

## ANALYSIS OF ELECTROCHEMICAL MICROMACHINING

GOVINDAN P<sup>1</sup>, ARJUN M<sup>2</sup>, ARJUN J<sup>3</sup> & AKSHAY S<sup>4</sup>

<sup>1</sup>Assistant Professor, Government College of Engineering Kannur, Kerala, India

<sup>2,3,4</sup>B. Tech Student, Government College of Engineering Kannur, Kerala, India

### ABSTRACT

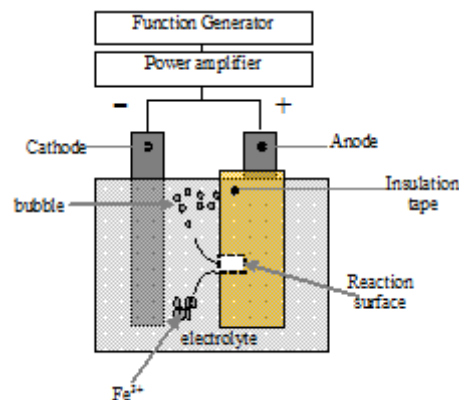
The present paper deals with the analysis of electrochemical micro-machining process at the basic level. This study has demonstrated the EMM process from both a theoretical and experimental point of views, based on earlier investigations. The functional aspects of EMM set-ups and systems were understood, considering the mechanism of removal as well as the precision of the machining process. Comparative analyses of the processing conditions governing the electrical and chemical aspects of the EMM process were performed. The input parameters chosen were: voltage ( $V$ ) and concentration of the electrolyte ( $C$ ). The effect of these parameters on productivity and quality of EMM were evaluated in terms of MRR and geometric overcut. It is observed that the maximum improvement in MRR with voltage and concentration were 100% and 70% respectively. The optimum processing conditions for EMM was obtained based on the parameter relationship graphs.

**KEYWORDS:** Electrochemical Machining, Micro-Machining, Inter-Electrode Gap, Electrolyte, Processing Parameter, MRR and Overcut

### INTRODUCTION

As world progresses, the need for precisely manufactured components became necessary. Accuracy and precision are now two key concepts in manufacturing industry. Researchers are engaged in lots of research activities for developing new manufacturing techniques of higher precision. Electrochemical micromachining (ECM) is a technique used for manufacturing components with extreme precision [1]. The term micromachining literally means the removal of small amount of material in the range 1-999  $\mu\text{m}$ . As a technical term, it also means the smaller amount of machining which cannot be obtained directly by using a conventional technique. It deals with processes capable of performing micro-manufacturing activities. This technique deals with material removal of small dimensions ranging from several microns to millimeters. This ensures developing more quality products [2]. Thus electrochemical micromachining ensure more accurately dimensioned components. Thus, micromachining is the most basic technology for production of miniaturized components. Since miniaturization will continue as people require efficient space utilization and better quality products, it follows that micromachining technology will be of immense importance in the future. Manufacturing of miniaturized parts and products cannot be achieved by conventional means. Small and microholes, slots and complex surfaces need to be produced in large numbers, sometimes in a single work piece, especially in electronic and computer industries [3-7]. The demerits of using conventional machining means are high tool wear rate, and generation of large amount of heat, alteration of work piece material properties, difficult to maintain 3D shapes, rigidity requirement of tools etc. To overcome these difficulties; a lot of researches were conducted and as a result ECM was introduced in the early 1950's in the aerospace and other heavy industries for shaping and turning operations [4]. When electrochemical machining process is applied to micromachining range for manufacturing ultra-precision shapes, it is called electrochemical micromachining. Eg: used in manufacturing of

metallic parts. It also has the additional advantages of high MRR [5-6], better precision and control and rapid machining time. It is also environmentally acceptable and permits machining of chemically resistant materials Titanium, copper alloys, super alloys and stainless steel which are widely used in biomedical, electronic and MEMS applications. Since the conventional machining operations produces heat affected zones non-conventional means are preferred over them [8]. The non-conventional means include electrochemical micromachining (ECM), Electro discharge machining (EDM), laser beam machining and Ultrasonic machining Etc. To exploit the full potential of EMM, research is still needed to improve the machining process by controlling the different machining parameters which immediately necessitates the development of a suitable EMM setup which has been attempted. The fundamental mechanisms of electrochemical micro-machining are presented in Figure 1.



