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Need & Overview of Electrochemical Micro Machining

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Abstract: Material removal techniques have a pivotal role to play in component fabrication. In recent years many high strength alloys are extremely difficult to machine using the traditional processes. The major difference between conventional and non-conventional machining processes is that conventional processes use a sharp tool for material removal by physical means where as the non-conventional techniques remove material by utilizing chemical, thermal, or electrical energy or a combination of these energies. These alloys were developed for a variety of industries ranging from aerospace to medical engineering. Machining these alloys with conventional tools results in subsurface damage of the workpiece and in tool damage. The tool size and geometry limit the final component shape that can be machined. Another problem with these tools is that they tend to leave burrs on the machined surface. These burrs are undesirable in many applications. For example, in the medical industry the presence of even very small burrs will damage living tissues where these machined parts are used as implants. In electronic devices where a number of components are in close contact, the burrs may lead to short circuits. In mechanical components burrs may result in a misfit. Hence in this paper discussed in brief about the need and overview of EMM.

Keywords: Electrochemical Micro Machining (EMM), Electro chemical Machining (ECM), Inter electrode Gap, Electrolyte, Micro Tool.

Introduction

The machining processes are non-traditional in the sense that they do not employ traditional tools for metal removal and instead they directly use other forms of energy. The problems of high complexity in shape, size and higher demand for product accuracy and surface finish can be solved through non-traditional methods. Currently, non-traditional processes possess virtually unlimited capabilities except for volumetric material removal rates, for which great advances have been made in the past few years to increase the material removal rates. As removal rate increases, the cost effectiveness of operations also increase, stimulating ever greater uses of non- traditional processes.

In non- traditional machining, most of the processes are thermal oriented, eg Electric Discharge Machining (EDM), laser beam machining (LBM), Electron beam machining (EBM), etc., which may cause thermal distortion of the machined surface. Chemical machining and electrochemical machining are thermal free processes, but chemical machining cannot be controlled properly as discussed by Bhattacharyya et. al. [1].

Electrochemical machining (ECM) can machine these alloys. Devices are becoming smaller as time progresses but their features are increasing at the same time. Machining materials on micro and sub-micro scale is considered a key technology for miniaturizing mechanical parts and complete machines.

Electrochemical Machining (ECM) is the controlled removal of metal by anodic dissolution in an electrolytic cell in which the work piece is the anode and the tool is cathode. ECM is widely used in machining of jobs involving intricate shapes and to machine very hard or tough materials those are difficult or impossible to machine by conventional machining. It is now routinely used for the machining of aerospace components, critical deburring, fuel injection system components, ordnance components etc. ECM is also most suitable for manufacturing various types of dies and moulds.

Micro manufacturing techniques find application in various industries such as electro-communications, semi-conductors, medicine, and ultra-precision machinery. A suitable manufacturing technique for mass production of these micro scale components needs to be established.

Electrochemical Machining

Electrochemical machining is a material removal process similar to electro plating. In this process, the work piece to be machined is made as anode and the tool is made as cathode of an electrolytic cell with a salt solution being used as an electrolyte. On the application of a potential difference between the two electrodes and when adequate electrical energy is available between the tool and the work piece, positive metal ions leave the work piece. Since electrons are removed from the work piece, oxidation reaction occurs at the anode. The electrolyte accepts these electrons resulting in a reduction reaction.

Hence the positive ions from the metal react with the negative ions in the electrolyte forming hydroxides and thus the metal is dissolute forming a precipitate. The electrolyte is constantly flushed in the gap between the tool and the work piece to remove the unwanted machining products which otherwise would grow to create a short circuit between the electrodes. The electrolyte also carries away heat and hydrogen bubbles. The tool is advanced into the work piece for the machining to be carried out. A pump system must filter the electrolyte and circulate it because the electrolyte carries away machining waste. The block diagram of ECM set up is shown in the following figure 1.

