface, which prevents the damage of the micron sized tool or precious workpiece surface [31]. CNC controller for synchronizing the movements of linear stages representing X, Y and Z axes facilitates the machining of complex or free-formed surfaces or micro structures. Damp proof structure helps to improve the machining accuracy by isolating the machining setup from the mechanical vibrations generated in surrounding.

8.8 EMM Setup Development

8.8.1 *Need of Setup Development*

The escalating demand of microproducts in various fields have forced manufacturing industries to fabricate microproducts of best surface qualities from advance engineering materials, in very short period of time. In recent years, applications of microproducts have been considerably increased in electronics, optical, medical, automotive, aerospace, and telecommunication fields. The demand for microproducts will increase exponentially in the coming years also due to the vast applications of microproducts and global competition among industries. Electrochemical micromachining offers unique advantages over competing micromachining technologies which has a great potential to machine microfeatures like surface structuring, patterning, microholes, microgrooves, microchannels, microcavities, and 3D microstructures of complex shapes with a high aspect ratio for various industrial and household microproducts. To fulfill the increasing market demand of micro products, an industrial EMM machine needs to be developed, which will be robust, will have a low price, maintenance free, and will have a higher production rate.

8.8.2 Challenges in Setup Development

Anodic dissolution of workpiece material by electrolysis demands several technical specifications of the setup. Precise microtool movement, narrow IEG and regulating it uniform throughout the machining, arrangement and rigidness of mechanical structure, power supply requirements, in-process monitoring, microtool and workpiece holding arrangements etc. are important criteria to be considered for the effective utilization of EMM. There has been few micromachining systems developed in research institutes, academic universities, as well as by commercial companies. Some of them are multipurpose systems or dedicated systems for EMM as well as for micro electro-discharge machining. Many research papers describes the machining capabilities of EMM for microtool fabrication, machining of micro holes and microstructures, still as of today there is no commercial, ready to use EMM machining set up for micromachining applications. This is because of the electrochemical micromachining parameters which do not remain same for the different electrode-electrolyte combinations, and required shape and size of micro features and machining accuracy etc. Therefore for machining specific micro feature of desired machining accuracy, specific electrode-electrolyte combination is required. Also various microtool movement strategies namely layer by layer machining, milling, sinking and milling, wire cut EMM demands different arrangements of machining setup [32]. Therefore, EMM setup development is facing the problem of combining the various requirements in single machine setup, and is under the developmental stage. Smaller inter-electrode gap in the range of few microns is preferred in EMM, since machining localization improves with reduction reduced IEG. Whereas, accumulation of sludge and generation of bubbles at narrow IEG hinders the EMM process that may reduce IEG gradually causing short circuit microtool damage. It is very much difficult to maintain the narrow IEG throughout the machining. Therefore, regulation of minimum IEG during machining demands online monitoring of the process to avoid short circuit, physical contact of the microtool with workpiece [33].

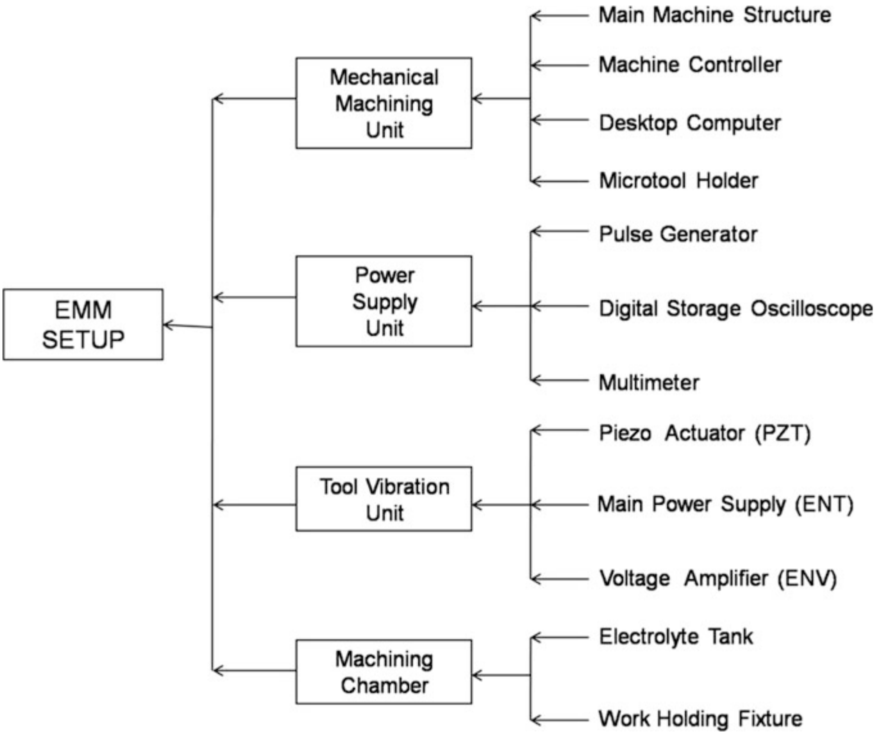


Fig. 8.11 Various subsystems of the developed EMM setup

8.9 EMM Subsystems

Controlled machining of micro features by EMM necessitates different tasks to be done simultaneously in-tune with time or in coordination with each other. Hence, to develop an electrochemical micromachining system setup, various subsystems along with their sub-components such as mechanical machining unit, power supply unit, microtool vibration unit and machining chamber along with work holding fixture have been interconnected as shown in Fig. 8.11. Individual subsystems are described in detail in succeeding sections.

8.9.1 Mechanical Machining Unit

The basic function of mechanical machine unit is to provide precise movements to the tool or workpiece and to provide mechanical support to tool holder, machining chamber etc. The mechanical machining unit of the developed EMM system setup

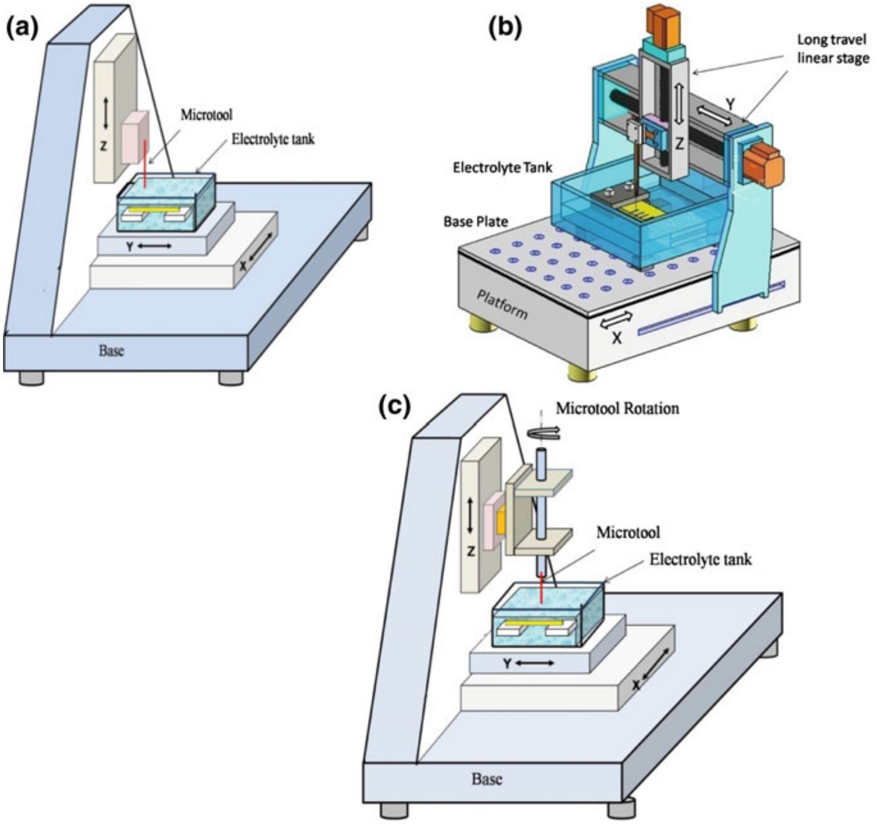


Fig. 8.12 Different types of Mechanical Machine units **a** column and Knee type, **b** gantry type, and **c** structure with rotational axis

comprises of the various machine elements like main machine structure, machine controller unit, and desktop computer with graphics user interface software.

(a) Main machine structure

Main machine structure provides rigid support to various components during machining, and space to mount the different components such as base plate, linear stages, tool holder at required positions. The main structure comprises of platform with support, vertical or horizontal supports, Stepper motor or servomotor operated long travel linear stages with precise movements to represent X, Y, Z axis. Figure 8.12 shows the different combinations of linear stages to fabricate mechanical machine unit.

(b) Machine controller unit

Machine controller unit controls the long travel linear stages through stepper motor or servomotor movements. It also synchronizes the movements all stages according to instructions of the program for a specified path. It is interfaced in between desktop computer and mechanical machine setup. Various feeds can be given to all or any of the three motors at a time through a motor controller unit using position controller software or labview programs installed on a desktop computer. The software enables the user to program movement of each stages in the form of commands executed sequentially. For machining of complex microprofiles and 3D microstructures, Computer Numerical Controlled (CNC) controllers are preferred.

8.9.2 Power Supply Unit

Power supply unit is very important unit in EMM system setup, since the nature of pulse and pulse parameters directly affect the machining accuracy. Machining takes place during pulse ‘on’ time only, and sludge removal from narrow machining zone mainly takes place during pulse ‘off’ time, therefore pulsed DC supply with short pulse period is preferred to machine the micro features by EMM. Better control over process needs pulse monitoring and control of the pulse parameters during machining operation. Main components of the power supply unit can be elaborated as:

(a) Pulse generator

Pulse generator generates DC pulses of required parameters and is the heart of power supply system. Continuous supply of the stable pulse patterns during machining is the prime function of a pulse generator. Various pulse parameters such as pulse period, pulse amplitude, pulse ‘on-time’ and ‘off-time’ i.e. duty ratio, pulse rise/fall times, positive or negative bias, as shown in Fig. 8.13 can be adjustable from a minimum to maximum value, resulting in different outputs for the same frequency.