**Figure 1: A Schematic Diagram of the Electrochemical Micro-Machining**

## PRINCIPLE

Electrochemical micromachining (EMM) appears to be very promising as a future micromachining technique since in many areas of applications it offers several advantages that include higher machining rate, better precision and control and a wide range of materials that can be machined. Electrochemical micromachining depends on the process of high rate anode dissolution. In ECM and electro-polishing processes the material dissolution occurs when the work piece is made an anode in an electrolytic cell [1]. The cathode tool is separated from the anode by a narrow electrolytic spacing through which electrolyte flows with high velocity. However, in EMM the inter-electrode gap control plays an important role. The Inter-Electrode Gap (IEG) is very vital in EMM as it dictates the resolution of the machining surface. When the IEG is a small value, say 10-50 $\mu\text{m}$ , the obtained resolution in machining is better, and hence the possibility of ECM in micromachining increases. A stable stage of uniform IEG is maintained, which is an important requirement in EMM for achieving high accuracy and surface finish [5]. The process requires the material or the specimen, to be machined, to be made the anode and the micro tool to be made the cathode. The electrolyte makes the common path between the specimen and the micro tool. It not only completes the electric circuit between the tool and work piece, but also allows the desired machining reactions to occur. Either DC full wave rectified or pulsed DC power supply is adopted. Decrease in current density decreases the current efficiency, which can improve the surface finish and accuracy of form of the work piece. In EMM the current density is maintained as low and operating voltages of less than 5 V are required.

The anodic electrochemical dissolution occurs during the ultra-short pulse on-time and the dissolved products, i.e. sludge, gas bubbles and heat can be flushed away from the inter electrode gap completely by the flow of electrolyte during pulse off-time. Pulses are used in the form of single pulses or multiple/group pulses to achieve necessary accuracy in the micromachining. In EMM, the distribution of metal dissolution rate on the work piece determines its final shape in relation

to the tool [7]. In the machining region where the work piece directly faces the cathode tools, the anodic reaction rate is constant for a constant inter-electrode gap and conductivity. Away from the machining area a current density on the work piece decreases asymptotically to zero with increasing distance. The metal removal rate (MRR) at any location is proportional to the product of current density ( $J$ ) and metal dissolution efficiency.

The material removal rate (MRR) is expressed as:

$$\text{MRR} = J a \eta / v F \rho \quad (1)$$

where,  $v$  is the valence of metal dissolution,  $F$  is Faraday's constant, and  $\rho$  is the density of metal ( $\text{g/cm}^3$ ).

The MRR in electrochemical micromachining basically depends on three factors: i) anodic reactions and current efficiency, ii) mass transportation effects and iii) current distribution and shape evolution. These factors are discussed in detail, in the following paragraphs:

### Anodic Reactions and Current Efficiency

The factors influence the machining performance namely: dissolution rate, shape control and surface finish of the work piece. The knowledge of anodic reactions that take place at high potentials is mostly derived from weight loss measurements and by applying Faraday's law. The current efficiency for metal dissolution is related to the weight loss,  $W$  by the following equation:

$$\eta = \Delta W v F / I t a \quad (2)$$

where ' $I$ ' is the applied current, ' $t$ ' is the time,  $F$  is Faraday's constant and ' $v$ ' is the valence of metal dissolution.

### Mass Transport Effects

When, due to high current density, the metal ion concentration at the surface exceeds the saturation limit, precipitation of a thin salt film occurs. At this stage, the limiting current density has been found to increase with increasing electrolyte flow. For an anodic reaction that is controlled by convective mass transport, the anodic limiting current density,  $J_L$ , is given by:

$$J_L = v F D C_{ast} / \delta \quad (3)$$

where, ' $D$ ' is the effective diffusion coefficient that takes into account, the contributions from transport by migration, ' $C_{ast}$ ' is the surface concentration and  $\delta$  is the diffusion layer thickness.

### Current Distribution and Shape Evolution

The current distribution at the anode depends on the geometry, anodic reaction kinetics, electrolyte conductivity and hydrodynamic conditions. Some of the very basic applications of ECM include:

- Die-sinking operations
- Drilling jet engine turbine blades
- Multiple hole drilling
- Machining steam turbine blades within close limits

## MATERIALS AND METHODS

The EMM setup consists of the following sub systems:

- Main Machine Body,
- Tool Feeding Device,
- Work Holding Platform,
- Machining chamber, and
- Table on which the machining chamber rest.