In ECM metal removal is obtained by anodic dissolution of the work piece. The shape of the anodic dissolution will be that of the mirror image of the shape on the cathodic tool. Hard metals can be shaped electrolytically by using ECM and the rate of machining does not depend on their hardness. The tool electrode used in the process does not wear, and therefore soft metals can be used as tools to form shapes on harder work pieces, unlike conventional machining methods. The tool is guided towards the work piece to maintain a constant inter-electrode gap between them. In some process conditions, that are too high movement of the tool towards the work piece, a contact between the two electrodes occurs. This causes a short circuit between the electrodes and hence premature termination of machining. Under short-circuit conditions the gap width goes to zero. Hence a constant inter electrode gap should be maintained for the machining operation to be carried out on the given work piece.

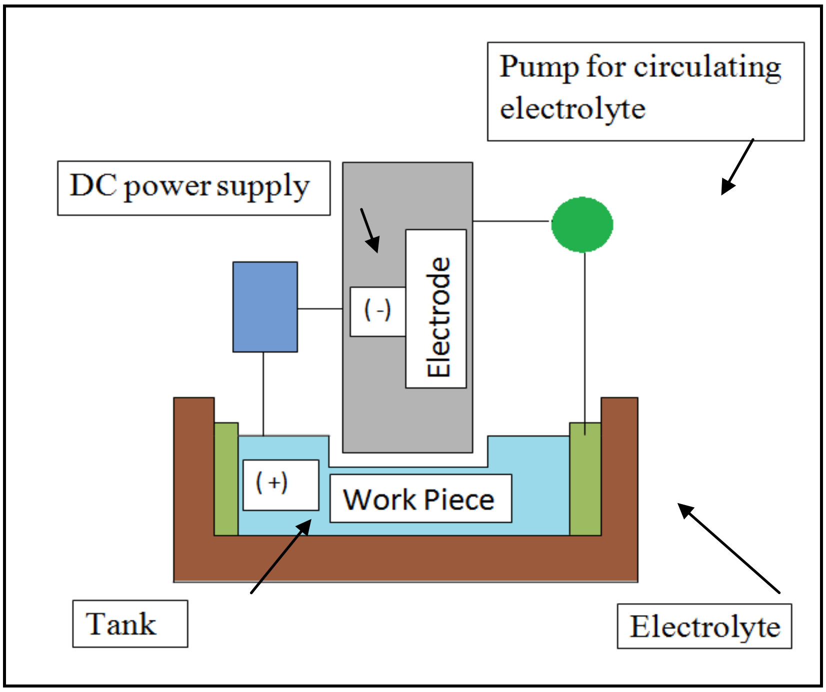

Figure 1 Block Diagram of ECM (as discussed by Sriharsha [8])

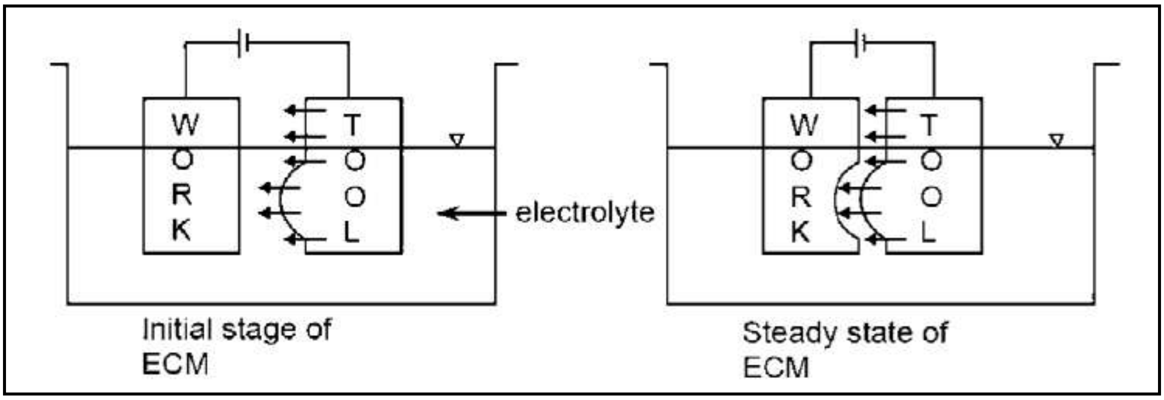

Figure 2 ECM Reactions (as discussed by Umasankar Mallick [2])

