ULTRAPRECISION HIGH RATE ANODIC DISSOLUTION PROCESSES IN ECM

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ABSTRACT

As electronic packages become smaller in size, the pitch of metal line is getting shorter. Decrease of line pitch in electronic packages and substrate of electronic component causes the electrochemical migration (ECM) more frequently. If the electronic components are exposed to high temperature and high humidity environments with authorized voltage condition, the metals in packages and substrate are easily ionized and form conductive dendrites, leading to insulation failure. ECM process consists of three steps: anodic dissolution, ion migration, and dendritic growth. Under low concentration of passivating electrolyte, low machining voltage and high-frequency short-pulse current, the machining gap can be reduced to about 10 mum. A deep micro-hole about 100 mum in diameter was drilled by edge-cut electrode on stainless steel with 750 mum thickness. The process of NC micro-EC milling is proposed, and microstructures with high-aspect ratio on stainless steel were fabricated by micro-EC milling, such as profiled micro-hole, micro spiral beam and micro array square columns

1.INTRODUCTION

The needs for miniaturization of various ultra precision items utilized for producing highly precision machines and equipments necessitate the development of manufacturing processes capable of performing micro manufacturing activities. The term micromachining refers to material removal of small dimensions that range from several microns to millimeters. Micromachining is the most basic technology for the production of miniaturized parts and components. Since miniaturization will continue as long as people require efficient space utilization with more efficient and better quality products, micromachining technology will become still more important in the future. The word micromachining may literally mean machining of dimensions within 1–999 mm. As a technical term, it also means machining which cannot be achieved directly by conventional techniques [1]. Advanced micromachining may consist of various ultra precision machining activities to be performed on very small and thin work pieces. Small and micro-holes, slots and complex surfaces need to be produced in large numbers, sometimes in a single work piece, especially in electronic and computer industries. When those things are performed by employing conventional machining techniques, the problems usually encountered are such as high tool wear rate and heat generation at the tool and work piece interface and subsequent alteration of work piece material characteristics, etc. [2]. Rigidity requirements for the tool are another major problem in conventional machining of small and deep holes, complex surface or shapes. In addition, it becomes troublesome to machine three-dimensional shapes. Non-conventional machining processes are getting their importance due to some of these specific advantages which can be exploited during micromachining operations. Electrochemical machining (ECM) was introduced in the late 1950s and early 1960s in aerospace and other heavy industries for shaping and finishing operations. All of these processes now play an important role in the manufacturing of a variety of parts ranging from machining of large metallic pieces of complicated shapes to opening of windows in silicon that are a few microns in diameter [3]. When this electrochemical machining process is applied to micro- machining range for manufacturing ultra precision shapes, it is called electrochemical micromachining (EMM). EMM can be advantageously employed in most applications related to micromachining of metallic parts which are presently fabricated mostly by chemical micromachining (CMM) [4]. A better understanding of high rate anodic dissolution processes is urgently required for EMM to become a widely employed manufacturing process in the electronic and precision manufacturing industries particularly in the micro manufacturing domain. Although esteemed institutions and researchers all over the world have already initiated some research, this area of micromachining still requires a lot of further investigation. Keeping in view of the above requirements of the EMM, an attempt has been made to develop an EMM setup for carrying out in depth independent research for achieving satisfactory control of ECM process parameters to meet the micromachining requirements**.**

2. NEED OF ELECTROCHEMICAL MICROMACHINING

Non-conventional machining processes, e.g. ECM [5], electrodischarge machining (EDM) [6], laser beam machining (LBM) [7], and ultrasonic machining [8], etc. have already been utilized for ultra precision machining. EDM and LBM are thermal processes; therefore they cause the formation of heat-affected zones and micro cracks on the work piece. ECM machining techniques however do not produce thermal or mechanical stresses on the work piece material and they have versatility that they can machine any kind of material. They have also additional advantage, such as they leave no heat-affected layer and produce no tool wear. The machining performance in ECM is governed by the anodic behavior of the work piece material in a given electrolyte. Hence ECM on the other hand appears to be very promising as a future micromachining technique since in many areas of application it offers several advantages that include higher machining rate, better precision and controlled material removal, and also wider range of materials that can be machined. It can also effectively utilize for removal and patterning of metal films and foils, which mainly require highly localized precision material removal [9].