**Main Machine Body:** Referring to the figure given below, the main machine body has a rectangular base (1) over which a rectangular column (2) is mounted which is slotted to accommodate other components.

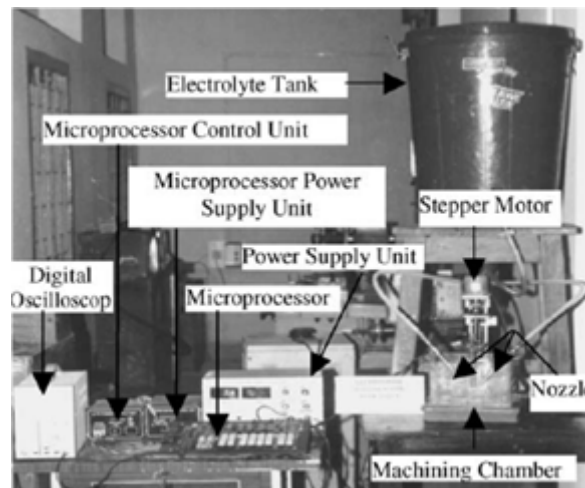


Figure 2: A Standard Experimental Set-up for Electro-Chemical Micromachining [1, 5]

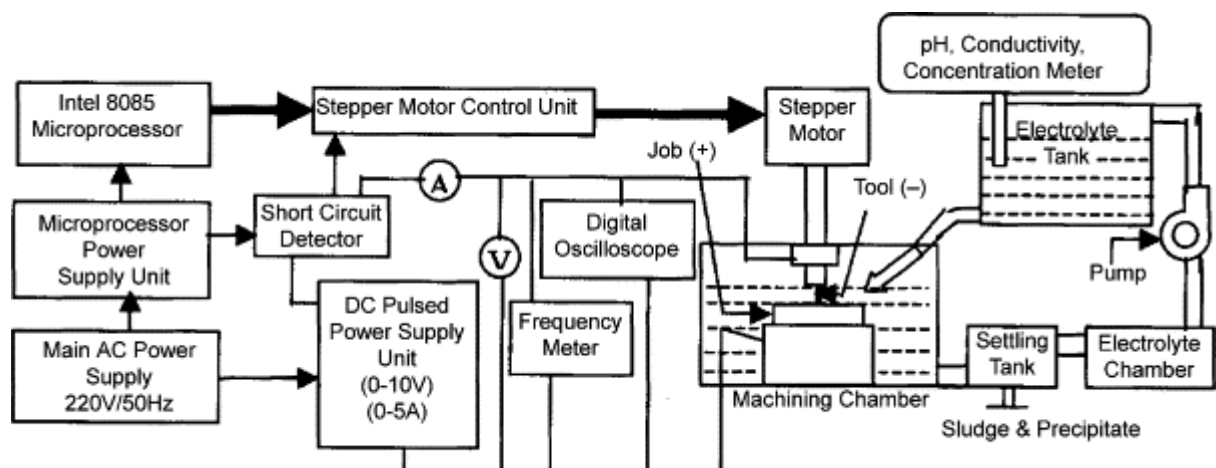
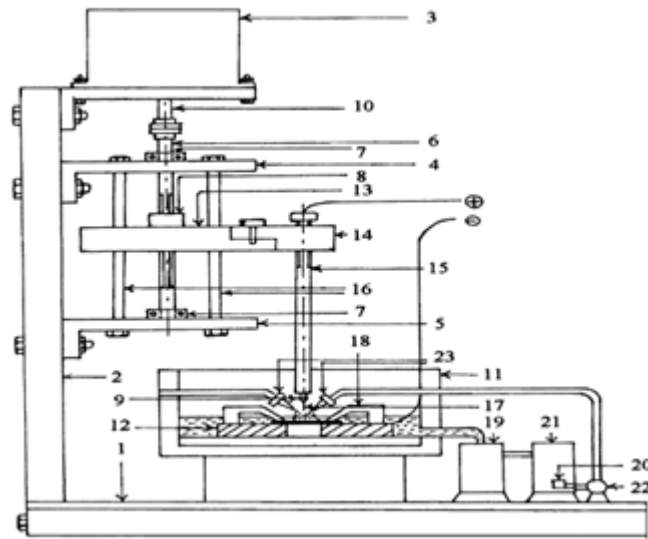