Theory of Electrochemical Machining

Electrochemical machining is developed on the principle of Faradays law. In this process the work piece to be machined is made the anode and the tool is made the cathode of an electrolytic cell with a salt solution being used as an electrolyte. The metal is removed by the controlled dissolution of the anode according to the well known Faradays law of electrolysis. When the electrodes are connected to electric supply source, flow of current in the electrolyte is established due to positively charged ion being attracted towards cathode and vice-versa. Due to electrolysis process at cathode hydroxyl ion are released which combine with the metal ions of anode to form insoluble metal hydroxide. Thus the metal is removed in the form of sludge and precipitated in electrolytic cell. This process continues till the tool has produced its shape in the work piece.

During ECM, there will be reactions occurring at the electrodes. Let us take an example of machining of low carbon steel which is primarily a ferrous alloy mainly containing iron. For electrochemical machining of steel, generally a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte. The electrolyte and water undergoes ionic dissociation as shown below when potential difference is applied.

$$NaCl \leftrightarrow Na^{+} + Cl^{-} \qquad\qquad H_2O \leftrightarrow H^{+} + (OH)^{-}$$

As the potential difference is applied between the work piece (anode) and the tool (cathode), the positive ions move towards the tool and negative ions move towards the work piece. Thus the hydrogen ions will take away electrons from the cathode (tool) and liberates hydrogen gas.

$$2H^{+} + 2e^{-} = H_2$$

Similarly, the iron atoms will come out of the anode (work piece) as:

$$Fe = F^{++} + 2e^{-}$$

Within the electrolyte iron ions would combine with chloride ions to form iron chloride and similarly sodium ions would combine with hydroxyl ions to form sodium hydroxide.

$$Na^{+} + OH^{-} = NaOH$$

In practice $FeCl_2$ and Fe $(OH)_2$ would form and get precipitated in the form of sludge. In this manner it can be noted that the work piece gets gradually machined and gets precipitated as the sludge. Moreover there is not coating on the tool, only hydrogen gas evolves at the tool or cathode. Figure 2 depicts the electro-chemical reactions schematically. As the material removal takes place due to atomic level dissociation, the machined surface is of excellent surface finish and stress free.

