WELCOME TO THE COURSE

ON

MICRO MACHINING PROCESSES

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ACKNOWLEDGEMENT

“MICRO ELECTROCHEMICAL MACHINING” from
Introduction to Micromachining (Ed. VKJain)

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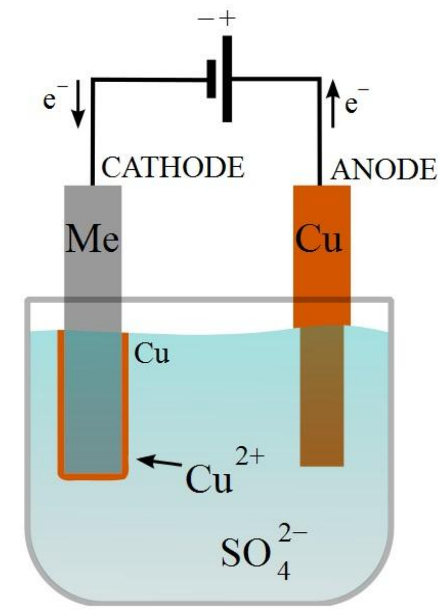
OUTLINE OF PRESENTATION

- **Introduction**
- **Overview on ECM**
- **Electrochemical Micromachining (ECMM)**
- **Parameters and Its Influence**
- **Different Components of ECMM**
- **Micro-tool Fabrication by ECMM**
- **Present State of Research**
- **Overview on Nano- Fabrication**
- **Nano-fabrication Using ECMM**
- **Conclusions**

Introduction

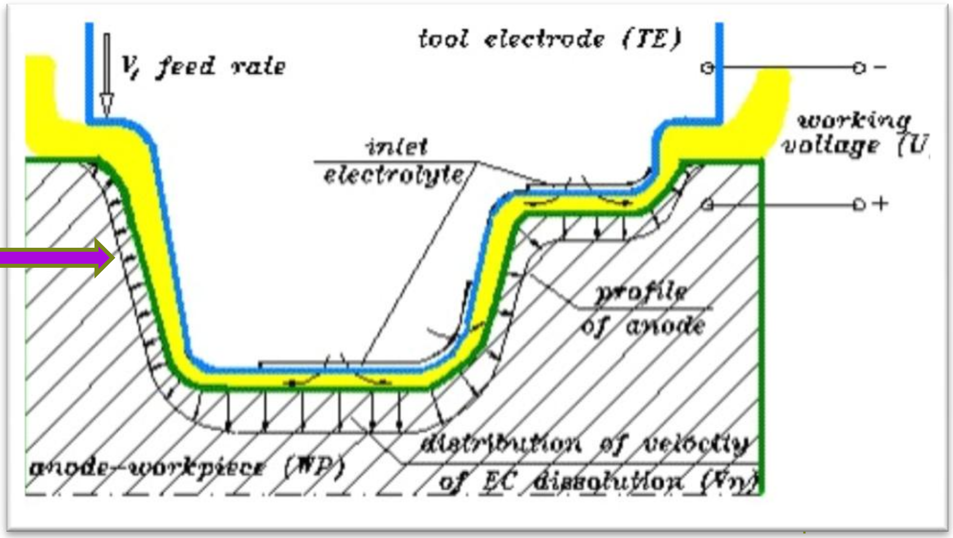
- ECM→ anodic dissolution process
- workpiece and tool are respectively anode and cathode,
- Separated by electrolyte.
- Gap between anode and cathode: IEG (inter electrode gap)

ECM is often characterized as "reverse *electroplating*," in that it removes material instead of adding it.



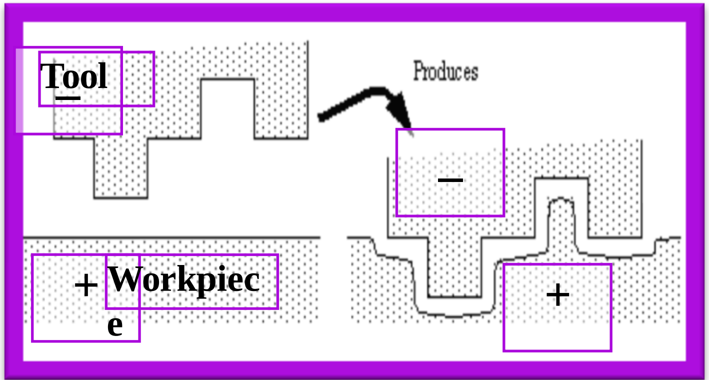
Electroplating

ECM: The anode workpiece dissolves locally so that the shape generated is approximately negative mirror image of tool.



Electrochemical Machining: Overview

ECM plays an important role in manufacturing of a variety of parts ranging from machining of complicated shape, complex, and large metallic pieces.



Farady's

ECM,Electroplating, Electropolishing based on the concept of Faraday's Laws.

ECM

ECM is based on electrolysis where material is removed from workpiece surface atom by atom.

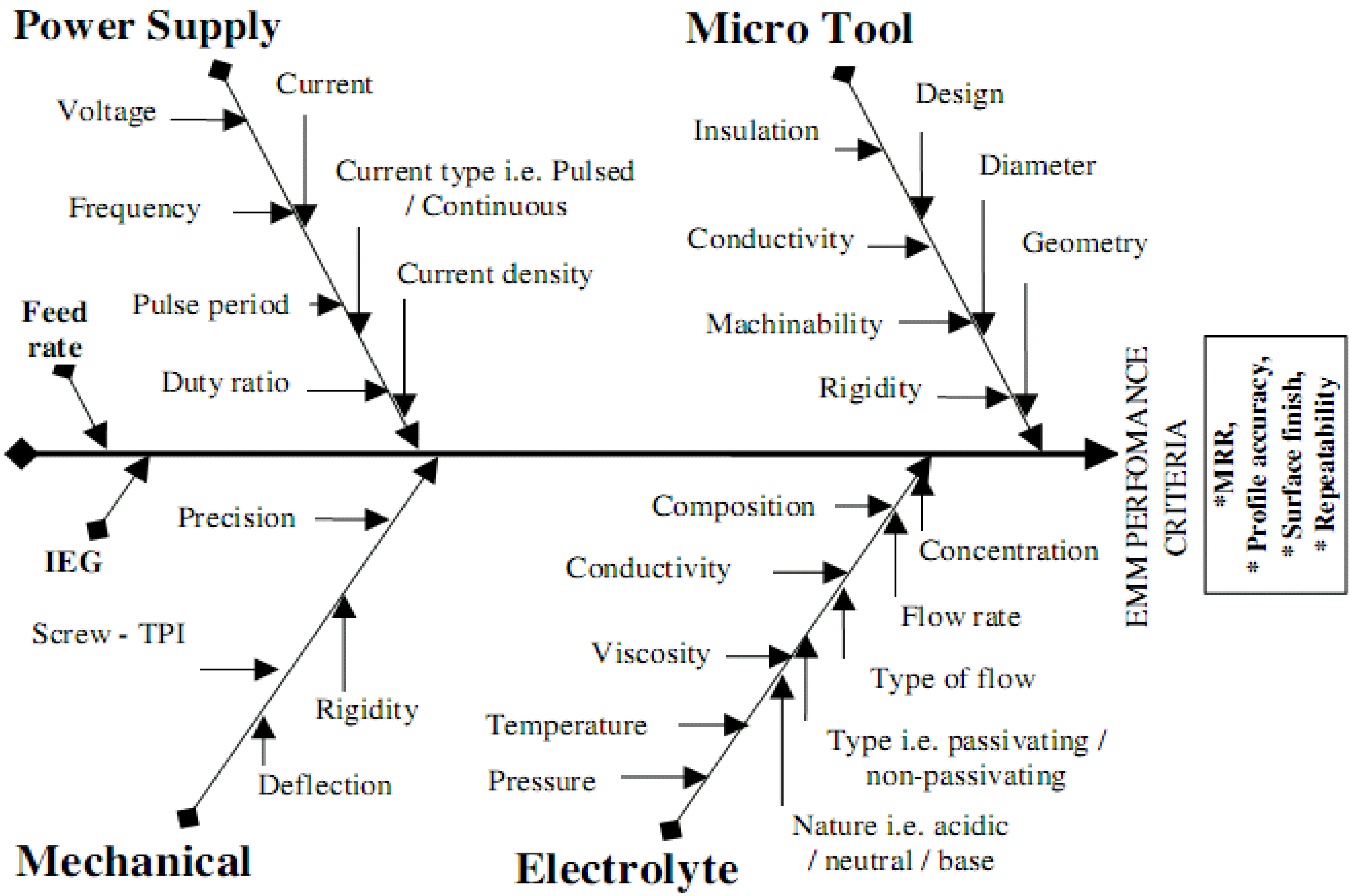
Param-eters

Input parameters: Supplied voltage, machining current, electrolyte type, concentration, flow rate and inter-electrode gap