Figure 3: Various Parts of the Electrochemical Micro-Machining System [1]

At the top, the stepper motor (3) is mounted by means of an angle plate attached to the column. The main driving screw (6) is passed through the nut (8) which holds the tool holding block (9). When the stepper motor rotates, the main driving screw rotate, which causes the stepper motor shaft (10) to rotate, in turn causing the nut along with the tool holding device to move linearly (along z-axis).



**Figure 4: Detailed Components of the Electrochemical Micro-Machining Set-up [5]**

**Tool Feeding Arrangement:** The main intention of EMM is to machine in the order of microns which actually requires the tool movement per pulse as low as possible around 5–20  $\mu\text{m}$ . The precision movement can be generated by a precision main feed screw. The tool-feeding block is made up of the two composite materials out of which one section (13) is made of stainless steel (SS) material and the other section (14) is made up insulating Teflon material. The tool holder is attached to the insulated section.

**Work Holding Platform:** All the material including the machine chamber and work holding device is made of corrosion resistance material. The job holding is so precise that it can hold the work piece of material thickness 200  $\mu\text{m}$ . The work piece is clamped by two tapered angle plates (18) which are made up of insulating material i.e. Perspex glass on the main base plate. On one side of the clamp, a copper plate is connected for electrical power supply to the work piece, which is called as anode.

**Machining Chamber:** The machining chamber (11) rests on the base of the setup that is just below the tool holding device. The chamber is filled with electrolyte, according to need the electrolyte re-circulation is carried out in the chamber. Inside the chamber a job holding device (12) is mounted. The work-holding devices for EMM are made of perspex. Different clamps and other parts are made up of corrosion resistance materials. The feeding device is actuated with the help of the rotational movement of the stepper motor used for the purpose. The other important systems are discussed in the following sections.

**Electrical Power and Drive System:** The nature of power supply requirement is pulsed as the electrical power required for the process is very low. The present power supply module has a voltage in the range 0-15V and current rating upto 5A. The main power line has 220 V, single phase AC power supply, which is converted to low voltage pulse DC power supply by a step down transformer, silicon controlled rectifier unit. A pulse generating module is utilized to provide the required nature of pulsed power supply. The voltage and current can be noted with the help of voltmeter and ammeter arrangement. A digital storage oscilloscope is provided for observing the nature of pulses.

**Inter-Electrode Gap Control:** It is observed that the resulting shape is better when the inter electrode gap is kept at a very small value. The electrical conduction method maintaining the electrode gap distance between tool and work piece can be applied for sensing the voltage. The tool is moved in the required fashion by using the stepper motor by giving appropriate signals to the microprocessor unit.

**Stepper Motor Drive System:** The stepper motor is controlled by the microprocessor. The programs as per requirements are stored in the microprocessor. The to and fro motions can be obtained by giving appropriate commands

**Electrolyte Flow System:** The electrolyte is pumped at medium velocity to the working zone. From here, it drives out the material removed during machining. The electrolyte is then passed through a settling tank (19) and filter (20) to get rid of the contaminated materials in it. The electrolyte chamber (21) stores the electrolyte solution. The electrolyte solution is then circulated along the machining gap by means of a centrifugal pump (22). Tool movement in the developed EMM setup is controlled through a microprocessor unit based on Intel 8085 processor. The unit generates number of pulses equal to the required number of steps in forward or in backward direction depending upon the program that is executing. The output of the executing program is sent to the interface card unit through the I/O port of the microprocessor. At the time of machining, the inter-electrode gap is kept at a very small value resulting in better machining accuracy and the possibility of applying ECM in the micromachining domain is increased. Electrical conduction method for maintaining the electrode gap distance between tool electrode and the work piece can be applied. Around 1V can be applied between the tool electrode and the work piece for measuring the current in such a way that the electrical contact of the tool electrode with the work piece can be checked. If the tool electrode is in contact with the work piece, it is fed upward step by step until the contact is broken. The number of passes through the loop to recover from contact is counted which is used later to control the feeding of tool electrode. An attempt has also been made to apply the machining pulse voltage for a fixed period, i.e. pulse on time when the required end gap is achieved. After the machining voltage is cut-off, the tool electrode is quickly moved up by reversing the stepper motor movement to help the sludge removal. Then, after delaying for pulse off time, the tool electrode is fed downwards.