(b) Digital storage oscilloscope

Digital storage oscilloscope provides the online image of the supplied pulse along with the detail information during machining. Digital storage oscilloscope can also be used during initial IEG setting and to monitor the machining conditions at narrow machining zone to detect the occurrence of short circuit if any between electrodes. As soon as the short circuit is detected, microtool feed and power supply is turned off, and microtool is retracted back by few microns to clear the IEG, and machining is continued again with required parameter settings. Digital storage oscilloscope can also be interfaced to the desktop computer for online monitoring, and pulse parameters can be directly stored using external storage devices for further analysis.

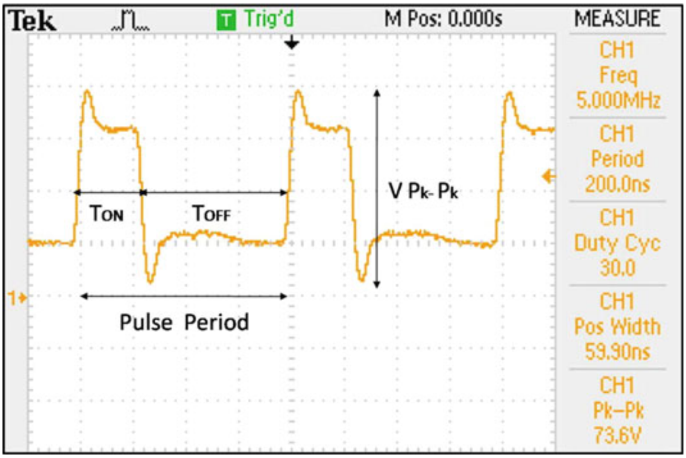


Fig. 8.13 Pulse parameters

8.9.3 Microtool Vibration Unit

Main objective of vibration system is to provide vibrations to the microtool to improve the machining performance by enhancing the availability of fresh electrolyte at narrow machining zone by displacing machining by-products, especially during machining of deep micro features. The microtool vibration produces pressure waves which help in flushing away the reaction product from the machining zone leads to generation of better quality micro features [34]. Microtool vibration system may consist of Piezoelectric transducer (PZT) actuated compact single axis translational stage and voltage amplifier system.

8.9.4 Machining Chamber

It is the space where electrochemical reaction takes place in between anode and cathode that are submerged in an electrolyte with very small IEG. It consists of an electrolyte tank and workpiece holding fixture. Material used to fabricate the electrolyte tank must be non-conductive, non-corrosive, light in weight, transparent, machinable into the required size. Perspex is one of the most suitable materials to satisfy all of these requirements [35].

8.9.5 Process Monitoring and Control

While fabricating micro features of desired dimensions by EMM, its process parameters, path of machining, microtool movement and control strategy has to be predetermined before machining. During machining, a micron-sized tool electrode moves with a constant feed rate toward the workpiece to maintain the IEG. Based on the machining strategy, the microtool tracks the scheduled path to fabricate the desired microfeatures such as microhole, microgroove, etc. Machining strategy followed during machining directly influences the machining accuracy, as well as process performance. IEG controls the dimensional accuracy of the machined feature in micro-machining. Minimum IEG needs to be maintained throughout the machining, for continuation of the process effectively. Accumulation of sludge and generation of bubbles at narrow IEG hinders the EMM process, and may reduce IEG gradually causing short circuit. Smaller IEG in the range of few microns results higher machining accuracy, whereas it is very difficult to maintain the narrow IEG throughout the machining. Physical contact of microtool with workpiece surface during machining may lead short circuit and may damage microtool or workpiece surface also. Sparking phenomena may damage both the microtool and the workpiece. When the tool feed rate is smaller than the material removal rate, the IEG increases gradually, and generates a higher machining gap that may affect the machining accuracy. Therefore, to maintain a constant IEG, the microtool feed rate should synchronize with the material removal rate, known as equilibrium speed. While machining microfeatures by EMM, the material removal rate varies according to various process parameters as well as the equilibrium speed of the microtool. Hence, to maintain a constant IEG during micromachining, different strategies have been developed and adopted by researchers. Various IEG control strategies for EMM adopted by researchers are reported from Figs. 8.14, 8.15, 8.16 and 8.17 as follows.

8.10 Accuracy Improvement Techniques in EMM

To exploit full potential of EMM, research is still needed to improve the machining accuracy by controlling different factors such as the effect of overcut and taper formation during the machining of various micro features. Geometrical shape, size and surface quality of the microholes, microslots and grooves affect the performance and service life of the various micro components. Hence, fabrication of micro features consisting of various types of microholes; microgrooves and slots with good shape accuracy and surface quality are the focused areas of research in EMM. To improve the machining accuracy of EMM, the control of stray current phenomenon is one of the major challenges. The proper removal of sludge, precipitates and gas bubbles from the very narrow machining gap in EMM is another major challenge to the researchers. Because of the improper flushing of machining

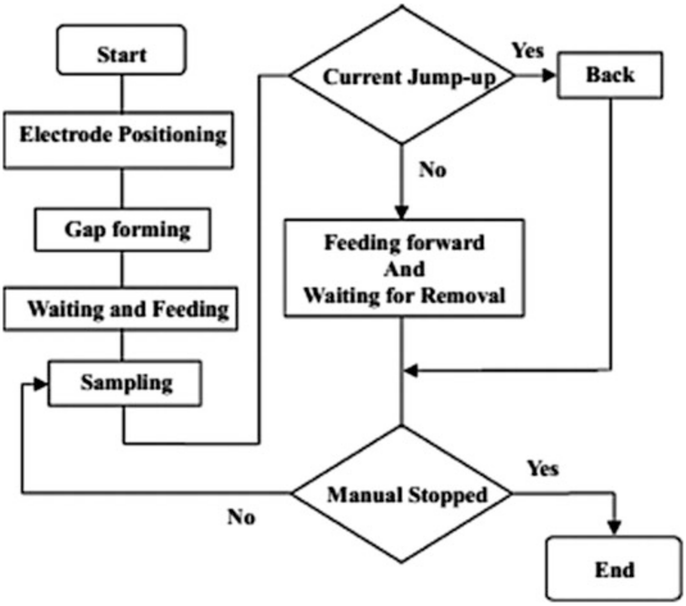
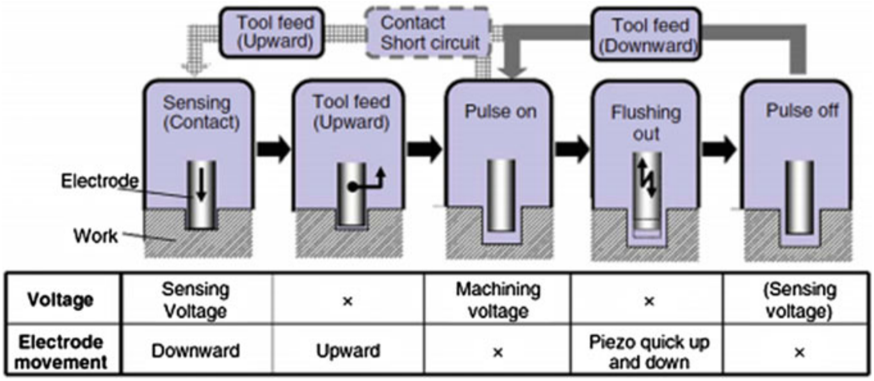


Fig. 8.14 Flow chart for IEG control [36]



Voltage	Sensing Voltage	×	Machining voltage	×	(Sensing voltage)
Electrode movement	Downward	Upward	×	Piezo quick up and down	×

Fig. 8.15 IEG control sequence [37]

zone as well as inadequate control of microtool feeding movement, micro sparks may generate between microtool and workpiece. Machining accuracy can also be improved by developing newer machining strategies and increasing the competence of anodic dissolution by incorporating other special methods and effects. The machining accuracy of EMM can also be improved by controlling and optimizing the combination of different influencing EMM parameters. Some of the important aspects by which accuracy of EMM can be improved have been discussed as:

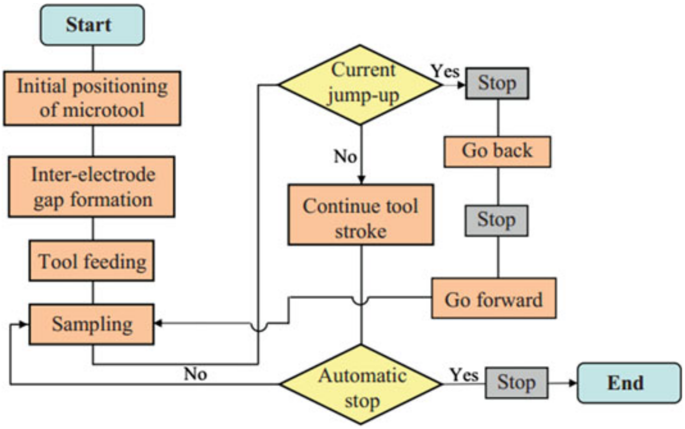


Fig. 8.16 Gap control strategy [38]

8.10.1 Geometry of Microtools

Geometry of microtools i.e. shape and size plays an important role during controlled anodic dissolutions to achieve the desired shape, size, and surface finish of the micro-features. In many application microfeatures like straight cylindrical microhole, taper free microgrooves and vertical walled 3D microstructures are essential, whereas during machining of such microfeatures of higher depths using straight cylindrical microtools, taper is formed on the sidewalls of the structure because of the machining time difference between top face and bottom face of the microfeature. Microtools of different shapes or end shapes such as reverse conical, spherical based, disc shape microtools as shown in Fig. 8.18 can be successfully used to improve the machining accuracy.