Output parameters: Metal removal rate, surface finish and profile accuracy

Electrochemical Machining: Overview

PROCESS PARAMETERS



FISH BONE DIAGRAM FOR ECMM

General comparison between ECM and ECMM

Major characteristics	Electrochemical machining (ECM)	Electrochemical micro-machining (ECMM)
Voltage	10–30 V	<10 V
Current	150–10000 A	<1 A
Current density	20–200 A/cm2	75–100 A/cm2
Power supply-DC	Continuous/pulsed	Pulsed
Frequency	Hz–kHz range	kHz–MHz range
Electrolyte flow	10–60 m/s	<3 m/s
Electrolyte type	Salt solution	Natural salt or dilute acid
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	100–600µm	5–50 µm
Operation	Mask/Maskless	Mask/maskless
Machining rate	0.2–10 mm/min	5 µm/min
Side gap	>20 µm	<10 µm
Accuracy	0.1 mm	0.02–0.1 mm
Surface finish	Good, 0.1–1.5 µm	Excellent, 0.05–0.4 µm
Problems due to waste Disposal/toxicity	High	Moderate

Ref:B. Bhattacharya, JU

Electrochemical Machining: Overview

Only electrically conductive materials can be machined .

Electrochemical reactions during the process take place in very small machining gap (IEG).

Gas bubbles generated in a small gap between the electrodes is a barrier to the current flow.

Passivation and gas mixed electrolyte, dual pole tool etc. are preferred for better accuracy and precision.

Importance of ECM

Miniaturization

- is the need of the time
- Medical, µ-tools, Mobiles, Mini robots, Bio-medical implants, utensils etc.

Advanced micro-machining

- consists the application of various ultra precision processes applied to make micro-sized holes, slots and micro complex surfaces that are needed in large numbers.

Limitations of traditional machining

- *High tool wear, lack of rigidity* of the process and *heat generation* at the tool-workpiece interface.
- *It is troublesome to machine three dimensional* micro-shapes

Most non-traditional micromachining processes are *thermal oriented*, e.g. electro-discharge machining (EDM), laser beam machining (LBM) and electron beam machining (EBM), which may cause thermal distortion of the machined part. Chemical machining and ECM are thermal-free processes, but *chemical machining cannot be applied* to machine chemically resistant materials

Electrochemistry of ECMM

The anodic work piece in ECMM is dissolved according to Faraday's laws of electrolysis. The dissolved material and other by-products generated in the process such as sludge and cathode gas, are transported out from the gap by the flowing electrolyte.

Methodology:

- **DC voltage is applied between work piece (anode) and tool (cathode)**
- **Many electrochemical reactions occur at the cathode, the anode and in electrolyte**

Factors influencing the oxidation potential

- **Nature of metal being machined**
- **Type of electrolyte**
- **Current density**
- **Temperature of electrolyte**

Electrochemistry of EMM

Cathode reactions

The possible reactions occurring at the cathode (at tool):
(i) Evolution of hydrogen gas,
(ii) Neutralization of positively charged metal ions

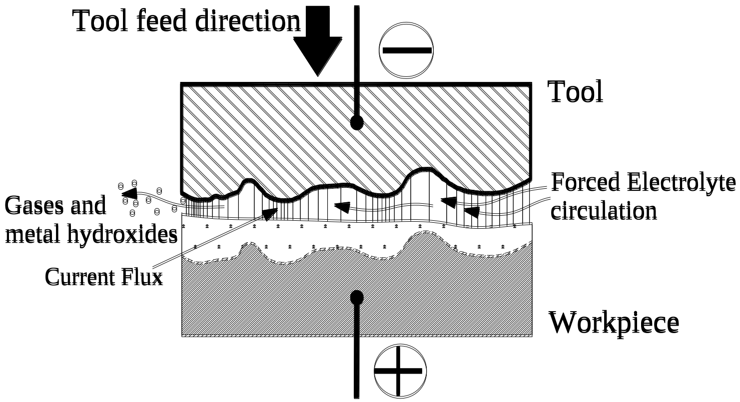


Fig.1: Basic scheme of ECM

Reactions causing evolution of hydrogen gas

- $2H^{+} + 2e^{-} \rightarrow H_2$ (when electrolyte is acidic)
- $2H_2O + 6e^{-} \rightarrow 2H_2 \uparrow + O_2$ (when electrolyte is alkaline)

Neutralization of positively charged metal ion is caused

- $M^{+} + e^{-} \rightarrow M$ (Metals)

Electrochemistry of EMM

Anode reactions

At the anode also two possible reactions are occurring as follows:

(i) Evolution of oxygen and halogen gas, and

(ii) Dissolution of metal ions.

Fig.1 Basic scheme of ECM

Reactions leading to the evolution of oxygen or halogen gas

- $2H_2O \rightarrow O_2 \uparrow + 4H^+ + 4e^-$ (*acidic electrolyte*)
- $4(OH)^- \rightarrow 2H_2O + O_2 \uparrow + 4e^-$ (*alkaline electrolyte*)

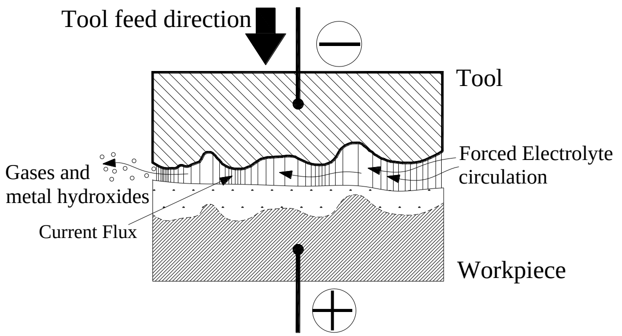
Reactions leading to the dissolution of the metal

- $M^+ \rightarrow M + e^-$ (Metals)
- $M + (OH)^- \rightarrow M(OH)^- + 2e^-$

Electrochemistry of EMM

Reactions during ECM

Reactions occurred during electrochemical machining process for machining of iron (Fe) workpiece with NaNO3 as electrolyte :



Anode

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

Cathode

- $2H_2O + 2e^{-} \rightarrow 2(OH)^{-} + H_2 \uparrow$

- $NaNO_3 \rightarrow Na^{+} + (NO_3)^{-}$
- $Fe^{++} + 2(OH)^{-} \rightarrow Fe(OH)_2$
- $4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3 \downarrow$ (*Sludge*)

***It has been established that metal dissolution reaction is the main or the only reaction that occurs at the anode.**
***Electrolyte is not being consumed.**
*** Metal is being machined at the expense of a very small amount of electrical energy.**

Material removal and machining accuracy in ECMM

The material removal rate is expressed in terms of **unit removal (UR)** in the micro-machining domain. UR is defined as a *material removed per unit cycle or per pulse* during machining.

Mass transport affects Current distribution and shape evolution.