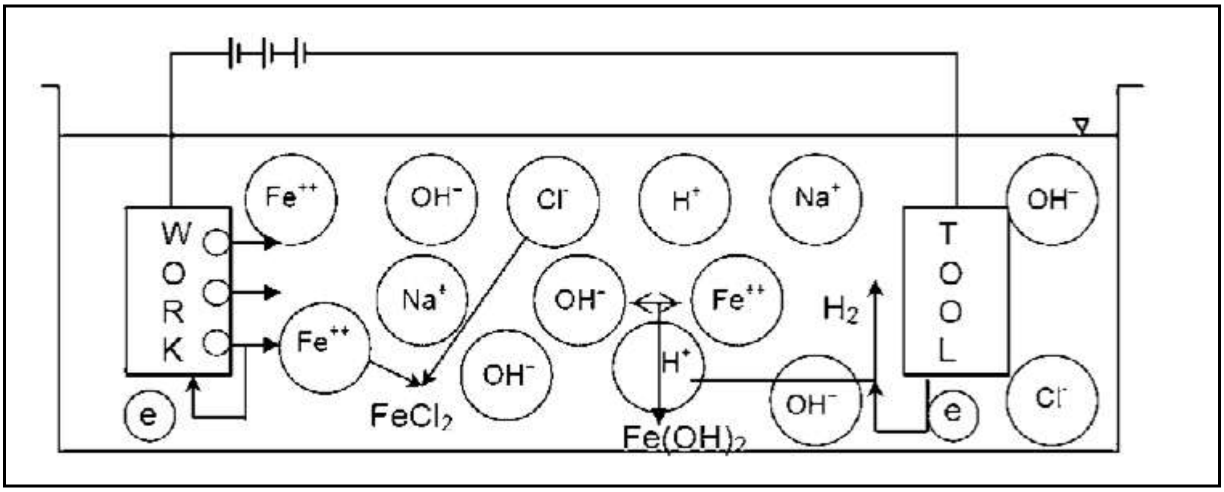

Figure 3 Schematic representations of ECM reaction (as discussed by Umasankar Mallick [2])

Reaction at anode

$$Fe \leftrightarrow Fe^{2+} + 2e$$
$$Fe^{2+} + 2Cl \leftrightarrow FeCl_2$$
$$Fe^{2+} + 2OH \leftrightarrow Fe(OH)_2$$
$$FeCl_2 + 2OH \leftrightarrow Fe(OH)_2 + 2Cl$$
$$2Cl^{-} \leftrightarrow Cl_2(g) + 2e^{-}$$
$$2FeCl_2 + Cl_2 \leftrightarrow 2FeCl_3$$
$$H^{+} + Cl^{-} \leftrightarrow HCl$$
$$2Fe(OH)_2 + H_2O + O_2 \leftrightarrow 2Fe(OH)_3 \downarrow$$
$$Fe(OH)_3 + 3HCl \leftrightarrow FeCl_3 + 3H_2O$$
$$FeCl_3 + 3NaOH \leftrightarrow Fe(OH)_3 \downarrow + 3NaCl$$

Reaction at cathode:

$$Na^{+} + e^{-} \leftrightarrow Na$$
$$Na + H_2O \leftrightarrow Na(OH) + H^{+}$$
$$2H^{+} + 2e^{-} \leftrightarrow H_2$$

It shows that only hydrogen gas will evolve at cathode and there will be no deposition.

Faraday's law of electrolysis

In electrolytic cell material removal is governed by Faraday's law of electrolysis which states that,

i. The amount of chemical change produced by an electric current or the amount of substance deposited or dissolved is proportional to the quantity of electricity passed.
ii. The amounts of different substances deposited or dissolved by the same quantity of electricity are proportional to their chemical equivalent weights

The Faraday's law indicates a relation between the numbers of electrons removed from an atom and the mass of the atom that would dissolve into electrolyte. The simple expression of Faraday's law can be described as:

m=k I t

Where,

m is the mass
k is the electrochemical equivalent of the anode metal (*=A/(Z・F)* in (g/C))
A is the atomic weight of dissolving ions
Z is the valence of dissolved ion immediately after dissolution
F is the Faraday's constant of 96,487 Coulombs(*C*)
I is the electric current (*A*)
t is the machining time

However, instead of assumption that all current is used to ionize the workpiece atoms during the process ECM, some of the current goes into other undesirable electrochemical reactions. Therefore, an efficiency term (η_I), which can describe the percentage of current applied to dissolve atoms in the overall current, is necessary. By using the electrochemical equivalent equation yields to:

m= η・k ・ I ・t

The dissolution of metal from the workpiece surface is the only useful reaction in the process of ECM and all the other reactions such as metal deposits on the tool and the production of gas contributes little to a loss of machining current.

Need for Electrochemical Micromachining

In recent years devices are becoming smaller and their features are increasing at the same time. Micromachining technology plays an increasing key role in the miniaturization of components ranging from biomedical applications to chemical micro rectors and sensors. Since miniaturization will continue as long as people require effective space utilization with more efficient and better accuracy products, micro machining technology will be still more important in the future. Micromachining refers to small amount of material removal of dimensions that ranges from 1 to 999 µm. The fabrication of microstructures by ECM is known as Electrochemical Micro Machining (EMM). The machining gap (distance between tool and work piece) of conventional ECM is as large as 0.1–0.7 mm. If it is possible to make the machining gap of ECM smaller, then ECM can be applied for micromachining. Attempts to be made to shorten the machining gap are:

i. Using pulsed power supply.

ii. An insulating film coating on the side surface of an electrode to prevent the undesired removal of work material.
iii. Controlling the electrode position by contact detection to maintain the micromachining gap.
iv. Using an electrolyte concentration that is less than conventional ECM.
v. Applying a smaller machining voltage than conventional ECM.