3. FUNDAMENTALS OF ECM RELATED TO EMM

In ECM and electro polishing processes the material dissolution occurs when the work piece is made an anode in an electrolytic cell. 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 resolution of machining shape is better for very small machining gaps. In addition, some fundamental observations relating to ECM can be listed herein under [10].

(i) Rate of dissolution (machining) depends only on the atomic weight ‘a’ and valence ‘n’ of ions produced, the machining current ‘I’ which is passed, and the time for which the current passes. The hardness or other characteristics of the material does not influence the dissolution rate.

(ii) Since only hydrogen gas is evolved at the cathode, the shape of the electrode remains unaltered during the electrolysis.

3.1. Material removal method in EMM

In EMM, the distribution of metal dissolution rate on the work piece determines its final shape in relation to the tool. Therefore, the machining performance is influenced significantly by the current density and the anodic reaction. 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 current density on the work piece decreases asymptotically to zero within creasing distance. The current efficiency for metal dissolution, which is a function of current density and local flow condition, varies as a function of distance from the tool. The metal removal rate (MRR) at any location is proportional to the product of current density (J) and metal dissolution efficiency. Shape prediction of ECM, therefore requires knowledge of not only the current distribution but also the functional dependence of metal dissolution efficiency (Z) on current density and electrolyte flow condition. Material removal rate (MRR)

r ¼ JaZ=nFr; ð1Þ

where n is the valence of metal dissolution, F is Faraday’s constant, and r is the density of metal (g/cm3). The MRR in electrochemical micromachining basically depends on the following three factors:

- Anodic reactions and current efficiency. According to the metal electrolyte combination and operating conditions, different anodic reactions take place at high current densities. 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:

Z ¼ DWnF=Ita; ð2Þ

Where ‘I’ is the applied current,‘t’ is the time, F is Faraday’s constant and ‘n’ is the valence of metal dissolution.

- Mass transport effects. An increase in current density leads to an increase in the rate of metal ion production at the anode. When 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. Therefore, the limiting current density is controlled by convective mass transport. For an anodic reaction that is controlled by convective mass transport, the anodic limiting current

Density, JL; is given by

JL ¼ nFDCast=d; ð3Þ

Where ‘D’ is the effective diffusion coefficient that takes into account, the contributions from transport by migration, ‘Cast’ is the surface concentration and d is the diffusion layer thickness.

- Current distribution and shape evolution. The prediction of the shape evolution during high rate Anodic dissolution requires solving of the current distribution at the anode along with a moving boundary algorithm. The current distribution at the anode depends on the geometry, anodic reaction kinetics, electrolyte conductivity and hydrodynamic conditions.

4. INflUENCE OF VARIOUS PROCESS CHARACTERISTICS OF EMM

Since the anodic shape change can be created in a controlled way by the application of external current source, the electrochemical process of metal removal offers better control over the micromachining process than CMM. 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.

(i) Nature of power supply and machining pulse. The nature of applied power supply may be of two types, such as DC (full wave rectified) and pulse DC. A full wave rectified DC supplies continuous voltage where the current efficiency depends much more on the current density. The efficiency decreases gradually when the current density is reduced, whereas in pulse voltage (duration of 1ms and interval of 10ms) the decrease is much more rapid. With decreasing current density the accuracy of the form of the work piece improves. A very low current density and an operating voltage in the order of 4–10V are required for proper operation of EMM process. The high concentration of reaction product can only be partly removed by the electrolyte especially if the gap is very small. As the gap is very small, the increasing contamination can cause a deposition to form on the tool, so that the work piece material no longer dissolves uniformly. Furthermore, the change in the electrolyte composition and the temperature rise increases the electrical resistivity, which in turn makes the machining accuracy worse. These problems can be largely avoided by applying a pulsed voltage instead of a continuous one [11]. When the pulse duration and the interval between the pulses are properly matched to the current density, the inter-electrode gap can almost be completely swept clean during the current inter- vals, given a regular EMM process. The use of pulsed voltage also improves the surface finish criteria of EMM.

(ii) Inter-electrode gap. The gap between the tool (cathode) and the work piece (anode) is important for metal removal in micromachining processes. If the electrode gap is kept to a very small value, the resolution of machined shape becomes better and the possibility of applying ECM to micromachining increases. In EMM, the electrode gap is lowered to several micrometers by lowering the machining voltage and the electrolyte concentrations. For accuracy in shape generation in EMM, the inter-electrode gap control plays a major role.