The machining performance is influenced by various predominant process parameters, such as current density, IEG, electrolyte flow rate, concentration and type of electrolyte, and also the anode reactions

Types of ECMM

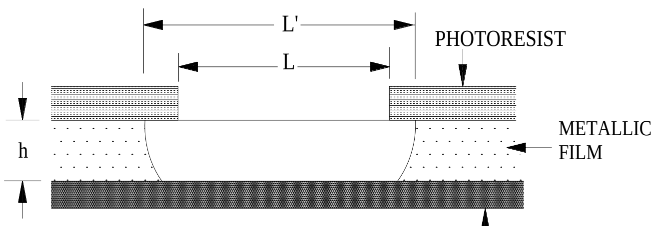
- **Electrochemical micromachining**
  - Through mask ECMM
    - One sided ECMM
    - Two sided ECMM
  - Maskless ECMM
    - Jet ECMM
    - Capillary ECMM
    - 3D ECMM

The material removal is restricted by a photo resist pattern on the metal surface and dissolution is allowed to take place only from the desired portion of the metal surface

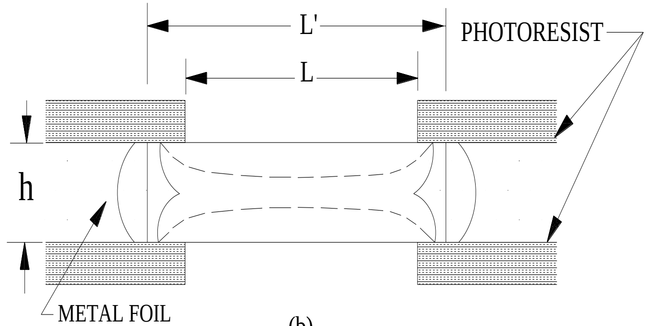
Material removal from the workpiece surface is not restricted by photoresist masking but controlled by highly localized material removal mechanism

Through-mask ECMM

- Metal dissolution takes place at the work piece surface that lies at the bottom of the cavity created by the photo resist mask, kwon et. al.
- A photo resist patterned metal work piece is made an anode in an electrochemical cell so that the exposed metal surface is removed by high rate anodic metal dissolution.
- Through mask ECMM can be of two types i.e. (a) One side through mask ECMM and (b) Two side through mask.



(a)



(b)

One side through mask ECMM

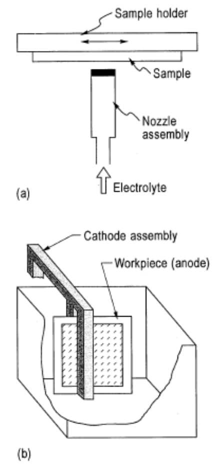
$$\text{Etching Factor } (EF) = \frac{h}{(L'-L)}$$

Two side through mask ECMM

$$\text{Etching Factor } (EF) = \frac{h}{(L'-L)/2}$$

Through-mask EMM

One side through mask ECMM



Two side through mask ECMM

# The workpiece is made of an ECM cell and mounted on a holding device	**# Workpiece is held vertically in the machining chamber. (Anode of Elelyt. cell).**
# Holding device is attached to a driving mechanism that consists of a precise XYZ µ-stage.	# Tool consists of two cathode assemblies mounted over vertically held job.
#The tool i.e. cathode of the ECM cell is a multi nozzle assembly which delivers electrolyte to the machining zone.	# Highly localized dissolution of metal from the unmasked region of two sides of work sample. It is achieved by scanning the tool
# For machining, the sample is moved at a constant speed above the multi nozzle tool.	# Electrolyte flows through the cathode assembly and passes across the surface between cathode tool & masked sample.

Maskless EMM

- There is no photo resist mask on the surface of the work piece sample.
- Highly localized selective metal dissolution from the surface of the workpiece can generate designed pattern or shape in two dimensions or three dimension scale by controlling the current density.
- The Inter-electrode gap is maintained at very low value such that the stray current effect can be minimized.
- Three types of maskless ECMM are: (1) Jet EMM, (2) Capilary drilling and (3) 3D EMM

Fig.6 Next slide

Jet EMM setup, Kozak et al.

Jet ECMM

- Electrolyte is used as a tool
- A jet of electrolyte flows through a nozzle, which is made cathode, and impinges on the workpiece
- Nozzle diameter: 50 to 200µm
- The temperature and conductivity of the electrolyte are monitored and controlled during machining operation.

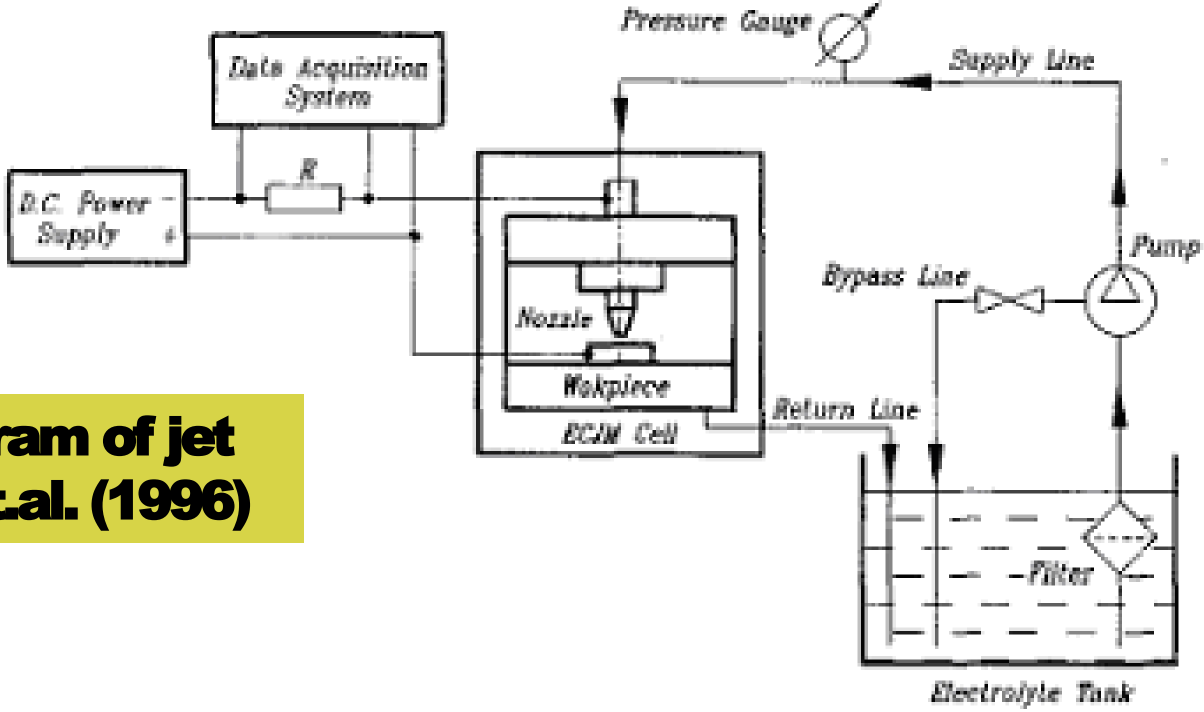


Fig. 6: schematic diagram of jet ECMM set up, Kozak et.al. (1996)

Maskless ECMM

Capillary drilling

- **Micro holes drilling utilizing anodic dissolution technique:**
- **Capillary drilling (CD), Electro stream drilling (ESD), Jet electrolyte drilling (JED).**
- **All these methods employ a jet of electrolyte for anodic dissolution of workpiece material**, (Kozak et al.)

3D ECMM

- **Micro tools with complex profiles are directly utilized in ECMM as a single run die sinking type conventional ECM technique.**
- **The complex shape micro tool is generally made by LIGA process.(LIthograohy, Galvanoformung (electrodeposition) and Abformung (moulding)**