Cylindrical microtools with a flat end are suitable for machining of microholes, microgrooves, and microcavities by controlling the movement of the tool. For machining straight cylindrical microholes, cylindrical microtools with a flat end and cut edge electrode can be effectively used with a rotary arrangement. Cut edge microtools enhance the supply of fresh electrolyte flow and improve the machining accuracy as compared to microtools with flat ends. Conical microtools are suitable for machining of conical microholes to fabricate micronozzles required for the applications in inkjet printers, etc. Reverse microtool electrodes are suitable for taper reduction of microfeatures, Disk shape, and spherical end-shaped microtools are suitable for reducing the taper formation on vertical walls of the microfeatures with straight edges as shown in Fig. 8.19. Use of disc shape microtool restricts the dissolution of the workpiece along the disc height only which minimizes the taper along the vertical wall of the microfeature.

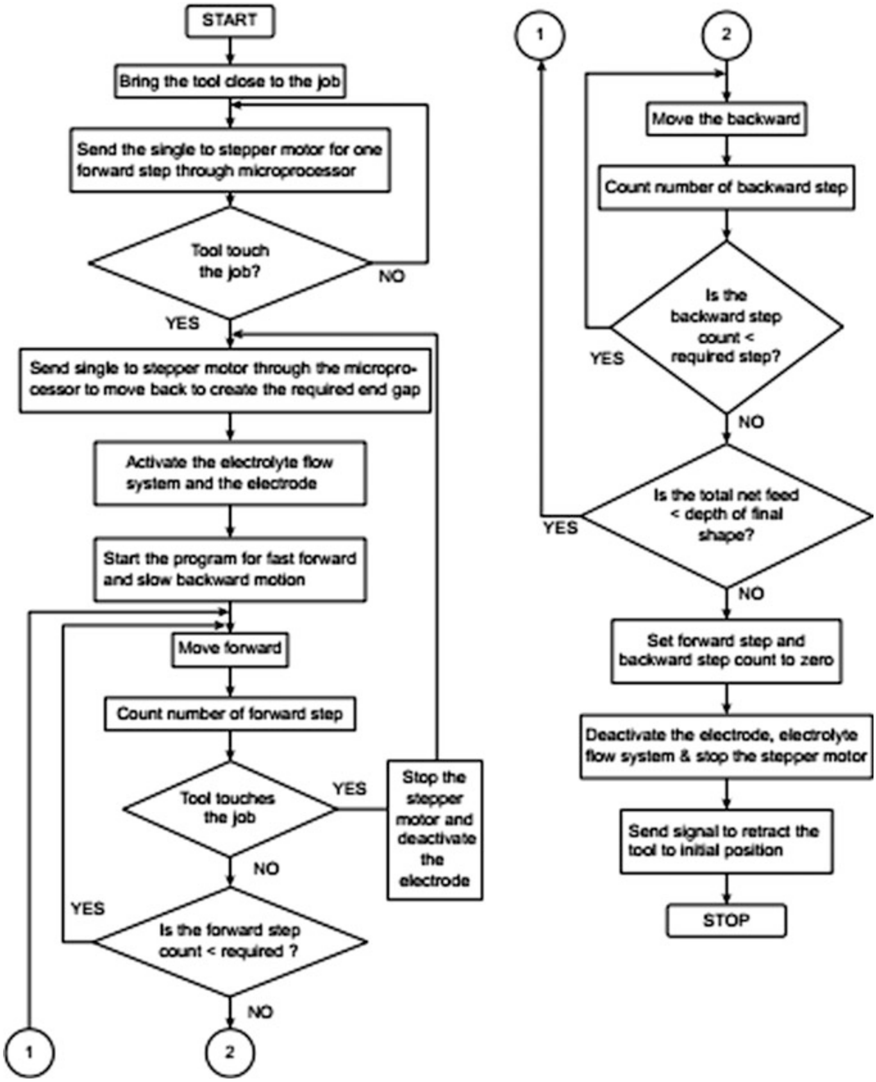


Fig. 8.17 Flow chart for IEG control [39]

8.10.2 Microtool Insulation

High aspect ratio micro features are commonly used in many applications. For the fabrication of these micro features, cylindrical microtools of a few microns in diameter are used in EMM, and scanning type machining strategies are followed for the microtool movement. The microstructures fabricated by un-insulated microtool are not capable of producing higher aspect ratio micro features, because of the

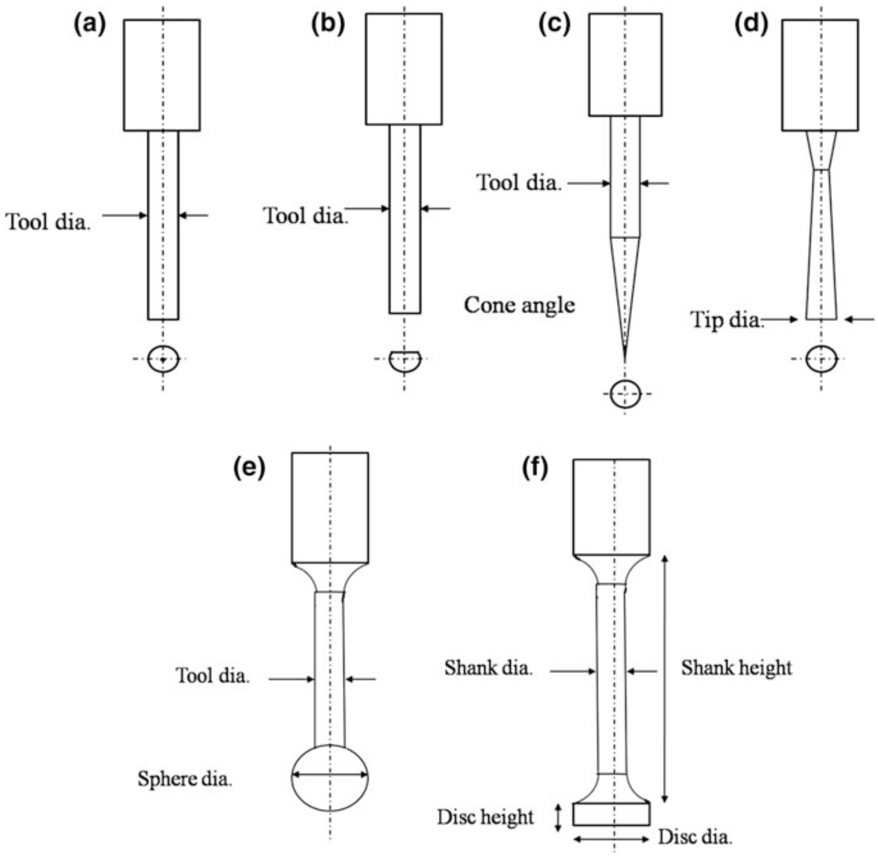


Fig. 8.18 Microtools of different end shapes **a** cylindrical **b** cut edge **c** conical **d** reverse conical **e** spherical and **f** disc shape

material dissolution from front as well as sidewalls of the microtool. Sidewall insulation of microtool restricts the material dissolution along the lateral surface and improve the machining accuracy in terms of reduced taper angle, stray current effects, with better surface quality [40]. Figure 8.20 illustrates the effect of sidewall insulation on vertical wall profile of microhole machined with cylindrical microtool.

There are various methods of insulating the microtools such as physical vapour deposition, chemical vapour deposition, spin coating, and dip coating etc. with uniform film thickness of few microns [41]. Uniform coating thickness in the range of few microns, difficulty in handling of the microtools, suitability of the insulating film in different electrolytes, method of opening the front end of the microtool for EMM, etc. are the major challenges in sidewall insulation of the microtools. Figure 8.21 illustrates the micro holes machined with and without sidewall insulations of the microtool at applied voltage 3 V, pulse frequency 8 MHz, 35% duty ratio, tool feed rate 0.1 μm/s, using 0.2 M H_2SO_4. Similarly microgrooves of 2000 μm length

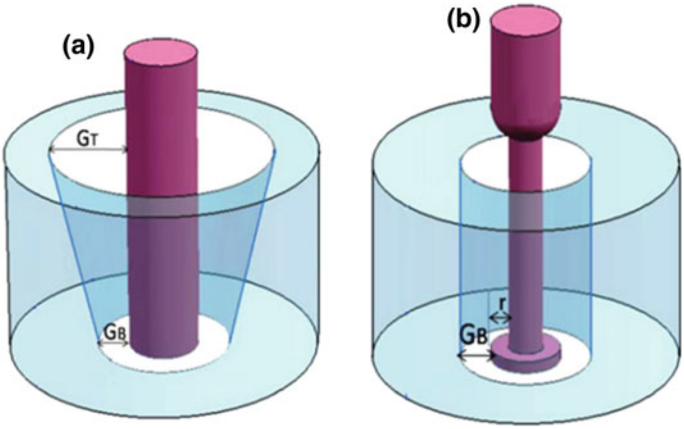


Fig. 8.19 Effect of microtool shape on wall profile of microhole machined by **a** cylindrical **b** disc microtool

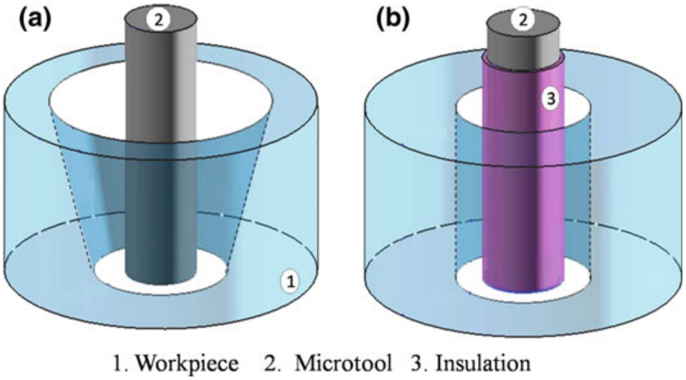


Fig. 8.20 Effect on wall profile of microhole machined **a** without **b** with, sidewall insulation

machined at 3 V, 8 MHz, 35% duty ratio and 0.2 M H_2SO_4. with scanning speed 93.75 μm/s and microtool feed of 0.3125 μm at the end of each scan, with and without sidewall insulations of the microtool are shown in Fig. 8.22 [41].