## RESULTS AND DISCUSSIONS

It is observed that the electrochemical process of metal removal offers better control over the micromachining process than chemical-based processes. Other advantages include higher machining rate, use of less-corrosive electrolyte, and are relatively less pollutant and ecologically safe. Furthermore the use of EMM will widen the range of materials application in electronic industries. The role of convective mass transport and current distribution on the surface finish and shape evolution is very important. Effective EMM process can be achieved by optimal combination of the process parametric conditions. In order to achieve the effective and highly precisioned material machining in the order of microns, the following process variables of the EMM system will have to be optimally controlled.

- Electrolyte concentration and flow
- Inter-electrode gap
- Power supply
- Material and geometrical characteristics of tool

The experimental observations and research studies were designed in such a way so as to carryout productive research analysis for deriving the effective research findings, which can be useful to the applied researchers and manufacturing industries in the area of micromachining area achieved through this process. To analyze the control of the desired performance characteristics of the process parameters of the ECM system, scheme was designed so as to utilize properly the developed EMM setup. Therefore, in this experimental work, the process outputs chosen for study were: material removal rate (MRR) and the overcut. The important input parameters influencing the EMM process are:

voltage (V) and concentration of the electrolyte (C). As both the voltage and concentration control the input energy and rate of the process, an increase in MRR is expected with an increase in these parameters. The independent influence of voltage and concentration are studied and discussed in detail. Four sets of experiments were and the variations in the MRR as well as the overcut were observed corresponding to each of the trials.

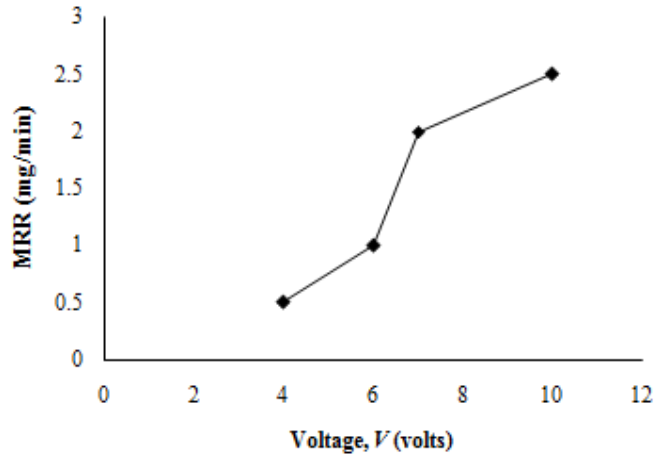


Figure 5: The Material Removal Rate (MRR) – Voltage (V) Relationship for EMM Process

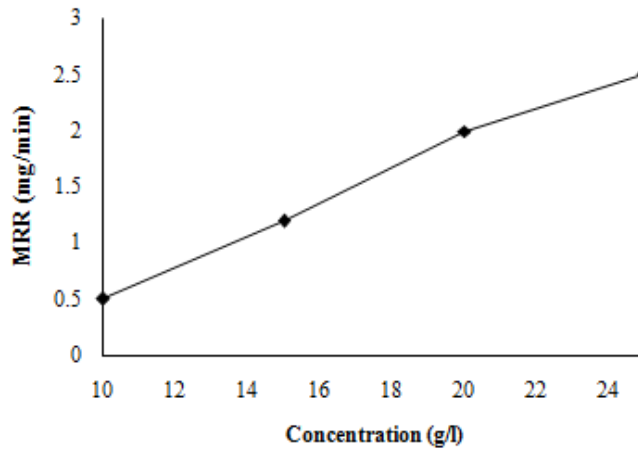


Figure 6: The Material Removal Rate (MRR) – Concentration (g/l) Relationship for EMM Process