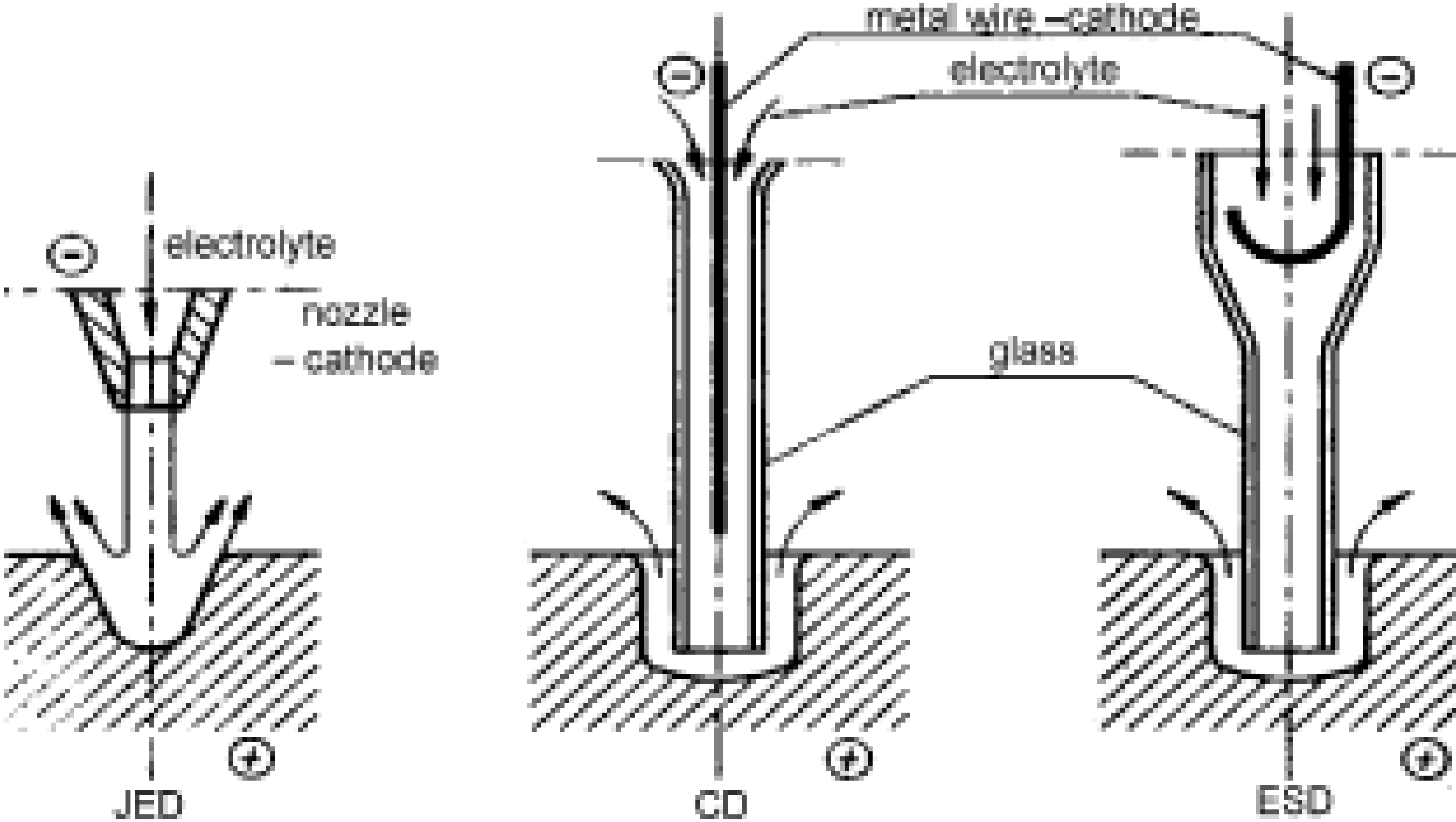


Fig. 10. Jet electrolyte flow for machining high aspect ratio holes [55].

Major factors of ECMM

EMM process parameters

- Nature of power supply
- Inter electrode gap
- Concentration, temperature and flow rate of electrolyte
- Micro-tool feed

Nature of power supply

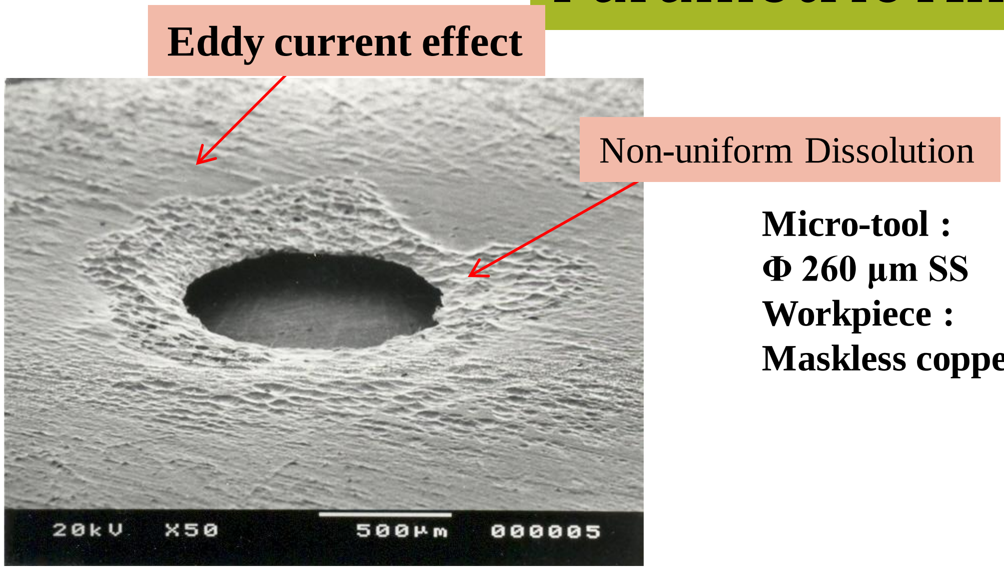
- **The nature of power supply: Full wave rectified DC and pulse DC .**
- **Low voltages of the order of 1 to 10 V.**
- **Normal current density requirement are very high:100 A/cm^{2}.**
- **The increase contamination can cause deposit on the micro tool.**
- **Workpiece material no longer dissolves uniformly.**
- **Changes in electrolyte composition and the temperature rise can make the accuracy worse.**
- **The problems can be reduced by applying the pulsed DC voltage.**

Major factors of ECMM

Inter electrode gap

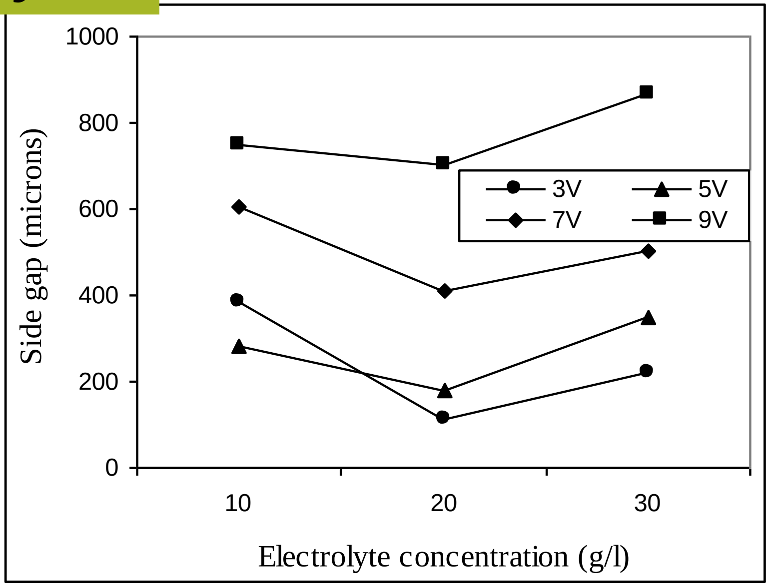
- **IEG is an important factor.**
- **Localization of the MR can be increased by reducing the gap width.**
- **Maintaining IEG 15 to 20 µm uniformly >>> to achieve high accuracy and surface finish.**
- **The need for on-line monitoring arises due to numerous complex, transient and stochastic processes occurring in the gap .**
- **The relation b/w pulse signal variance and gap size becomes significant when a shorter pulse on-time (<1ms) is used.**
- **Online monitoring of IEG is important.**