8.10.3 Electrolyte Circulation

In EMM, presence of fresh electrolyte at narrow machining zone is essential for the continuation of the process. Practically, IEG between tool and workpiece is very small i.e. of few microns and the circulation of electrolyte through machining gap is difficult task. Fresh electrolytes cannot be circulated with high velocity through

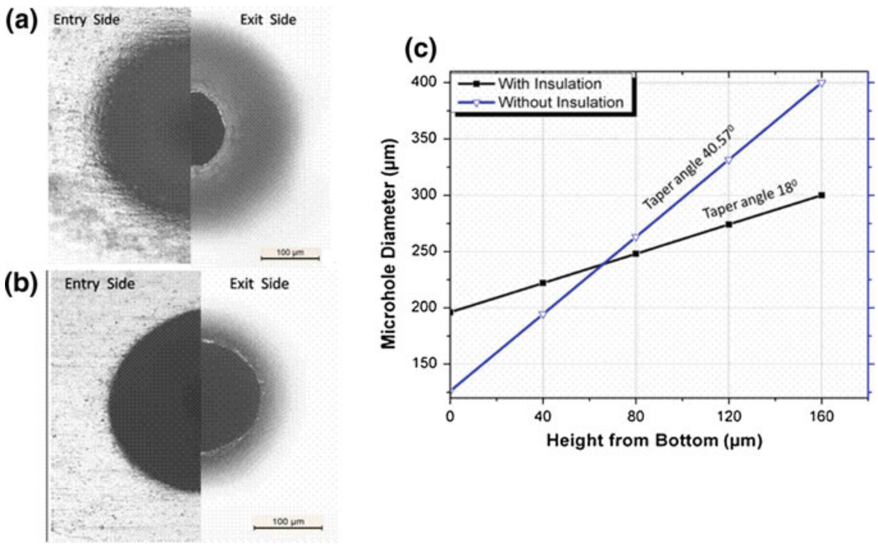


Fig. 8.21 Micro holes machined **a** without, **b** with sidewall insulations [41] and **c** variation in microhole diameter

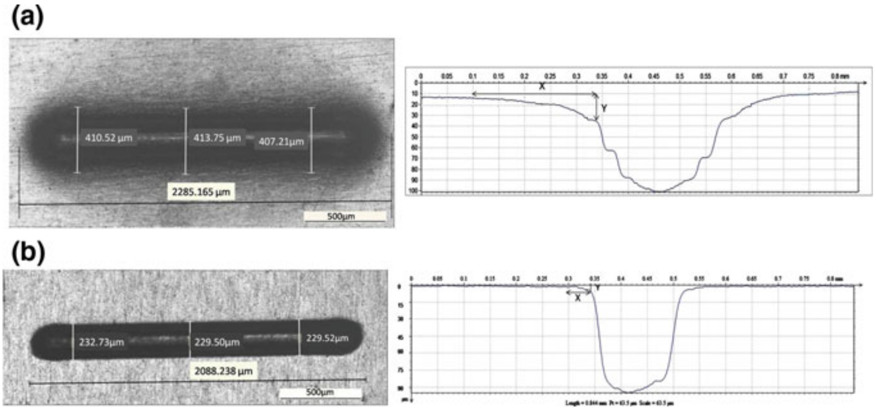


Fig. 8.22 Microgrooves and its depth profiles machined **a** without and **b** with sidewall insulations [41]

machining zone, since it may vibrate the microtool and delicate workpiece which will affect the stability of dissolution process and may deter the machining accuracy. However, it is essential to remove process by-products, heat, precipitates as well as gas bubbles from the narrow machining gap to achieve higher machining accuracy. There are various techniques by which electrolyte circulation in the machining zone can be improved. Electrolyte circulation can be improved by hybridized EMM with low-frequency tool vibration. The microtool vibrates longitudinally with the definite combination of amplitude of vibration and frequency of vibration. Vibrations within the machining zone, in the stagnant electrolyte, have considerable influence on the diffusion and convection of dissolved metal ions. As the microtool vibrates, the generated bubble collapse, which will be maximum very near to the microtool [42]. The impact of the micro jets in the machining zone, results in the enhanced convective mass transport of dissolved ions, the disruption of diffusion layer and supply of fresh electrolyte. To improve the machining accuracy in EMM, circulation of fresh electrolyte by completes flushing of sludge and precipitates from the very narrow gap between tool and workpiece is essential.

8.10.4 Microtool Movement Strategy

The achievable machining accuracy of EMM changes depending on the tool movement strategy. The effect of uncontrolled machining due to the improper flushing of the machining zone as well as the poor localization effect of current can be greatly minimized by regulating the movement of the microtool. During machining, microtool may move horizontally along X–Y plane and vertically along Z axis as well as it rotates. During EMM by scanning, microtool moves mainly along the combination of XY plane and Z axis following the specific tool movement strategy for three-dimensional shape generation. Microtool may move with faster or slower feed rate which directly controls the time of interaction between microtool and workpiece; thus controlling the anodic dissolution in the machining zone results in the degree of machining accuracy. The tool movement also controls the flow of electrolyte in the narrow machining zone thus facilitating the removal of machined products. Rotary movement to the microtool while it is fed along the desired path enhances the effective circulation of electrolyte in the machining zone. The rotary tool generates centrifugal force in stagnant electrolyte along its peripheral surface which may create micro-pumping action in the confined machining zone. This helps to stir up the micro machined products and gas bubbles to eject from the machining area to the periphery and create cavitations effect in the machining zone. Due to the availability of fresher electrolyte in the machining zone, the efficiency of the anodic dissolution improves which in turn increasing the machining accuracy.

8.10.5 Micro-sparks Phenomena in EMM

Micro sparks in the narrow machining zone cannot be eliminated completely, which deteriorates the machining accuracy of EMM. The micro sparks are occurring in narrow machining zone due to the variation in machining parameters apart from tool feed rate, heat generation across IEG accumulation of sludge and gas bubbles in the very small IEG. The increase in gap resistance due to various reasons such as generation of gas bubbles, sludge formation etc. leads to the occurrence of micro sparks, causing higher overcut as well as micro spark affected zone that results in the poor quality of final products.

8.11 Applications of EMM

EMM has improved in reliability through continuous developments, permitting its industrial implementation for automated large-scale micro manufacturing. The various applications of electrochemical micro fabrication technologies covering micromachining, finishing, as well as surface engineering applications have been illustrated through selected industrial examples. It has also some technical limitations that may constrain its full-fledged applicability in the micro fabrication field. Typical applications of EMM technologies for micro fabrication of components can be categorized in three domains such as machining, finishing, as well as surface structuring applications. Some of the machining applications are discussed as:

8.11.1 Machining Applications

Machining of micro features on micro or macro devices has become an important issue in recent technologies. EMM is one of the best techniques which can be successfully utilized to machine different micro features with high accuracy and surface quality. Very few techniques are available to machine microstructures with three-dimensional (3-D) features on advanced engineering materials like copper, aluminum, nickel, titanium, steel, and their alloys. Some of the important machining applications of EMM are as:

8.11.1.1 Micronozzles

Micronozzles with high surface quality can be fabricated on advanced high strength temperature resistance (HSTR) materials such as titanium, nickel alloys, and stainless steel utilizing the EMM technique. These micronozzles can be successfully utilized in various applications such as injectors for automobile and aerospace applications, microfluidic applications for heat transfer devices, as well as for various biomedical applications. Figure 8.23 shows a magnified view of a micronozzle fabricated by EMM utilizing a conical microtool [43].

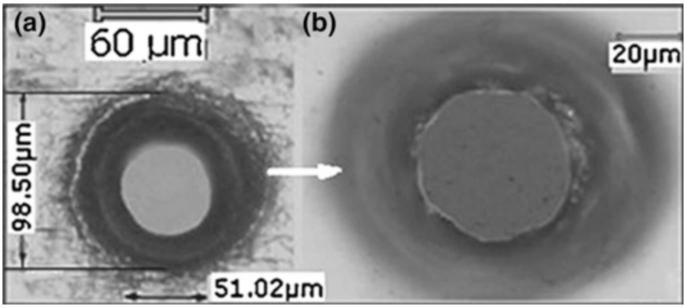


Fig. 8.23 **a** Micronozzle fabricated by EMM. **b** Surface quality of internal wall [43]

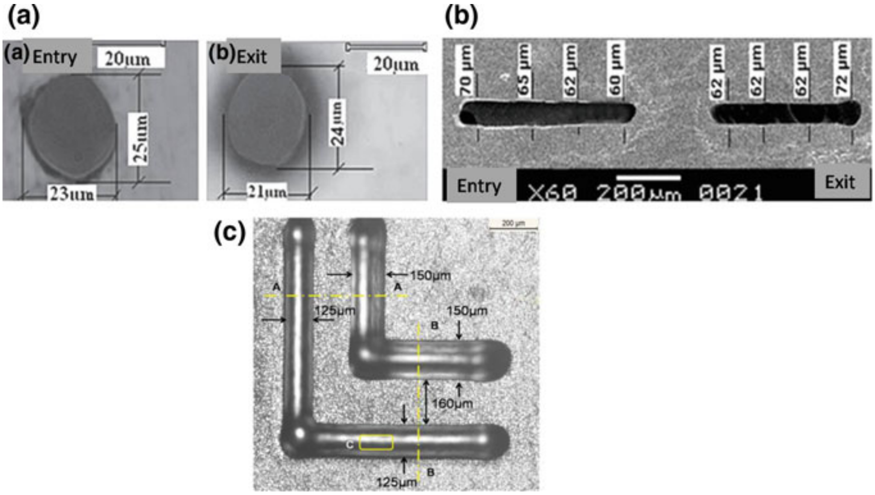


Fig. 8.24 Microscopic image of **a** microhole [50], **b** micro slots [45] and **c** microgrooves by EMM

8.11.1.2 Microholes, Slots, and Channels

Microholes, slots, and channels can be fabricated successfully by EMM with high precision and quality. Figure 8.24 shows the microhole of average entry diameter 24 μm and exit diameter 22.5 μm drilled on an SS-304 plate. Conical microtool can be used for the generation of taperless micro channel. Initial drilling followed by milling, i.e., sinking and milling method, is used for the generation of micro channel. Microchannels separated by very thin fins can also be fabricated by EMM [44].