(iii) Electrolyte type, concentration and flow. ECM electrolyte is generally classified into two categories: passivity electrolyte containing oxidizing anions e.g. sodium nitrate and sodium chlorate, etc. and non- passivity electrolyte containing relatively aggressive anions such as sodium chloride. Passivity electrolytes are known to give better machining precision. This is due to their ability to form oxide films and evolve oxygen in the stray current region. From review of past research, in most of the investigations researchers recommended $NaClO3$, $NaNO3$, and NaCl solution with different concentration for electrochemical micro- machining (EMM). The pH value of the electrolyte solution is chosen to ensure good dissolution of the work piece material during the ECM process without the tool being attacked. It is usual to work with natural $NaNO3$ electrolyte solution (pH=7). In case of EMM, the material removal by machining is very low. The gap between the tool and the work piece can be decreased to a lower level by decreasing the electrolyte concentration. The fluid flows from a storage tank via a pressure controller and a filter to the machining gap. After passing through the gap, the fluid goes to a settling tank where the sludge is removed. The concentration of dissolved impurities can be reduced by the addition of adaptive chemicals. Upon the concentration of 1mol/l the addition of $NaHSO4$ additive does not affect the ECM process adversely.

(iv) Size, shape and material of the tool. The tool must match the required shape of the work piece depending on the material and the profile to be produced. Tool materials used in ECM and EMM must have good thermal and electrical conductivity; corrosion resistance must be highly machinable and should be stiff enough to withstand the electrolytic pressure without vibrating. Highly conductive material having high melting point and temperature-resistant characteristics can be used for tool material in EMM systems. The diameter of the tool is in the order of 150–200 mm which gives a high current density. It is necessary to ensure good electrolytic flow through the end gap which necessitates rigid fixture of the tool. The choice of tool material is determined by the electrochemical properties required for EMM. Suitable metals for the tool include platinum, tungsten, titanium, molybdenum and copper alloys. The tool should be properly insulated for minimizing the stray current effect for which specified coating technique is required. A proper insulation of the tool in EMM is must for achieving high machining accuracy. It is found that some coating, e.g., epoxy resins are not suitable.

5. DEVELOPMENT OF THE EXPERIMENTAL MACHINE

Setup for EMM It is evident from the past research that the effective utilization of ECM process in micromachining domain for precision manufacturing demands for optimal controlling of major parameters and other related factors that mainly influence the micromaching requirement criteria. Keeping in view the influence of predominant process characteristics as discussed previously, a well-planned research program has been considered for the indigenous development of the EMM setup. The developed EMM setup mainly consists of various sub-components and systems, e.g., mechanical machining unit, micro tooling system, electrical power and controlling system and controlled electrolyte flow system, etc. All these system components are integrated in such a way that the developed EMM system setup is capable of performing basic and fundamental research in the area of EMM fulfilling the requirements of micromachining objectives. Fig. 1 represents a schematic view of the various system components of the developed EMM setup to which the authors have paid much attention for having a greater and a precise control over the electrochemical dissolution rate.

5.1. Mechanical machine setup

The mechanical system for the development of the EMM set up comprises of the following elements:

- Main machine body,
- Tool feeding device,
- Work holding platform,
- Machining chamber, and
- Table on which the machining chamber rest.

All these elements have been designed to fulfill the design requirements of EMM systems. Mechanical body of the machining system is depicted in Fig. 2. It consists of a rectangular machining base [1]. Over the machining base, a rectangular column [2] is mounted. The rectangular column is slotted along the Z-axis to provide provision for mounting other auxiliary components. At the top a stepper motor [3] is mounted with the help of an angle plate which is attached to the rectangular column by nuts and bolts. There are two other angle plates [4,5] which are fitted with the column slots, one below the stepper motor and another below