Parametric Analysis

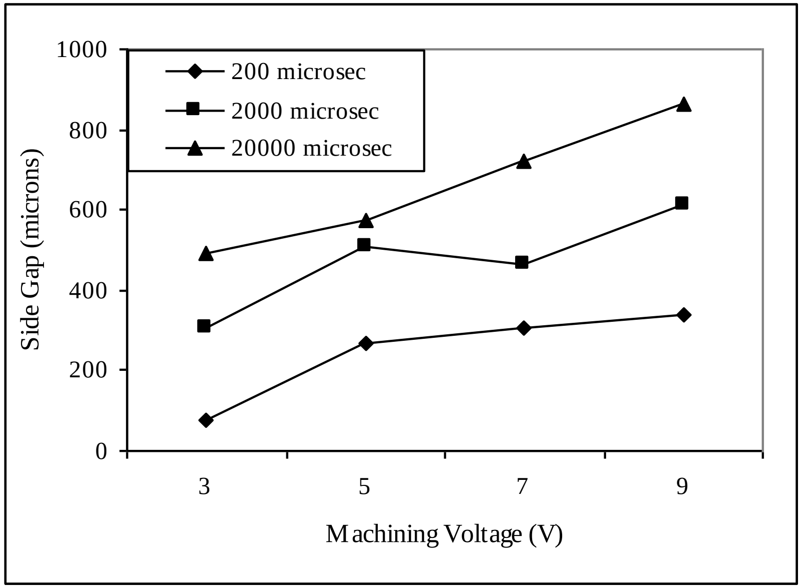


7V, 30 g/l, 20000 µsec, 80%

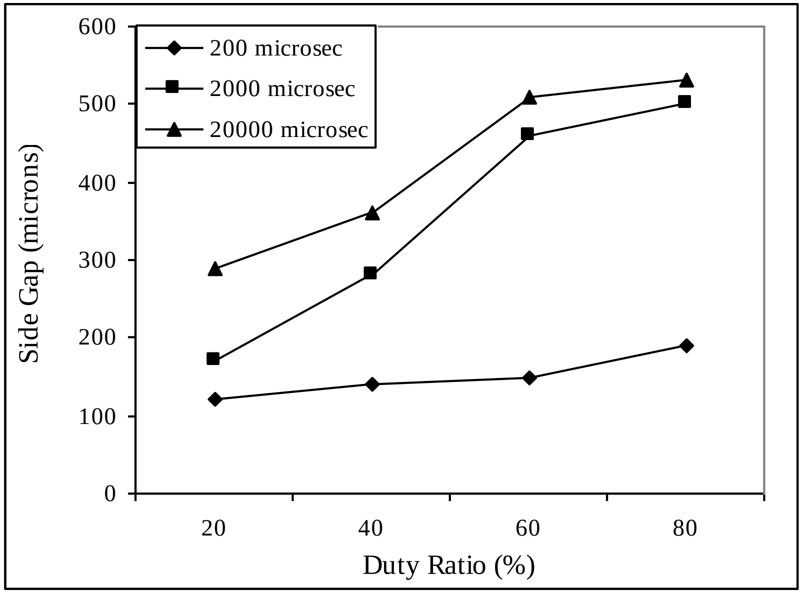
Micro-tool : Φ 260 µm SS
Workpiece : Maskless copper



20000 µsec, 80%

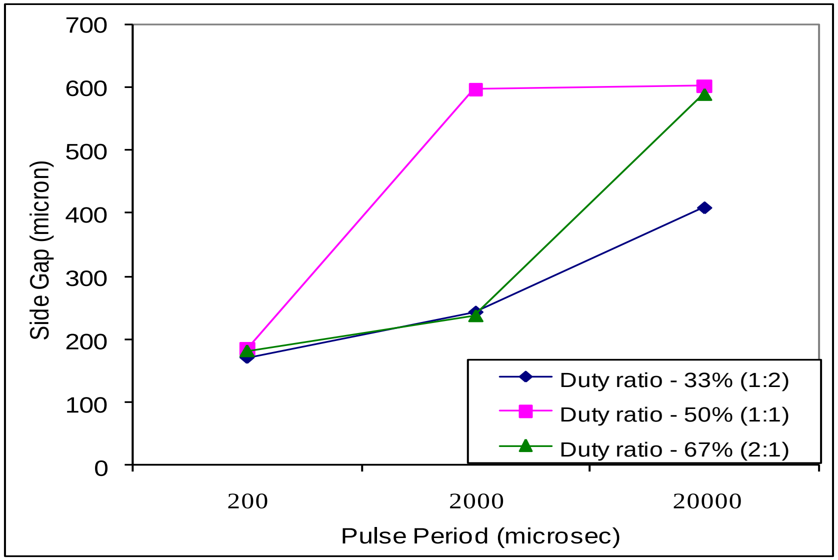


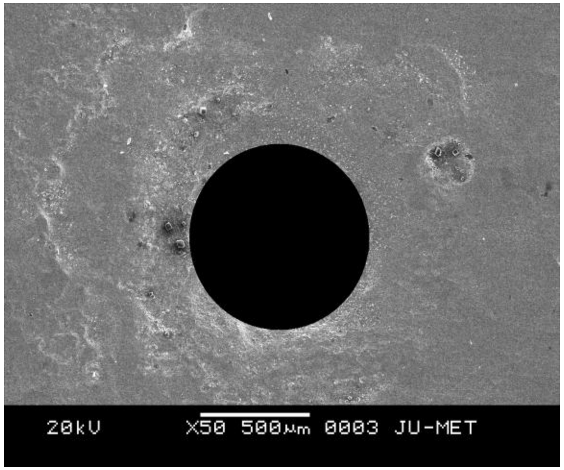
20 g/l, 80%



20 g/l, 3V

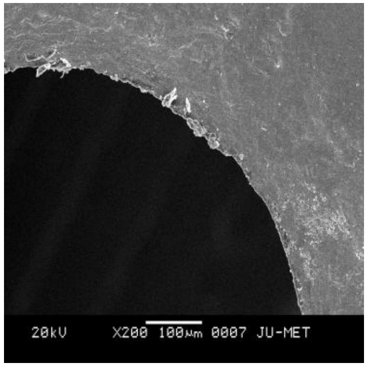
Parametric Analysis



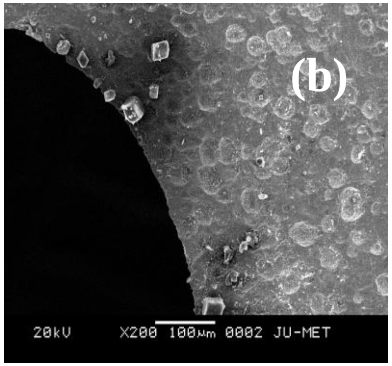


SEM Micrograph of machined micro hole
(20 g/l elect. 3V, 33% and 200 µsec pulse period)

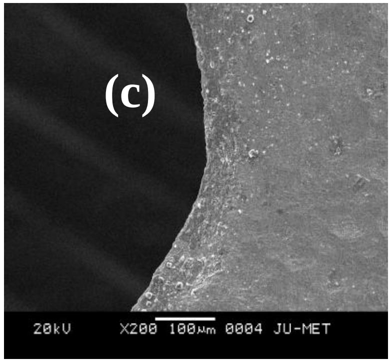
SEM Micrograph of machined micro holes periphery



(a) 20 g/l, 3V, 33% & 2000 µsec,



(b) 20 g/l, 5V, 33% & 2000 µsec



(c) 20 g/l, 3V, 33% & 200 µsec

Major factors of ECMM

Temperature, concentration and flow rate of electrolyte

(a) 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.**
- These changes would flow rate/ pressure characteristics of the electrolyte

(b) Concentration:

- A concentrated electrolyte offers **low resistance to flow** of machining current.
- A greater **current density** is achieved for a specific operating voltage.
- The disadvantage is that **salts crystallize out of the solution** at higher concentration and **clog t**he areas in the machine enclosure
- **Dilute electrolytes are used** when the surface finish is most important machining criterion.