8.11.1.3 Three-Dimensional Micro Features

Three-dimensional microstructures can be machined successfully by EMM utilizing scanning movement of the microtool at the desired path. Figure 8.25 shows the microscopic images of the various three dimensional micro features machined by EMM. Micro features have been machined utilizing cylindrical microtool adopting layer by layer machining.

Figure 8.26a shows the SEM micrograph of micro hemisphere machined on SS. Micro hemisphere has been machined on SS with 6 V, 60 ns pulse on-time, 1 µs pulse period. This structure has been machined in three steps. As the rough cut, the cylinder has been machined and the hemisphere with 100 µm diameter was machined on the cylinder. As the finish cut, the hemisphere with 60 µm diameter was machined [46]. Figure 8.26b shows the single crystallites of the steel that is cut without changing the texture. Micro cube has been machined into SS foil with flat

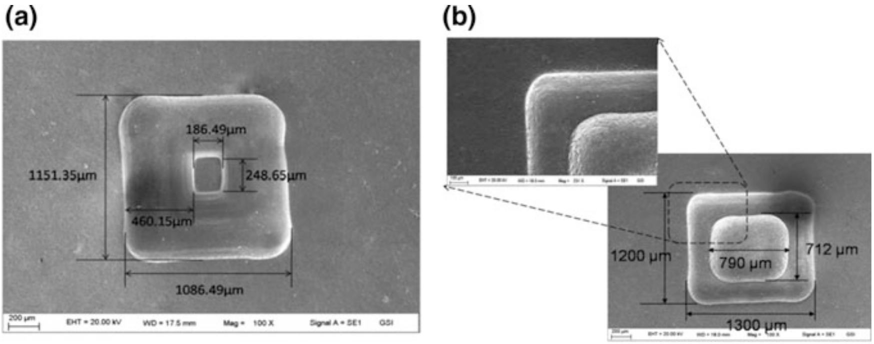


Fig. 8.25 3D microstructures with plane surfaces

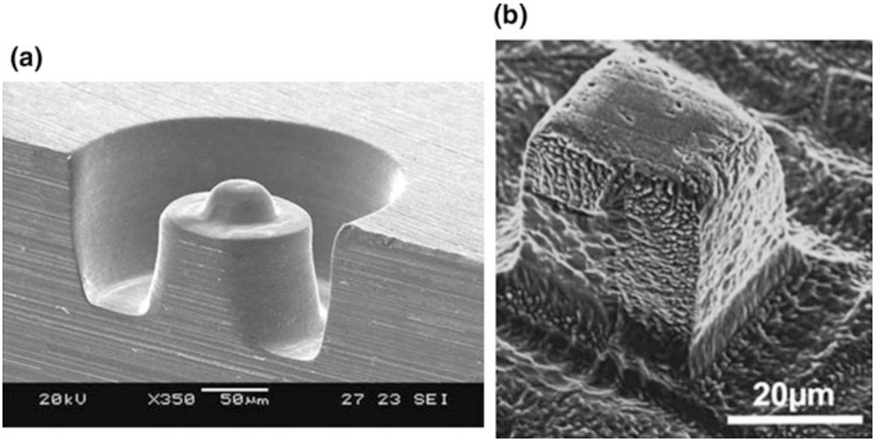


Fig. 8.26 Complex 3D microstructures **a** micro hemisphere [46] **b** micro cube [58]

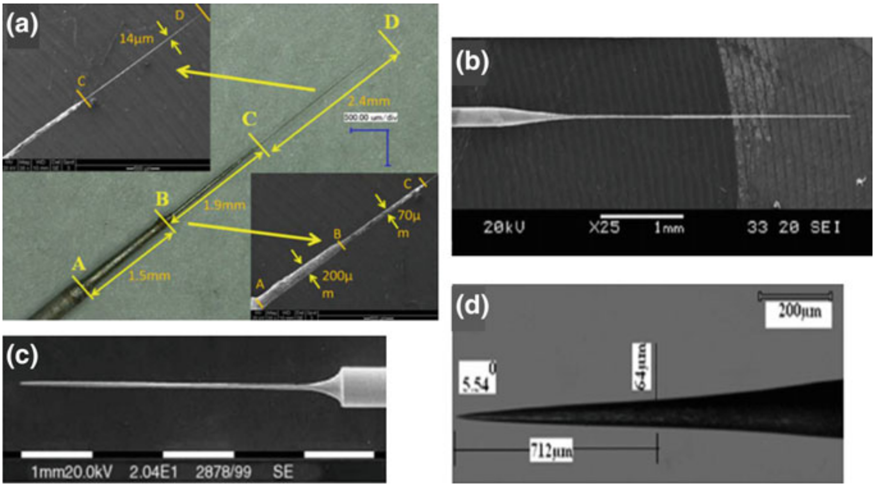


Fig. 8.27 Microrods fabricated by EMM **a** microelectrode of 5.8 µm length with diff. diameters [47] **b** WC micro-shaft of ϕ 5 µm diameter and 3 mm length [48] **c** micro electrode of ϕ 50 µm [49] **d** sharp conical microtool [50]

end cylindrical wire having 50 µm diameter. Upon applying pulse frequency 1 MHz, 100 ns pulse period, voltage 2 V, the wire was fed 30 µm into the work-piece vertically, followed by lateral movement along a rectangular path. Sharp grain boundary to a crystal with a different orientation can be seen in the lower left part on the front face of the cube.

8.11.1.4 Micropins or Microtools

Micropins or microrods of different shape and size are used for different applications, such as ultra high aspect ratio penetrating metal microelectrodes can be used in biomedical applications for painless surgery [47]. Microrods can also be used as microtools in EMM for machining of various micro features. These types of micropins or microrods of different features can be easily fabricated by reverse EMM by regulating various process parameters [48, 49]. Figure 8.27 shows the various microtools fabricated by EMM.

8.11.1.5 Disc Shape Microtools

Disc shape microtools have already proven their effectiveness in EMM for machining of taper free micro features. Disc shape microtools of different features namely disc height, disc diameter, shank diameter, and shank height can also be fabricated by EMM. Figure 8.28 shows the microscopic image of precise disc shape microtool fabricated by EMM from microrod of 300 µm diameter, under the machining conditions of applied voltage 1 V, 1 MHz, 80% DR, and 1 M NaOH

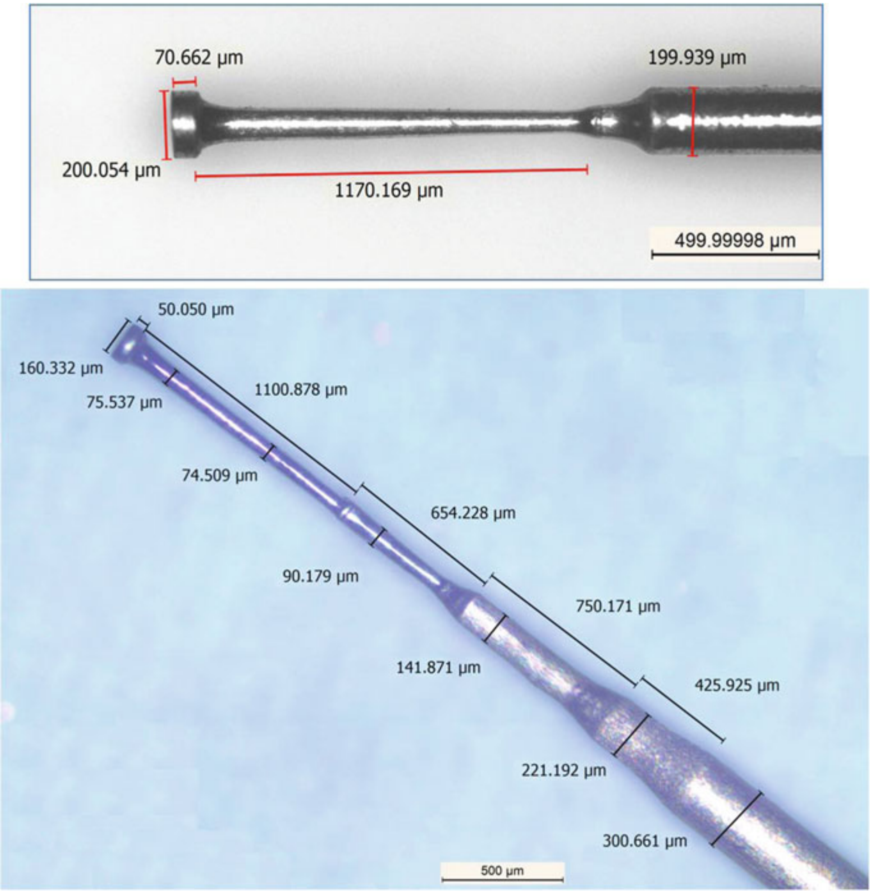


Fig. 8.28 Disc shape microtools fabricated by EMM

electrolyte [51]. For achieving strength and rigidity to the microtool, disc microtool has been fabricated in multiple steps of diameter reduction.