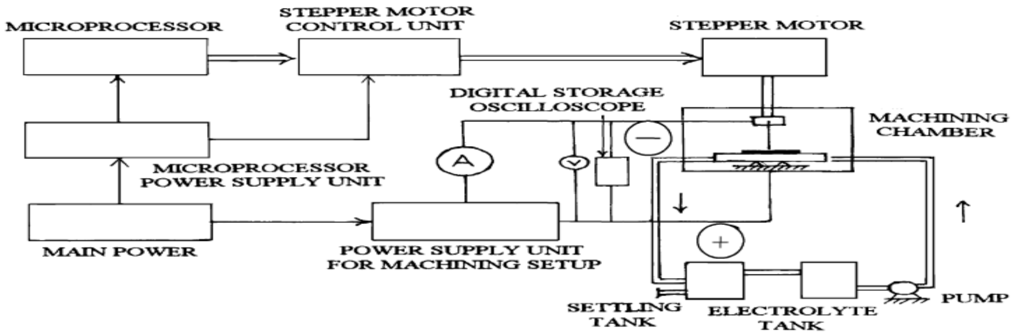
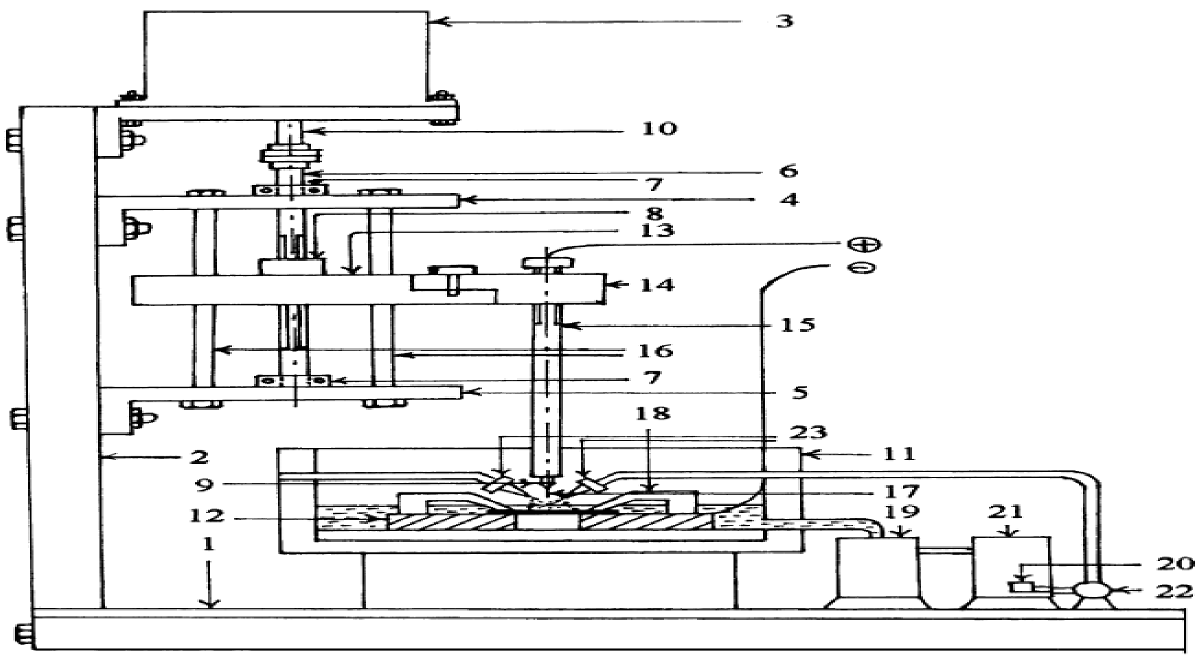


Fig. 1. Various system components of the EMM setup.



He tool holder to support the main driving screw [6] with the help of two bearings [7]. The main driving screw is passed through the nut [8], which actually holds the tool holding block [9]. The screw rod is keyed with the stepper motor shaft [10]. When the stepper motor rotates, the screw rotates which in turn moves the nut linearly along with the tool holding device. 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.

5.1.1. 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 mm. 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 that is attached to the main screw rod through a nut and screw. Another section [14] is made of insulating material, i.e., of Teflon. With the insulated section, the cylindrical bar tool holder [15] is attached. The tool holder's SS block will slide along the vertical column through the tie rods [16]. The main screw rod is coupled with the stepper motor. When the stepper motor moves by one assembled step, through the arrangement of a screw and nut the feeding block makes a Z-axis movement. As the tool vibration is advantageous for better micromachining, the tool can move forward and backward by providing appropriate command signals to the stepper motor with the help of a microprocessor unit. Platinum wire of radius 0.2mm is utilized as tool [17] in the developed EMM setup. Thin compact film of polycrystalline silicon carbide is used for providing insulating coating layers on the circumference of the tool. Insulation coating layer of SiC is very thin in the order of less than 15 mm and has been applied on the platinum tool by the process of chemical vapor deposition (CVD). The tool holding device is fitted to the tool-feeding block rigidly. Through the small hole which is centrally drilled in the tool holding bar the electrical conductor can be connected to the main power supply. That main electrical conductor is soldered to the tool for having a better flow of current. The hole, which is made on the conical teflon tool holder should be of high precision and hold the tool tightly such that the electrolyte flow does not vibrate the tool.