Major factors of EMM

Temperature, concentration and flow rate of electrolyte

(c) Electrolyte flow

- The electrolyte is **pumped** from a storage tank via a pressure controller and a filter to the machining gap.
- **Different delivery systems and multi nozzle systems.**

Micro-tool feed rate

- During the course of machining, **IEG always tries to increase** due to removal of metal from workpiece.
- **The tool is fed towards the workpiece to compensate the increased gap and maintain the preset IEG. However, the process always tries to attain the equilibrium gap.**
- The micro tool feed rate should be chosen so that it is always **equal to linear MRR to avoid short circuit** during machining, since short circuit can **severely damage both the micro tool and delicate surface of the workpiece.**

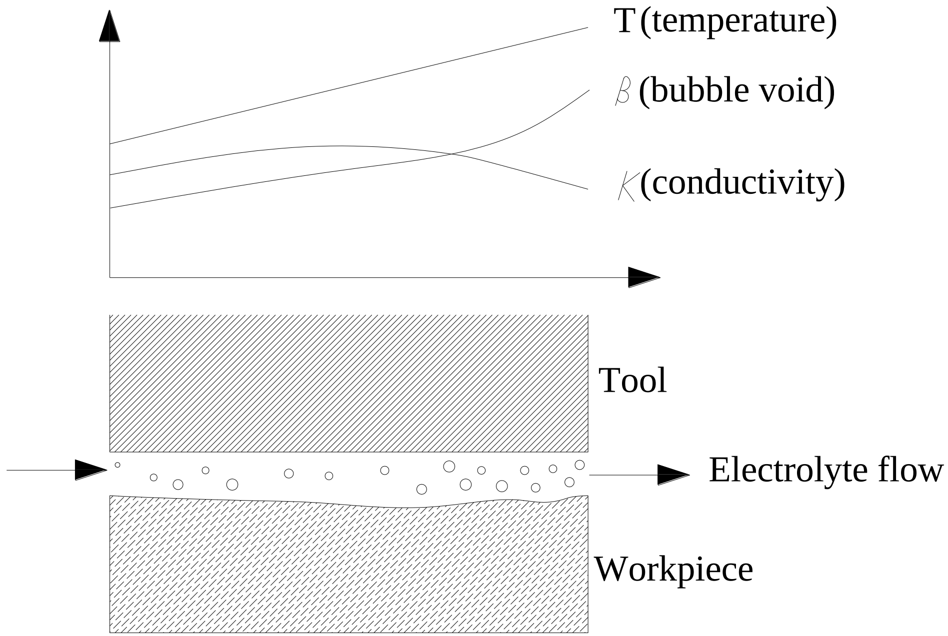


Fig. 9: Variations of electrolyte condition along the machining length, Rajurkar et. Al. (1999)

ECMM Electrolyte

ECMM electrolyte

- ❖ The Electrolyte not only completes the electric circuit between the tool and work piece, but also allows the desired machining reactions to occur.
- ❖ Generally anodic films are allowed to form on workpiece surface which helps to achieve anodic smoothing, finally some times it may cause for short circuiting during ECMM operation due to smaller IEG.
- ❖ The electrolyte carries away the heat and reaction byproducts from the zone of machining.
- ❖ Recirculation is avoided to reduce the possibility of micro tool damage.

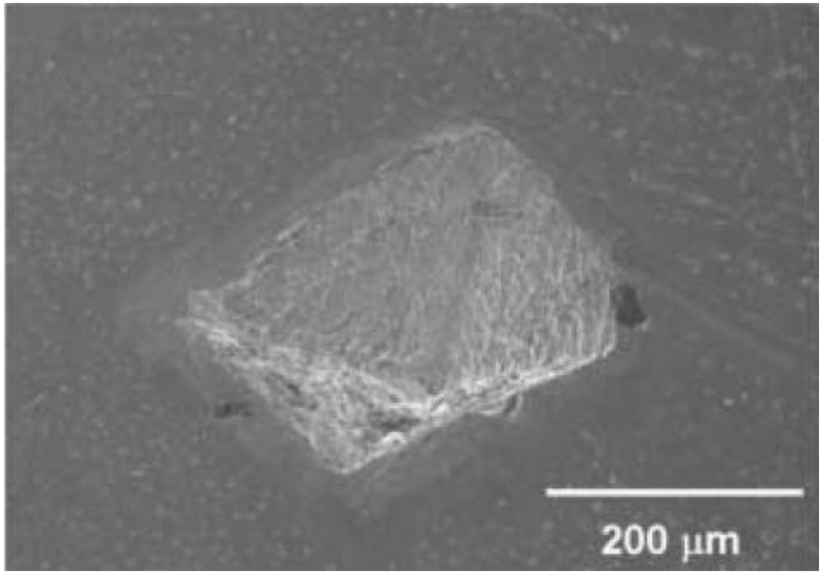
Passivating electrolyte	• Contains oxidizing agent i.e. sodium nitrate, sodium chlorate • Are known to give better machining precision
Non-passivating electrolyte	• Contains relatively aggressive anions such as sodium chloride
Acidic electrolyte	• In some cases acidic electrolyte are preferable for EMM process because it does not create any insoluble reaction products {e.g. Sodium nitrate chloride (pH=7)}

Advantages over other ECMM techniques:

(1) **No liquid electrolytes, which are difficult to handle, are required,**

(2) **high-resolution direct structuring can be achieved without masking or coating,**

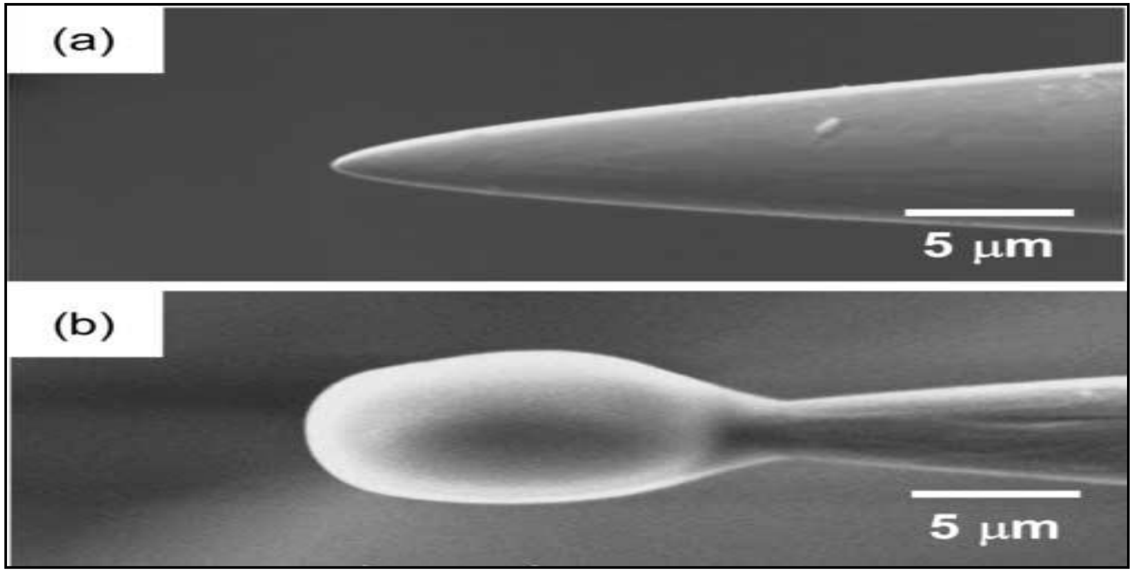
(3) **the shape of the apex of an ion conductor can be transferred to the metal surface. SSEM of several metal substrates (Ag, Cu, Zn, and Pb) was carried out.**



Metal surface after SSEM of Ag at 100 mA and 873 K for 60 min

EMM with polymer electrolyte coated micro-electrode

- ✓Solid electrochemical micro-machining has been performed using an **ion conducting polymer** coated tungsten needle microelectrode in place of a Na-β”-Al_2O_3 pyramid.
- ✓The present development employs a tungsten microelectrode coated with a polymer electrolyte layer.
- ✓The shape of the apex of an ion conductor can be directly transferred to the metal surface because the solid electrochemical reaction proceeds only at the solid-solid micro contact of the polymer and target metal plate.