A general comparison between ECM and EMM is presented in Table 1.

Table 1 Comparisons between ECM and EMM (as discussed by **Bhattacharyya et al., [3])**

Parameters	**ECM**	**Micro ECM**
Voltage	10-30 V	<10v
Current	150-10000A	<1A
Current density	20-200A/cm^2	75-100A/cm^2
Power supply-DC	Continuous/pulsed	Pulsed
Frequency	Hz-KHz range	KHz-MHz range
Electrolyte flow	10-60m/s	< 3m/s
Electrolyte type	Salt solution	Natural salt or dilute acid/alkaline solution
Tool size	large to medium	Micro
Inter electrode gap	100-600 um	5-50 um
Machining rate	0.2 - 10 mm/min	5 um/min
Surface finish	Good	Excellent

Major Factors of EMM

In order to achieve the effective and high precision machining in the order of microns, the process variables of the EMM system will have to be optimally controlled as discussed by Kozak et al. [4]. Some of the predominant process parameters, which have major influences on EMM criteria, as discussed by Bhattacharyya et al. [3], are identified as follows:

i. Nature of power supply,
ii. Inter electrode gap, i.e. gap between the micro-tool and the work piece,
iii. Electrolyte
iv. Temperature, Pressure and flow rate of electrolyte, and
v. Micro-tool design.

Nature of Power Supply

The nature of applied power supply may be of two types, Direct current (D.C) and pulse D.C. The EMM process needs low voltages of the order of 1 to 10 V. Normal current density requirements are very high in the order of 100 *AI* cm^2 for proper operation of the EMM process. It may give very high concentration of reaction products, which can only be partly removed by the electrolyte, particularly if the end gap is very narrow. The increasing contamination can cause deposition on the micro tool, so that the work piece material no longer dissolves uniformly. Moreover, changes in the electrolyte composition and the temperature rise, and also the change of electrical resistivity can also make the accuracy poorer. These problems can be avoided by applying the pulsed DC voltage instead of continuous one as discussed by Rajurkar et al. , [5].

Pulsating current consist of three parameters such as pulse on-time, pulse off-time and peak current density, which can be varied independently in order to achieve the desired machining rate.

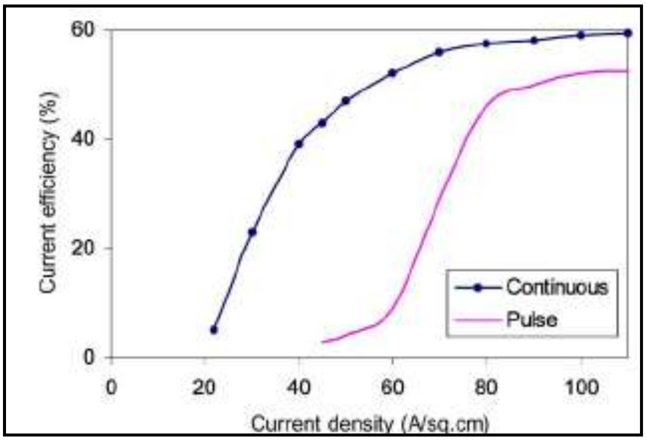

Figure 4 Current efficiency Vs current density

The pulse off-time should be long enough to ensure a complete flushing of the electrolyte out of narrow end gap. The current efficiency is much more dependent on the current density when pulsed voltage is used than the use of continuous voltage. As shown in figure 4 with the continuous DC voltage the efficiency decreases gradually when the current density is reduced, where as with the pulsed DC voltage the decrease is much more rapid. A steep fall in efficiency with decreasing current density improves the accuracy of the work piece. This improvement depends upon the pulse duration and to somewhat lesser extent on the interval. By using pulsating current, extremely high instantaneous current densities can be applied to the work piece. This is possible since each current pulse is followed by a relaxation time of zero current, which allows for removal of reaction products and heat from the inter electrode gap. Compared to direct current dissolution where only average current can be chosen, pulsating current has various parameters. By suitable choice 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 much lower than the direct ECM.