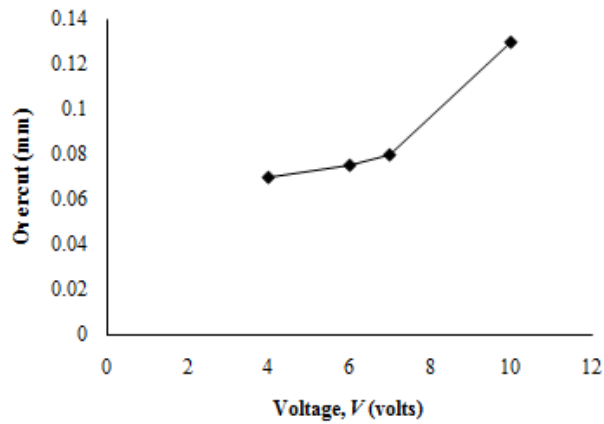
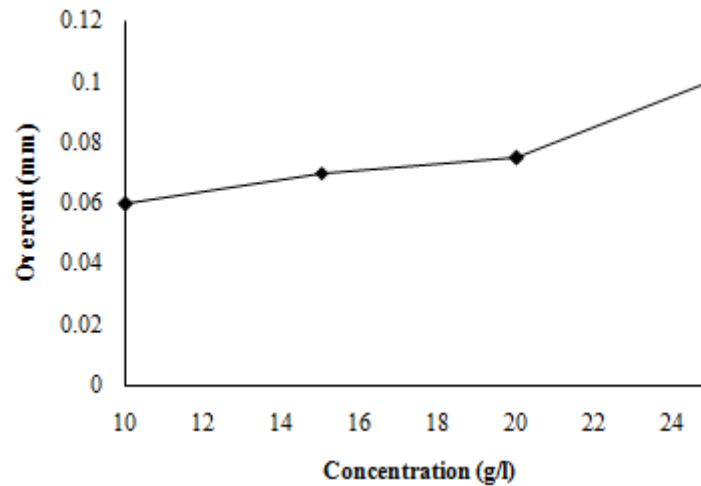


Figure 7: The Overcut– Voltage (V) Relationship for EMM Process



**Figure 8: The Material Removal Rate (MRR) – Concentration (g/l) Relationship for EMM Process**

The experimental results show that MRR increases with the voltage. As the voltage increases from 6 to 7 V, the improvement in MRR is by 100%. With increase in voltage, current also increases. Faraday's law states that MRR is proportional to the machining current. But the graphs evidently shows that MRR is not varying linearly with machining voltage, see Figure 5 and Figure 7. With the increase of machining voltage, the localization effect of current flux flow decreases. Due to less localization effect, which in fact increases the stray current flow in the micromachining zone in turn effects additional material removal from the bigger area of the workpiece, which causes increase in over cut. At elevated voltage, i.e. more than 7 V, overcut phenomena is more leading. Electrochemical reactions create hydrogen gas at the micro-tool. At elevated machining voltages, hydrogen gas bubbles break down resulting in the occurrence of micro-sparking. This micro-sparking leads to unrestrained material removal from the work piece and results in bigger overcut. Hence at higher machining voltage zone, overcut increase is more. Further, as the electrolyte concentration increases, the MRR increases (Figure 6 and Figure 8). At higher concentration, the larger number of ions associated with the machining process increases current and thus results in higher MRR. With the increase in electrolyte concentration, ions associated with the machining operation in the machining zone also increase. Higher concentration of ions reduces the localization effect of electrochemical material removal reactions. This leads to the higher overcut of the work piece and thus reduces the machining accuracy. Dissolution of material in the stray current region increases with the increase of electrolyte concentration. Thus the MRR in the stray current region is significantly higher at higher zone of electrolyte concentration.

## CONCLUSIONS

This paper has discussed the fundamental perceptive and analysis of the electrochemical micro-machining process. The developed concept is unique and has adaptable components for carrying out different investigations. The modifications in the basic principles of electrolysis were very well understood for adapting it for electrochemical micro-machining. It is observed that there is a significant variation in the MRR as well as the geometric overcut with the chosen input parameters. This study has demonstrated EMM under different processing conditions. It is observed that at higher concentration, the larger number of ions associated with the machining process increases current and thus results in higher MRR. Higher concentration of ions reduces the localization effect of electrochemical material removal reactions. This leads to the higher overcut of the work piece and thus reduces the machining accuracy. This study has indicated the need for an independent and in-depth analysis of input voltage and current.



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