8.11.2 *Finishing Applications*

Micro components fabricated by different methods may consist of uneven and sharp edges, microburrs, and rough surfaces, which needs further finishing operations to make them suitable for various applications. Finishing of such micro components is a challenging task due to the size limitations. EMM can be effectively utilized for finishing of different micro components. Some of the finishing applications using EMM are specified as:

8.11.2.1 Finishing of Print Bands

The print bands used in high-speed impact printers are fabricated from stainless steel. The print band system consists of group of formed characters. Precise location of all the characters on a band is achieved through timing marks. The characters and timing marks on the print bands must have special characteristics to meet the desired trade-off between ribbon life and print quality. Bands with round-edge characters increase the ribbon life. To provide a high degree of character rounding, the EMM should involve a high rate of dissolution. Surface finishing of print bands is most important in print band manufacturing process. An electropolishing process has been developed that gives microsmooth surfaces of print bands. Figure 8.29 shows a print band (a) before finishing and (b) after electropolishing and character rounding [52].

8.11.2.2 Edge Finishing

Electrochemical micro finishing can be successfully utilized to remove microburrs from the cutting edge of micro structures. The process uses a very simple fixture for microburr removal. Figure 8.30 shows the microscopic images of micro channel junction machined with conventional micromachining milling in minimum quantity lubrication. Excessive burrs can be clearly seen at the junction before processing, that has been removed after polishing [53].

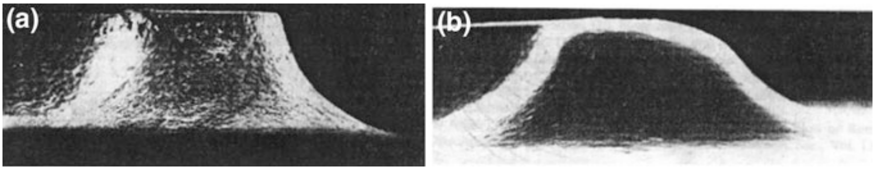


Fig. 8.29 SEM micrograph of a print band character

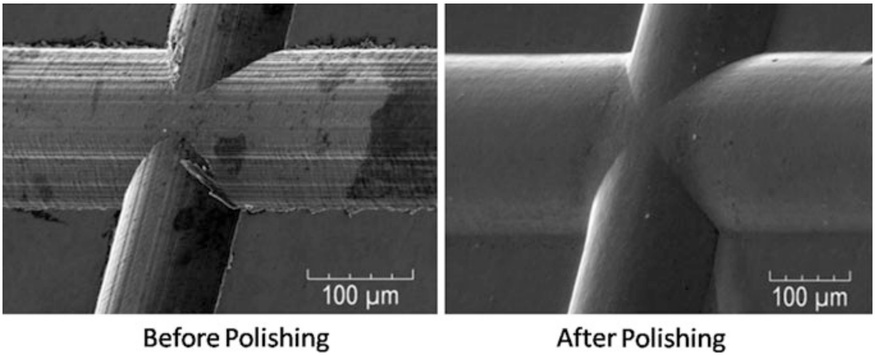


Fig. 8.30 Micro channel junction before and after polishing

8.11.3 Surface Engineering Applications

Surface quality is an important property of the microproducts, as it affects the performance and service life of products. Different types of surface topography can be engineered on industrial products by EMM. Microscopic features on the surface of the product may provide different advantages during various engineering applications such as biomedical, tribological, and aesthetic. EMM offers viable means to produce surface engineering applications, since it involves the material dissolution at atomic level. EMM does not bring in mechanical and thermal residue stresses that are generally accompanied by laser micromachining or dry etching processes. Some of the surface engineering applications achieved by EMM can be described as:

8.11.3.1 Generation of Micro Pattern on Stainless Steel

Surface phenomena, particularly at the microscale, have played an elementary role in the development of many advanced fields such as energy, machining, optics, tribology, and biomedicine. Surface engineering features such as shape of the micro fabricated pattern, size, depth, and its functionality can be varied easily by changing the process parameters of EMM. Surface texturing with micro-dimple is a well known method for friction reduction under lubricated sliding contact. Figure 8.31 shows the micrographs of micro-dimple patterns machined on carbon steel machined with applied voltage 9.5, 2 μs pulse on-time and 10 s of nominal machining time, in 2 M sodium nitrate solution [54].

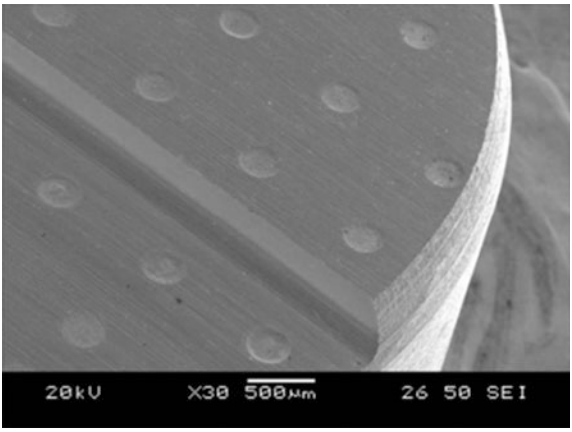


Fig. 8.31 Micro-dimple pattern on the step-shaped specimen [54]

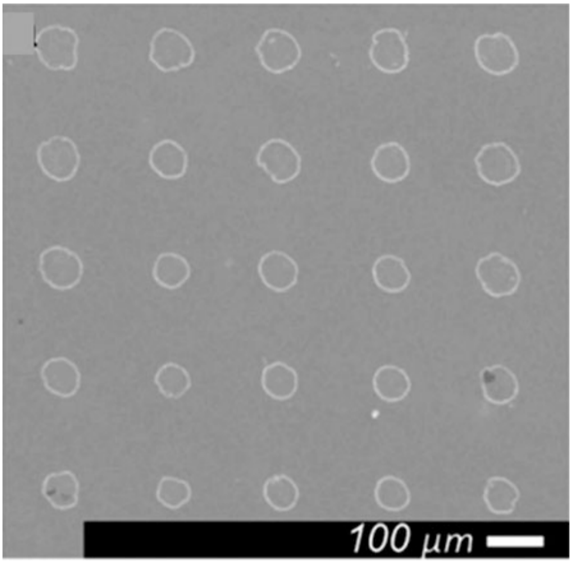


Fig. 8.32 SEM micrograph of a regular pattern machined on a titanium surface [55]

8.11.3.2 Surface Structuring of Titanium by EMM

Titanium and its alloy have very good mechanical and chemical properties, because of which they are in high demand for various engineering applications. Surface structuring of titanium is a main requirement in micro engineering and biomedical applications. EMM is one of the important process for surface structuring of titanium, whereas micro structuring of titanium surface is a challenging task due to the rapid formation of passive oxide layer, which obstructs the smooth anodic dissolution of titanium. Figure 8.32 shows SEM micrograph of a regular pattern machined on a titanium surface by 20 V, 200 ns pulse length and 20% duty cycle, using ethylene glycol as an electrolyte.

8.11.3.3 Surface Structuring for Biomedical Implants

Microscopic features on surfaces are critical factors that affect successful application of titanium as a load-bearing implant in orthopedic surgery. EMM offers a means to produce patterns on titanium surfaces. Figure 8.33 shows the microscopic image of microhole patterns machined on Ti6Al4V for biomedical applications. Jet electrochemical micromachining (jet-EMM) is used to machine microholes with a high aspect ratio on titanium surfaces. The etching process was con-ducted with a voltage of 200 V and average current of 45 mA.

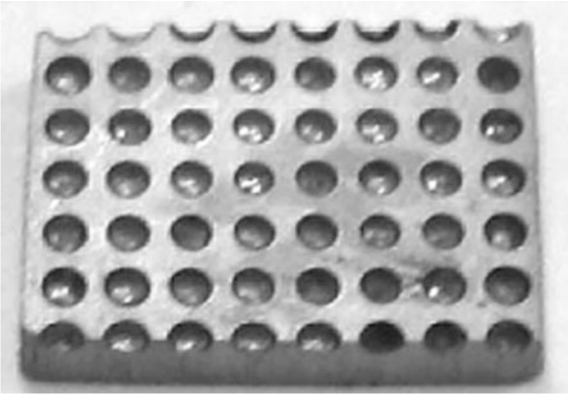


Fig. 8.33 SEM micrographs of microholes produced on the Ti6Al4V [56]

8.12 Recent Advances in EMM

Anodic dissolution in EMM can be utilized for metal removal in micro as well as nanoscopic level, because of which EMM has emerged as one of the best alternatives for fabrication of micro components with high quality and precision economically. In recent years EMM technology has been introduced to meet the increasing demands of advanced micro as well as nanoscale applications in various fields of applications. Over the years through research and development in this area, EMM has diversified its operational capabilities by the introduction of different features to exploit its potential in the area of submicron and nanorange fabrication. Different variants of EMM such as wire EMM, solid-state EMM, surface structuring by EMM, micropatterning and stamping by EMM, and nanofabrication by applying EMM have been established. Recent advancements in the area of EMM demonstrating the potential of EMM as a solution to the various challenging problems especially those that arise in the micro and nanofabrication areas have been presented as:

8.12.1 Fabrication of Micro Features for MEMS

Basic properties and characteristics of the materials are to be retained after fabrication of microdevices for MEMS. Advanced engineering such as copper, aluminum, steel, nickel, titanium, and their alloys, are some of the most suitable materials for the fabrications of mechanical microdevices. Machining of these materials is a difficult task, when features as well as components are in the microscale size. EMM can be successfully utilized for micromachining of various microfeatures made of different metals without altering the basic material characteristics and properties because of the unique mechanism of material removal by anodic dissolution at atomic level. Therefore the process can be precisely controlled

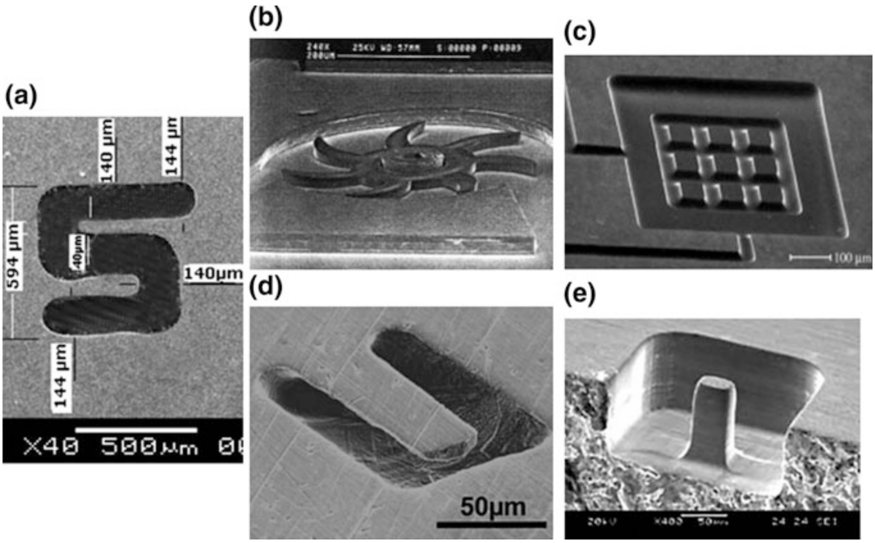


Fig. 8.34 **a** Channel-net of symmetrical micro cantilevers [45], **b** magnetically driven micro turbine of nickel [11], **c** two-level structure machined in titanium [57], **d** freestanding micro cantilever [58], **e** high-aspect-ratio micro column [46]

with submicrometer resolution to achieve highly accurate microfeatures that are most acceptable for MEMS. Electrochemical micromachining of various microfeatures proposed for microdevices that are well suited for functional applications of MEMS have been attempted by various researchers detailed as:

Figure 8.34a shows microscopic image of taperless and through, microchannel band generated by the straight cylindrical micro tool of 115 µm diameter in SS sheet of 35 µm thickness. Machining parameters were 5 MHz pulsed frequency, 0.2 M H_2SO_4, 40% duty ratio, sinking depth 75 µm, and feed rate along the path was 0.781 µm/s [45]. Figure 8.34b shows the magnetically driven micro turbine fabricated by electro-deposition of magnetic alloys through ultraviolet-patterned photo-resist on nickel. The casing and the axis in the middle have been fabricated by electro deposition of 50 µm thick Ni, whereas the wheels have been fabricated in a separate substrate by electro deposition of 40 µm thick NiCo alloy having diameter of 400 µm. Figure 8.34c shows SEM image of multilevel microstructure machined on titanium using oxide film laser lithography which can be utilized for MEMS applications. Figure 8.34d shows the freestanding micro cantilever of 80 µm long, 32 µm wide, and 11 µm thick fabricated in stainless steel by EMM using ultrashort voltage pulse and microtool of 10 µm Pt wire as microtool. Use of EMM milling strategy with a disk-type electrode, ultrashort pulses tens of nanosecond duration, and 0.1 M sulfuric acid, enables the machining of 3-D microstructures of high aspect ratio on SS as shown in Fig. 8.34e.

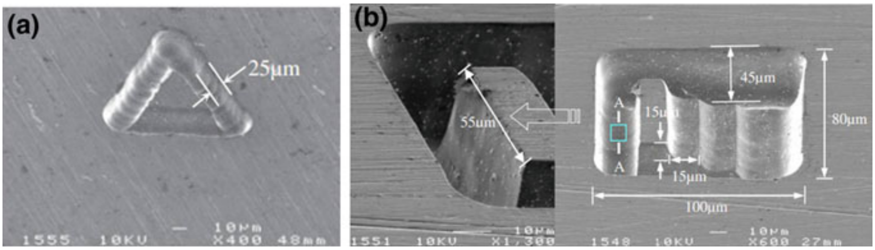


Fig. 8.35 Complex microstructures by micro electro-chemical milling **a** 2D micro complex shapes, **b** 3D micro structure with three step [59]

Micro-scale metal complex structures have a wide range of application in many fields, including biomedicine and aviation. Micro electrochemical milling can be applied to the fabrication of micro metal parts also. Figure 8.35 shows complex 2D and 3D micro metal structures machined on the hard-to-cut material super alloy plate, utilizing microtool of 10 μm diameters. 2D micro shape having width of about 25 μm, and 3D structure with three steps has been machined with machining feed rate of 1 μm/s, nanosecond pulses with pulse amplitude of 4.5 V, pulse on time of 95 ns, and pulse period of 1 μs, with milling layer thickness of 5 μm. The total depth of the cavity is about 45 μm, and each single-step size was about 15 × 55 × 15 μm [59].

Micro features like microgrooves and microholes are to be machined on majority of the microdevices in various applications such as microactuators, micropumps, and microdies etc. Presently the demands of microgrooves and microholes with internal features have increased, since specific cross-sectional shape i.e., geometry and internal surface quality, improves product functionality as well as product performance. If the microgrooves and microholes contain different internal features, the fabrication of microgroove becomes difficult. These types of microfeatures can be easily machined by EMM by regulating the process parameters during machining. Figure 8.36 shows microgrooves and microholes with different internal features machined by EMM using sidewall insulated microtool. EMM has successfully proved its capability as an alternative technique for machining different micro features, high-aspect-ratio 3-D microstructures with high resolutions for MEMS and various micro engineering applications.

8.12.2 Solid-State EMM

Solid state EMM is an application of anodic electrochemical reaction at micro contact between the ion conducting microelectrode and metal substrate as a result of continuous application of direct current. The metal substrate is locally incorporated into the ionic conductor in the form of metal ions through the micro contact [61]. This method can easily control the machining size and depth by adjusting the

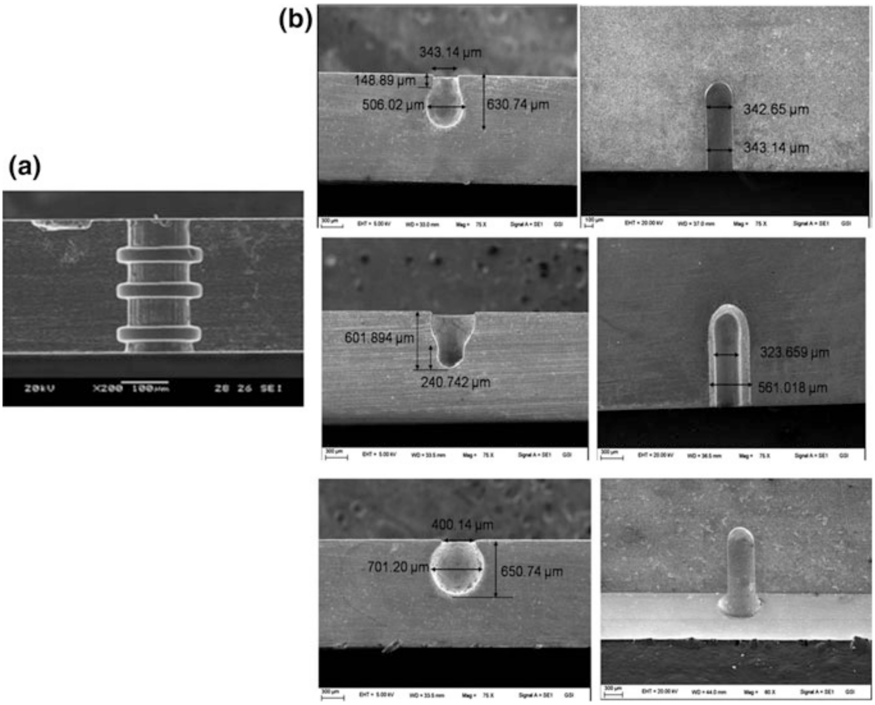


Fig. 8.36 **a** Micro hole with array of internal microgrooves [60], **b** microgrooves with internal features, machined by EMM

contact areas, i.e., shape of the apex or other electrochemical machining parameters. Figure 8.37a shows the basic arrangement of solid-state EMM cell silver with pyramid like microelectrode as cathode and target metal substrate M: Ag or Zn as anode in the system. SEM image of the Ag surface after micromachining under a constant current of 100 μA for 7 min at 873 K, is as shown in Fig. 8.37b.