Inter electrode Gap (IEG)

The gap between the micro tool (cathode) and the work piece (anode) are called inter electrode gap (IEG). It is an important factor assures a stable metal removal in EMM processes. The inter electrode gap in conventional ECM is considerably larger than that of the EDM and the resolution of machining shape is inferior to EDM. However, if the electrode end gap is kept at very small value, the resolution of machined shape will become better and the possibility of applying ECM to micro machining will increase. Localization of the dissolution process can be increased by reducing the gap width. The gap width is only one parameter characterizing the micro-machining accuracy and precision. Maintaining the specific range of IEG, i.e. 15-20 µm uniformly is an important requirement to achieve high accuracy and surface finish. In a pulsed EMM system, the IEG and tool position monitoring can be done during pulse off-time, leading to a significant reduction in the indeterminacy of the gap. Machining inaccuracy is directly proportional to the IEG size.

The need for on-line monitoring arises due to numerous complexes, transient and stochastic processes occurring in the gap. From the on-line monitoring, linear correlation between the pulse signal variance and the gap size has been found. This relationship becomes significant when a shorter pulse on-time (<1 ms) is used and more importantly, it exists within the most gap range (0.1-0.2 mm) commonly used by industry. For on-line monitoring of IEG, application of eddy currents in a technique aimed at the implementation of a system for non-intrusive measurement of the gap as discussed by Bhattacharyya et al. [3]. This method achieves the measurement by determining the magnitude of an induced eddy current circulating in the work piece resulting from an emitting coil embedded in the tool. Some success is reported in the application of this method, but it leads to experimental ambiguities i.e. the composition and density of the work piece/tool, conductivity of electrolyte and size of micro tool affect the measurement. These factors would be particularly problematic in the implementation of a broad range of measurement system in EMM.

Radio frequency emission has also been used for the IEG monitoring and control. In ultrasonic measurement system, ultrasonic is used as a full passive (independent of process conditions) non-intrusive, on-line gap measurement, Such an approach has become practical due to recent developments in the resolution of ultrasonic sizing technologies. Using this, IEG can be measured by direct and indirect means. A direct measurement determines the gap based upon the propagation delay through the electrolyte between the tool surface/ electrolyte interface and work piece surface/ electrolyte interface. Indirect gap measurement would be computed by subtracting the tool face position from the work piece height referenced to the same origin.

Most of the methods as discussed for monitoring and measurement of IEG are actually applicable in the normal ECM process. However, these principles and methods can also be applied to the EMM process.

Electrolyte

The electrolyte is one of the main components of the machining system. The electron movement from the cathode to the anode is dependent on the properties of the electrolyte. The electrolyte conductivity in the gap between the cathode and the anode was dependent on the following parameters: the starting electrode distance, concentration of salt in the solution, local hydroxide concentration in electrolyte, bulk and local temperature, electrolyte flow rate, and the velocity of electrolyte as discussed by Jain [6]. High flow rates of electrolyte were not desirable as they caused tool erosion.

Surface brightening was achieved only under conditions where the dissolution mechanism was independent of structure. One of the main considerations in the design of the tool is that it should provide the desired agitation of the electrolyte. The control of electrolyte speed and flow direction was important for the machining process to continue. It is a difficult task to maintain the flow of electrolyte in the extremely small gap without affecting the tool stability as discussed by Rajurkar et al. [7].