5.1.2. Work mounting device

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 mm. 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. The chamber is well equipped for circulation of electrolyte flow system. The chamber is mounted on the machining base by using some clamping arrangements.

5.2. Electrical power and drive system

In electrochemical micromachining the electrical power required is very small, the voltage range is high and the current range is comparatively low. The nature of power supply requirements in EMM is pulsed but not continuous. The present power supply module has a voltage in the range 0215V and current rating upto 5A. The main power line has 220V, 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. For having a delicate protective circuit for the machining system, it also has the protection device for short-circuit phenomena and overload conditions. A digital storage oscilloscope is also provided in the main line for observing the nature of pulses and other related electrical phenomena, which may occur during EMM operation.

5.3. Monitoring and controlling of the inter-electrode gap

At the time of machining if the electrode gap is kept at a very small value, then the resulting machining shape is better and the possibility of applying EMM through ECM is increased. The electrical conduction method maintaining the electrode gap distance between the tool electrode and the workpiece can be applied for sensing the voltage. Around 1V can be applied between the tool electrode and the work, for measuring the current in such a way that the electrical contact of the tool electrode with the work can be checked. If the tool electrode is in contact withthe work, it is fed upward gradually until the contact is broken through the loop to recover from the contact. The number of passes through the loop to recover from contact is counted which is used later to control the feeding of the tool electrode. An attempt has also been made to apply the machining pulse voltage for a fixed period, i.e. pulse time when the required end gap is achieved. After the machining voltage is cut-off, the tool electrode quickly moves up by reversing the stepper motor movement to help the sludge removal. Then after delaying for pulse off time, the tool electrode is fed downward. As the electrode gap is difficult to be measured, the side gap is observed. The side gap can be calculated as half of the difference between the diameter of the machined hole and that of the tool electrode.

5.3.1. 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. The tool is moved in the required fashion by using the stepper motor by giving appropriate signals to the microprocessor unit. Initially the tool is moved in the forward direction to reach the work. During machining it is moved initially in the forward direction and then immediately in the reverse direction to give vibration movement to the tool.

5.4. Electrolyte flow system

The flow of the electrolyte is one of the important components in electrochemical micromachining. A pumping electrolyte directed to the working zone witha medium velocity drives out the material removed during the machining. The electrolyte is then passed through a settling tank [19] and a filter [20] which removes the contaminated material from the electrolyte. The electrolyte chamber [21] then stores the electrolyte solution. A centrifugal pump [22] is used for circulating the electrolyte solution through the machining gap. There are two nozzles [23] mounted in the main machining chamber that are facing each other at the machining zone. The electrolyte passes through these with a certain pressure without affecting the tool and workpiece position. The material removed from the workpiece is dissolved into the electrolyte, which comes out from the chamber, by the outlet channel. Then the contaminated electrolyte is filtered and subsequently recirculated to the chamber by a pump.

5.5. Detailed specifications of the EMM setup

Mechanical structure details All the materials except that of the base plate are made up of stainless steel. Base plate is made up of mild steel witha stainless steel cover on it. The design details of some of the important mechanical components are as
follows:

(i) dimension of the base: (30020030)mm;
(ii) dimension of the vertical column: (3005020)mm;
(iii) dimension of the main driving screw: f10150L, 40 tpi, 50mm thread;
(iv) dimension of the main screw nut: (255040)mm. Internal thread of 40 tpi;
(v) main machining chamber: (10020080)mm3 ;
(vi) bearing: 10mm bore, 10mm thick.

DC pulsed power supply:

nature of power supply: rectangular pulsed, variable on and off time and frequency;
range of voltage: 0–15V;
range of current: 0–5A.
Microcontroller: ATMEGA 16, ATMEL:
Digital oscilloscope: make: YOKOGAWA, Japan,
Model: DL 1520.
Stepper motor specification:
step angle: 1.81;
step angle accuracy: 5%;
holding torque: 40N-cm;
detent torque: 4N-cm;
weight: 0.5 kg.
Tool: platinum, +250 mm.
Specification of pump:
power: 0.125HP/0.09 kW;
type: centrifugal;
AC: 240V;
impeller material: Teflon.

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