SEM images of W microelectrode before (a) and after Nafion coating (b)

Micro tool design and analysis

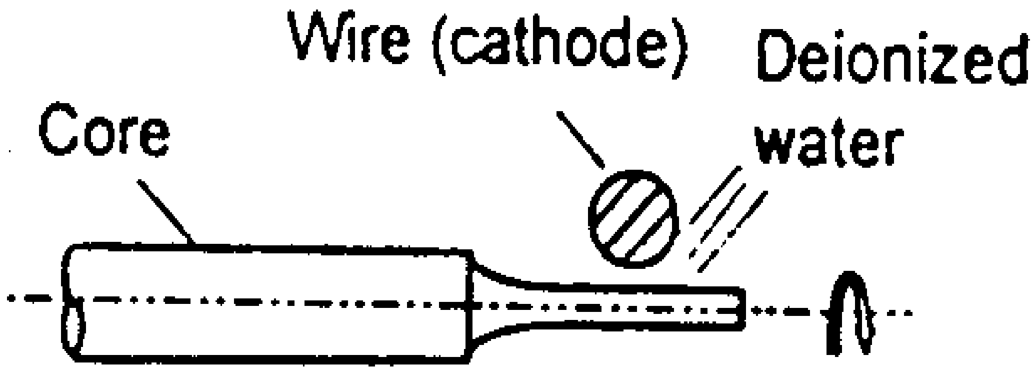
Design of micro tools

- Determination of tool shape is a **challenging task** due to the complex gap configuration.
- The tool shape is **negative mirror image** of sample to be produced.
- Prediction of the tool shape is formidable **inverse boundary problem involving Laplace equations.**
- The **correction factor method of tool design.**
- **Early investigation** to tool design procedure were mainly limited to **"simplified methods"** like analytical solution,, graphical, geometrical and complex variable techniques.

Fabrication of micro tools

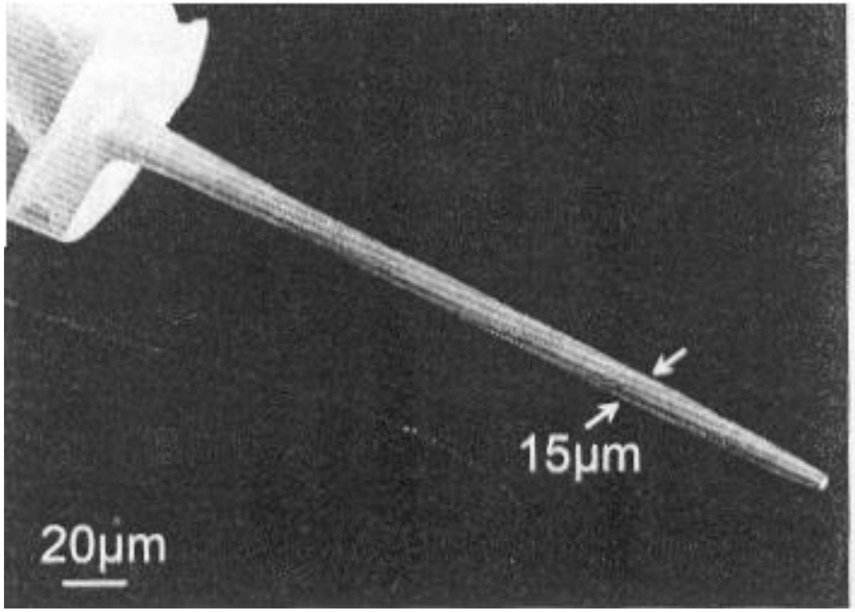
- Micro tools are fabricated using (i)electrochemical etching and (ii)wire electro discharge grinding (WEDG).
- Material for micro tool: chemically inert, good electrical conductivity and easily machinable.
- For reducing the effect of stray current , the micro tool is also insulated.
- An insulating cover of SiC/Si_3N_4 may be coated on the cathode tool by means of chemical vapor deposition (CVD).

Micro tool Fabrication by WEDG

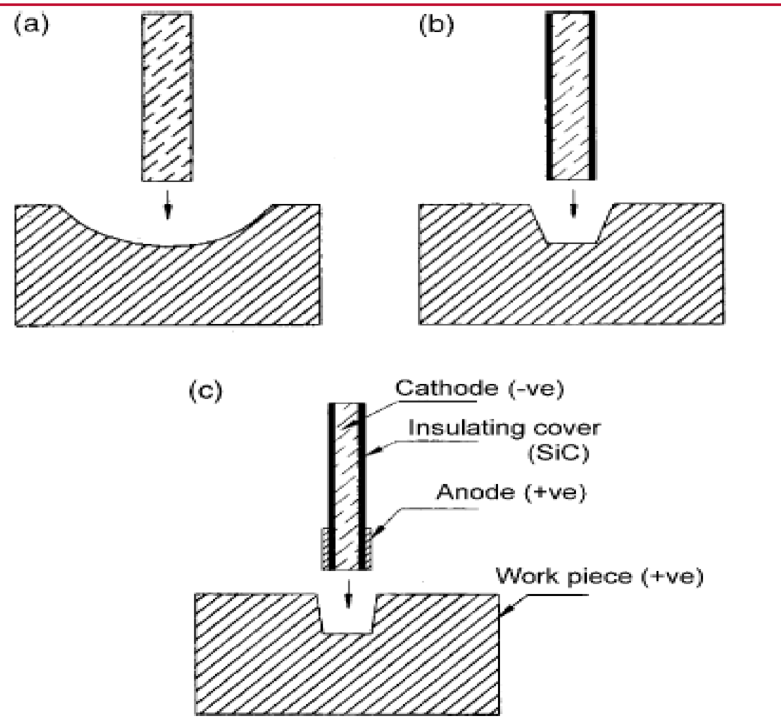


Fabrication of micro tool

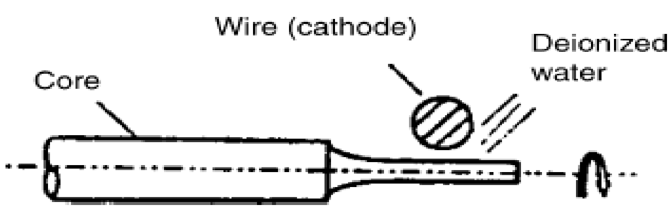
Micro-tool manufactured by WEDG



Design and development of Microtools

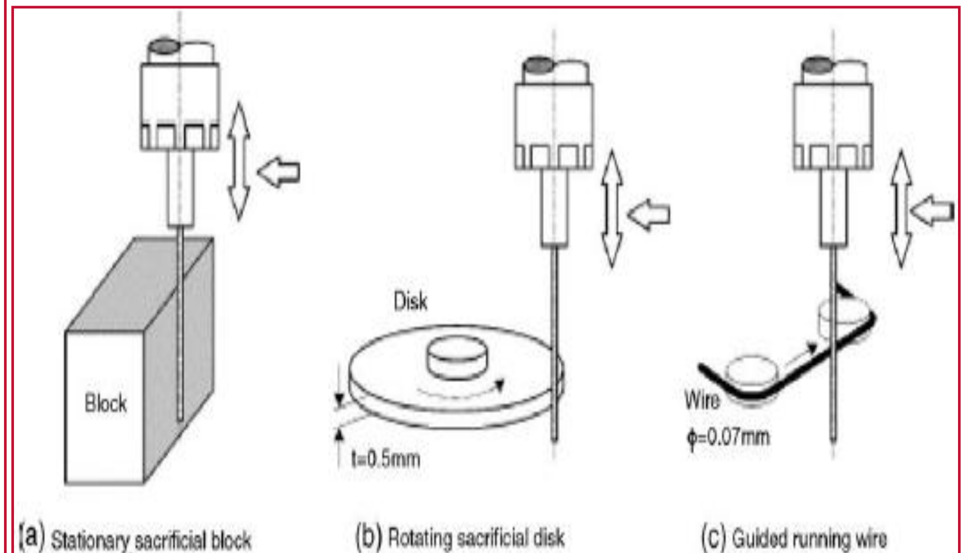


Influence of (a) uninsulated, (b) insulated, and (c) dual pole n machining accuracy.