8.12.3 Wire-EMM

Wire electrochemical micromachining is a novel method for machining of high aspect ratio metallic microstructures by electrochemical micro machining using very thin micro wire as a tool. Figure 8.38 illustrates the principle of Wire EMM, utilizing tungsten micro wire as tool instead of complex shape electrodes. During machining, ultra short voltage pulses are applied between workpiece as anode and wire electrode as cathode that are separated by narrow IEG ranging from 1 to 10 μm. Electrolyte flows around the micro wire electrode accompanying bubbles up and process by-products. Workpiece material dissolves electrochemically and narrow groove is produced as the cathode wire moves towards the anode

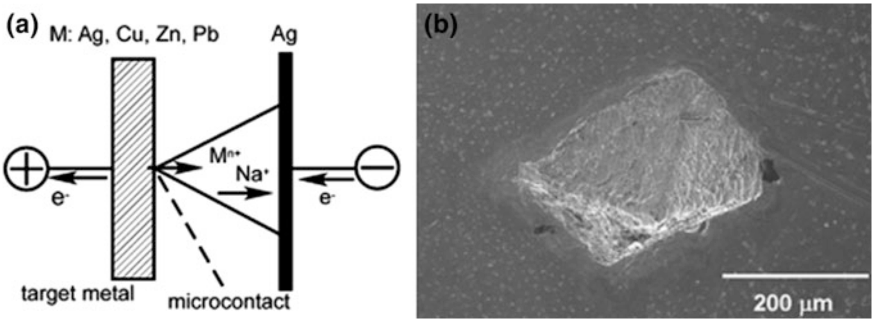


Fig. 8.37 **a** Basic arrangements of solid-state electrochemical micromachining **b** pyramid-shaped micro-features fabricated by SSEM [62]

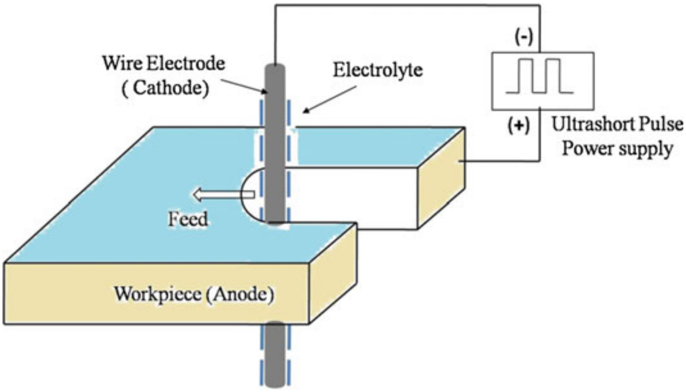


Fig. 8.38 Schematics of wire EMM

workpiece. The motion and path of the micro wire electrode is controlled by computerized numerical control system, and complex shape parts of high aspect ratio can be fabricated. Different process parameters of WECM such as feed rate, pulse voltage, and pulse on time influence the size of the machining gap that affects the machining accuracy. Very thin wires of diameter 5–10 μm are used in this process [63]. Platinum, tungsten, and copper are some of the common types of wires used in wire-EMM.

In WEMM microstructures with high aspect ratio up to 30 could be fabricated by electrolyte flushing and wire traveling. However, with further increase in aspect ratio, machining gap becomes extremely narrow and long, during which electrolyte flushing is less effective. Mass transport inside the machining gap plays an important role in WEMM. The machining stability, the material removal rate and surface quality can be significantly improved by introducing microwire vibration along with electrolyte flushing and wire traveling during machine [64].

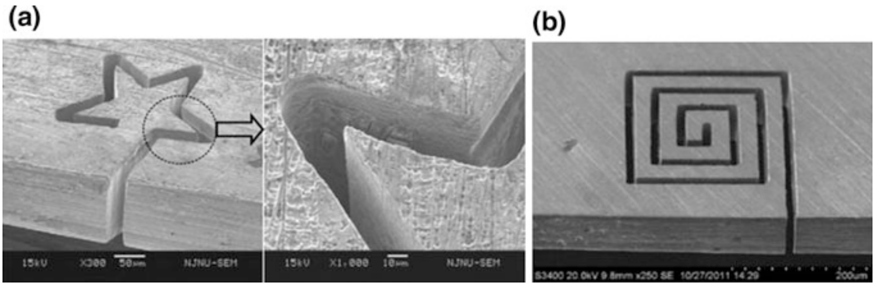


Fig. 8.39 Micro structures by WEMM **a** complex micro structure [63], **b** micro square helix [64]

Figure 8.39a shows the SEM image of with the slit width of 20 µm machined using micro tungsten wire with the diameter of 5 µm, wire feed rate 0.125 µm/s., slight vibration of workpiece with the frequency of 5 Hz, nanosecond pulses with pulse amplitude of 4.2 V, on-time of 50 ns and off-time of 1 µs [63]. Figure 8.39b shows the SEM image of micro square helix fabricated with 10 µm tungsten wire and 2 Hz wire vibration [64].

8.12.4 Nanofabrication by EMM

Anodic dissolutions can be controlled to atomic scale in EMM, which permits the use of EMM for nanofabrication in many applications. Use of ultrashort voltage pulses of nanosecond duration, material dissolution can be localized by spatial confinement of electro-chemical reactions which leads to high precision machining of metallic materials with nanometer accuracy. Use of few pulses of ultrashort duration, complicated shapes in the nanoscale can be fabricated on the workpiece by utilizing an appropriate shaped microtool containing nanofeatures, which allows parallel nano-fabrication that is difficult to attain by traditional techniques.

Figure 8.40a demonstrates the improvement in machining resolution improves with reduction in pulse duration, while machining troughs by EMM on nickel sheet with different pulse durations, machining voltage 2.2 V, 10% duty ratio, 0.2 M HCl and feed rate of 2 µm/min with tungsten tool tip of 2 µm diameter [65]. Figure 8.40b shows a spiral trench machined into Ni sheet with 3 ns pulses and 2 V. The depth of the spiral trench is about 5 µm and surface roughness is less than 100 µm. It proves that application of ultrashort voltage pulse in EMM may improve the precision up to the nanometer range. Figure 8.41 shows SEM images of high aspect ratio nanometer features fabricated by EMM in nickel sheet with 2 ns pulse duration, machining voltage of 2.2 V, 10% duty ratio, and 0.05 M HCl electrolyte [66]. The width of parallel lines in the center of the fabricated structure is 90 nm. The nanometer features are machined in very short period of time, hence the same microtool or array of microtools can be repeatedly utilized for mass production.

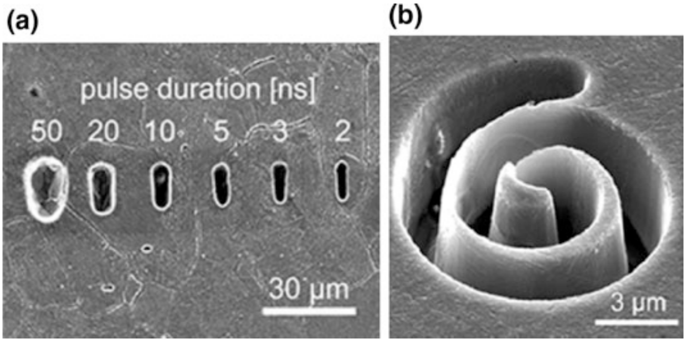


Fig. 8.40 **a** Influence of pulse duration **b** spiral trench on Ni sheet by EMM [65]

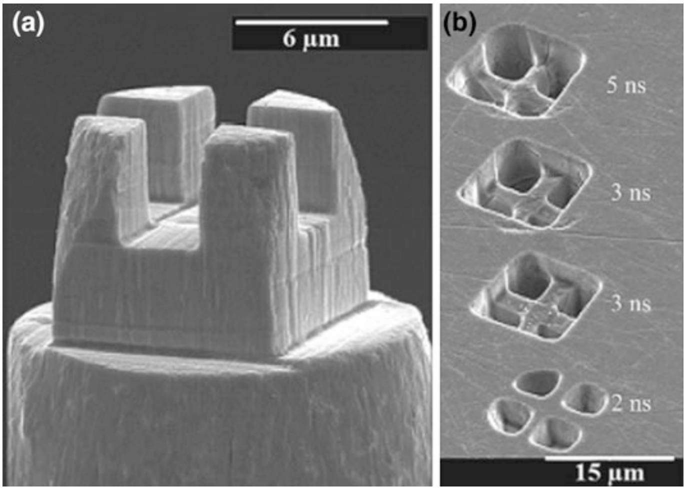


Fig. 8.41 **a** Tungsten microtool fabricated by FIB, **b** nano-features fabricated by EMM [66]

Application of ultrashort voltage pulses with very small IEG in EMM improves the machining precision to nanoscale and provides an alternative to the existing nanoscale fabrication techniques which are mostly limited to two-dimensional structures. EMM can also be successfully utilized for nano-fabrication of three-dimensional structures economically, and in shorter time which is still a challenge to the researchers. However, the area of EMM requires in-depth research to make it commercially successful in various nanotechnology applications.

8.13 General Conclusions

Electrochemical micromachining has become one of the most important micromachining process because of its numerous advantages. This chapter on electrochemical micromachining highlights the fundamental concepts in EMM process, role of EMM in micromachining, material removal mechanism, types of EMM, important process parameters, challenges in EMM setup development, and applications of EMM in various fields along with the recent advancements of it. The EMM technique can be efficiently applied for precise machining applications such as fabrication of micronozzles, microholes, slots, three dimensional micro structures, and micropins or microtools of high aspect ratio. EMM can also be applied effectively for surface finishing applications like edge finishing of print bands, and surgical blades, and also for the generation of micro pattern on stainless steel, and for biomedical implants, etc. Extensive research efforts and continuous developments are required for effective utilization of EMM in various fields of applications. This may include the improvements in machining setup, microtool design and development, monitoring and control of IEG, control of material removal and accuracy, power supply, elimination of micro sparks generation in IEG and selection of electrolyte to enhance the applications of EMM technology in modern industries. For better control over the material removal i.e. improving the machining accuracy in EMM, geometry of microtool, sidewall insulation of the microtool, supply of fresh electrolyte at narrow machining zone, and eliminating micro sparks at IEG during machining are the important factors to be focused. EMM offers many opportunities that have been unexplored till now. Further research in EMM will open up many challenging possibilities for effective utilization of ECM in the microscopic domain. Electrochemical Micromachining technique will be more successful and will be able to play a key role in micro and nano fabrication considering its advantages i.e., quality, flexibility, productivity and ultimately cost effectiveness.

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