Electrolyte removes the machining products generated at the electrodes and dissipates the heat generated. Machining performance is governed by the behavior of anodic work piece in a given electrolyte. In micro machining because of the small gap between the tool and the electrode, the density of current is very high which results in vaporization of the electrolyte. The electrolyte must be chosen in such a way that it does not vaporize and carries the machining products away from the work piece. Table 2 shows the electrolytes that can be used for various alloys in order to achieve the best results.

Table 2 Electrolyte for different alloys (as discussed by Sriharsha , [8])

Alloy	**Electrolyte**
Iron based	Chloride solutions in water
Ni based	HCl or mixture of brine and H_2SO_4
Ti based	10% HF + 10% HCL+10% HNO_3
Co-Cr-W based	NaCl
Wc based	String alkaline solutions

The main functions of the electrolyte are to provide the ideal conditions for the dissolution of the work piece material, conduct electricity, carry away the unwanted machining products and heat generated, and maintain a constant temperature in the machining gap. The accumulation of reaction products at anode and cathode was undesirable as they reduced the specific conductivity of the electrolyte.

Electrolytes need to satisfy certain requirements so that they can be used effectively for EMM process as discussed by Sriharsha,[8].

i. The cations and the anions present in the electrolyte should be such that the anions permit the dissolution of the work piece without forming a film on its surface and the cations do not deposit on the tool. The anions mostly used are chlorides, sulphates, nitrates, and hydroxides.
ii. The electrolyte needs to have a high conductivity and low viscosity so that it is able to flow easily in the narrow gap between the tool and the workpiece.
iii. The electrolyte should be such that it is non toxic, safe to use, and does not erode the machine. Neutral salt solutions are most commonly used as electrolytes.
iv. The electrolyte should be cheap and readily available and should not exhibit large variations in its properties as the machining progresses.

The selection of an electrolyte for a particular application depends on the following considerations:

i. The nature of the workpiece material.
ii. Surface finish and dimensional tolerance requirements.
iii. Productivity expected.

The electrolytes used in electrochemical machining can be broadly classified into two categories:

i. Passive electrolyte.
ii. Non - passive electrolyte.

Passive electrolytes contain oxidizing anions such as sodium nitrate and non-passive electrolytes contain aggressive anions such as sodium chloride. Passive electrolytes are known to give better machining precision due to formation of oxide films and oxygen evolution in stray current region. The electrolyte in the electrolytic cell could be divided into two zones, one near the electrode surface where a stagnant diffusion layer existed in which there was no convection and the other zone was the bulk solution where no concentration gradient existed because of perfect mixing. The current convection conditions existing in the solution affected the thickness of the stagnant diffusion layer. The thickness was estimated from dimensionless mass transport relations. The most commonly electrolytes are sodium chloride and sodium nitrate. The relationship between current efficiency and current density varies for each electrolyte and this relationship ultimately governs the material removal rate. Sodium nitrate is preferred over sodium chloride because at small gaps, the current density and the current efficiency are high resulting in a higher material removal rate where as at large gaps the current density and efficiency are low resulting in a low material removal rate. The electrolyte concentrations commonly used range from around 20 g/L to 35 g/L and a pH of around 7 that can enhance the dissolution of metal without affecting the micro tool.

By using an electrolyte with a lower concentration, inter electrode gap could be reduced resulting in improved accuracy as discussed by Thanigaivelan et. al.[9].The particular method chosen for supplying electrolyte to the machining gap depends on the process configuration. There are many ways by which the electrolyte can be supplied as discussed by Dharmalingam et. al [10].

i. The electrolyte is supplied continuously and allowed to flow through the gap and on the workpiece.
ii. The electrolyte is supplied through a capillary in the tool so that it flushes away the machining products.
iii. The tool and the workpiece are sprayed with an electrolyte continuously.

The electrolyte in the gap must be a good electrical conductor and should produce a slight passivation of the work piece surface. The types of electrolyte and pH value of the solution are chosen so as to ensure good dissolution of work piece material during the EMM process without the tool being attacked good choice is $NaNo_3$ solution.

Temperature and Pressure

The difference in the temperature of the electrolyte at the entrance and exit of the tool work gap is an important factor. Rise in temperature of electrolyte tends to decrease its specific resistance, but in contrast to that the insoluble sludge material increases the resistance. But these changes would definitely affect the flow rate/ pressure characteristics of the electrolyte. There are many advantages of using hot electrolyte too. An increase in the temperature speeds up the electrode reactions and reduces the requirement of higher voltages.

Concentration

A concentrated electrolyte offers low resistance to flow of machining current. A greater current density is achieved for a specific operating voltage. However, the disadvantage is that salts crystallize out of the solution at higher concentration and clog the areas in the machine enclosure. Dilute electrolytes are used when the surface finish is most important machining criterion. In the case of high machining accuracy, dilute electrolyte and a small gap should be employed instead of low voltage and concentrated electrolyte.

Electrolyte flow

The electrolyte is pumped from a storage tank via a pressure controller and a filter to the machining gap, e.g. through the designed flow path. Different electrolyte delivery systems that are applicable in EMM include channel flow, electrolytic jet, slotted jet and multi nozzle systems. It has been noted that jet induces defects in forms, which are influenced by the electrolyte flow hydrodynamics and especially by cavitations phenomenon. The improvement of machining accuracy in normal ECM can be achieved by modifying electrolyte flow distribution. Laminar flow of electrolyte in the IEG is the better choice for producing a machined product of better surface quality. After passing through the gap, the fluid goes to a settling tank, where the sludge is settled down. The fresh electrolyte is overflowed to another electrolyte tank though a filter to remove rest of the foreign materials present in the electrolyte. The concentration of dissolved impurities can be reduced by the addition of chemicals. So, the system should be well capable of circulation and purification of electrolyte.

Micro tool design

Tool design mainly deals with the determination of tool shape, which will produce a workpiece with proper dimensions and accuracy. The tool shape is a perfect negative mirror image of the workpiece to be produced. Micro tools are fabricated using electrochemical etching and wire electro-discharge grinding (WEDG). An accurate tool profile is achieved by controlling the current density and voltage. EMM is suitable for surface finishing of micro-pins and micro spindles. These micro-pins can be used as micro tools in EMM, which can improve accuracy. In general, the material for micro tools should consist of a chemically inert material, which has good electrical conductivity and which is easily machinable. The stray current effect in EMM is reduced by proper insulation of the micro so that current flows only through the front face. An insulating cover of SiC/Si_3N_4 may be coated onto the cathode tool by means of chemical vapour deposition (CVD), which can increase the accuracy and surface finish. The resin or bonding liquid can be used for insulating the micro tool. Giving an orbital movement, tool vibration to the cathode tool electrode can also increase accuracy. The bottom shape of the tool also affects the machinability of the workpiece. Hence the tool design should provide not only the cathode dimensions but also an appropriate electrolyte path to prevent undesired overcut.

Concluded Overview :

Advantages of Electrochemical Micro- Machining

For drilling micro-holes in the difficult to machine materials like turbine blades, EMM is the better choice because of the following features.

- There is no residual stress.
- Versatility to machine any kind of material.
- There is no problem of heat affected zone.
- There is no tool wear.
- Short machining time.
- Cost effective.
- High precision can be achieved.
- Good surface finish which makes this process more attractive for drilling holes for components exposed to high temperature.

Applications of Electrochemical Micro-Machining

Electrochemical machining finds majority of its applications in deburring and hole drilling. Burrs are undesirable in any machined work piece. Deburring the machined components manually is a time consuming process and also not effective. Electrochemical machining with its advantages is a suitable choice for deburring. Electrochemical micromachining can be used to machine either a single hole or a series of holes with the same characteristics. The typical applications of EMM technologies for the micro fabrication of components are introduced.

Surface finishing of print bands

Nozzle plate for ink-jet printer head

Cooling holes in turbine blades

Production of complex shapes

Automobile applications - monolithic accelerometer, which has been developed for airbag release and other automotive applications.

Micro fluidic devices and systems

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