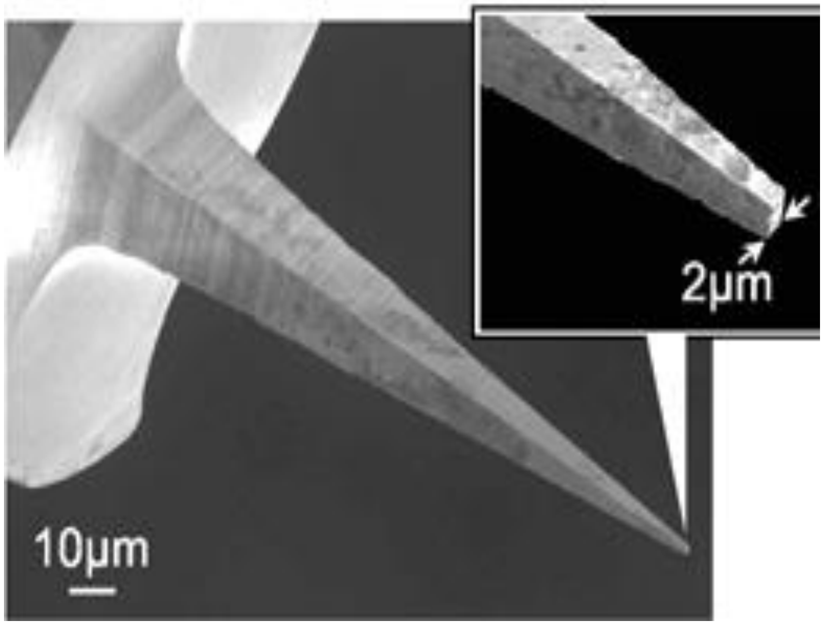


Fabrication of microtool.

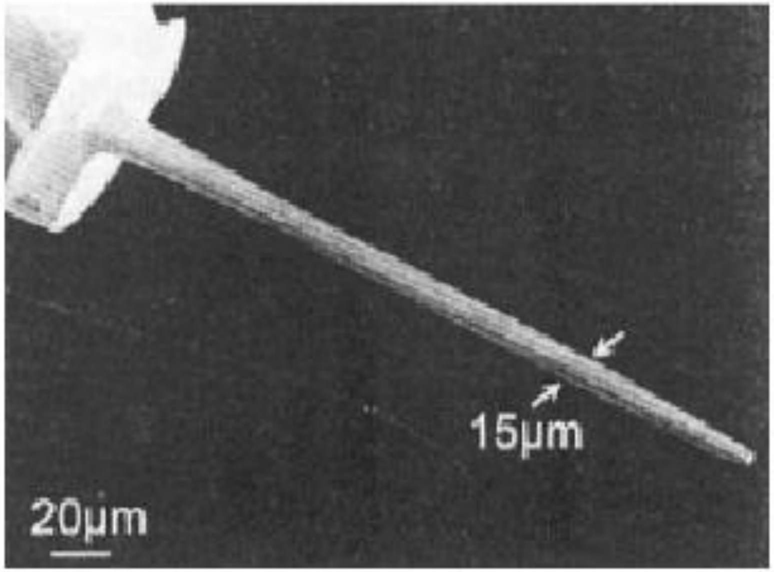
- **Design** – *size, shape and profile*
- **Manufacturing** – *WEDM, reverse EDM & ECM, conventional etc*
- **Coating** – *CVD, sol gel etc or dual pole tool*



Microtools Manufactured by Different Methods



Micro-tool manufacture by ELID grinding



High aspect ratio microtools

Microtool vibration unit of ECMM

Need for tool vibrating system

IEG : 5-15 μm for effective machining

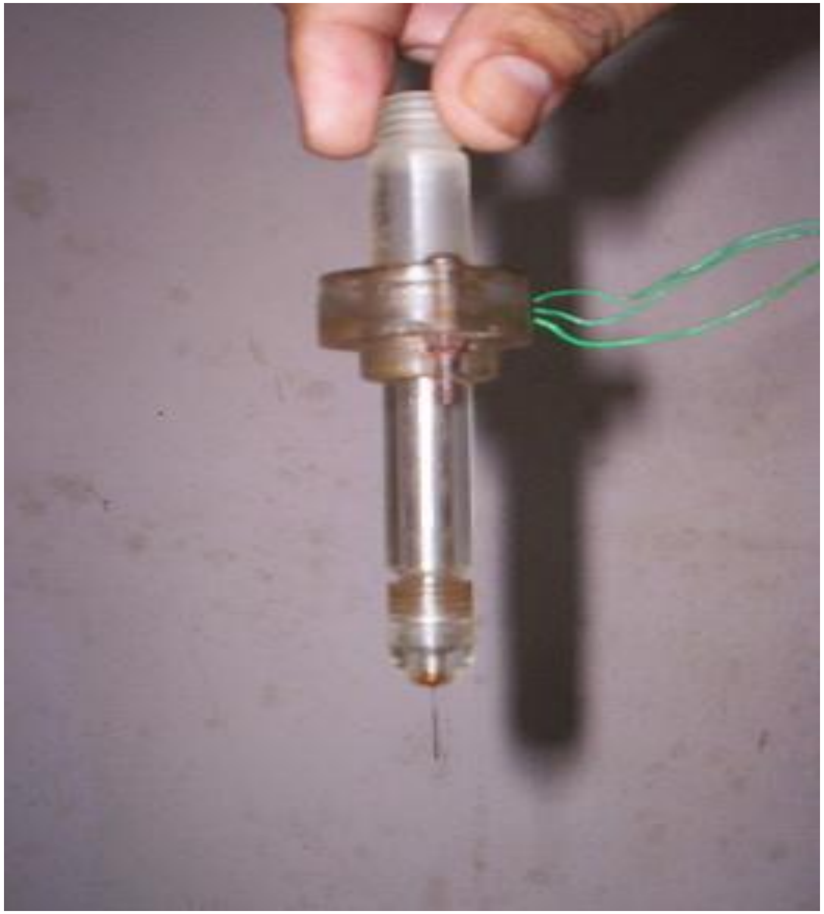
Removal of reaction products → micro sparks

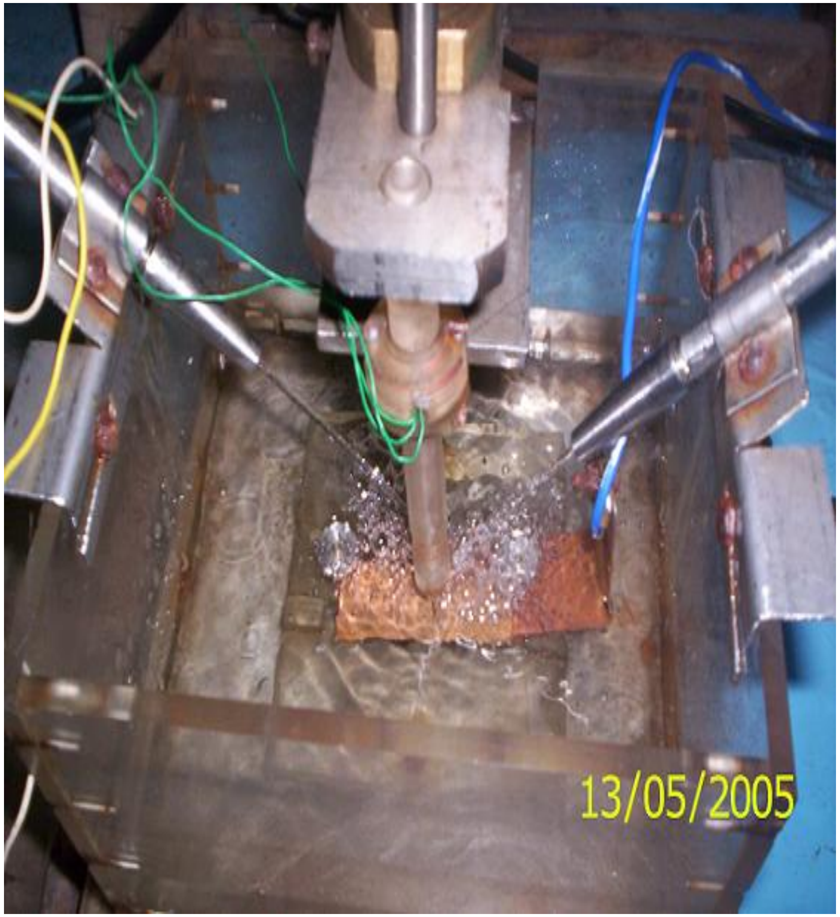
Micro sparks can be avoided by using

- ✓ **Acidic electrolyte, but may cause chemical reaction with base material**
- ✓ **Vibration of micro tool, PZT is used to enhance the end gap and minimize the sparks**

Piezo-electric ceramic plate (PZT) is connected with an audio oscillator circuit to get required electrical pulses that create desired vibration, which in turn vibrates the micro tool.

Microtool vibration unit of ECMM and its usage



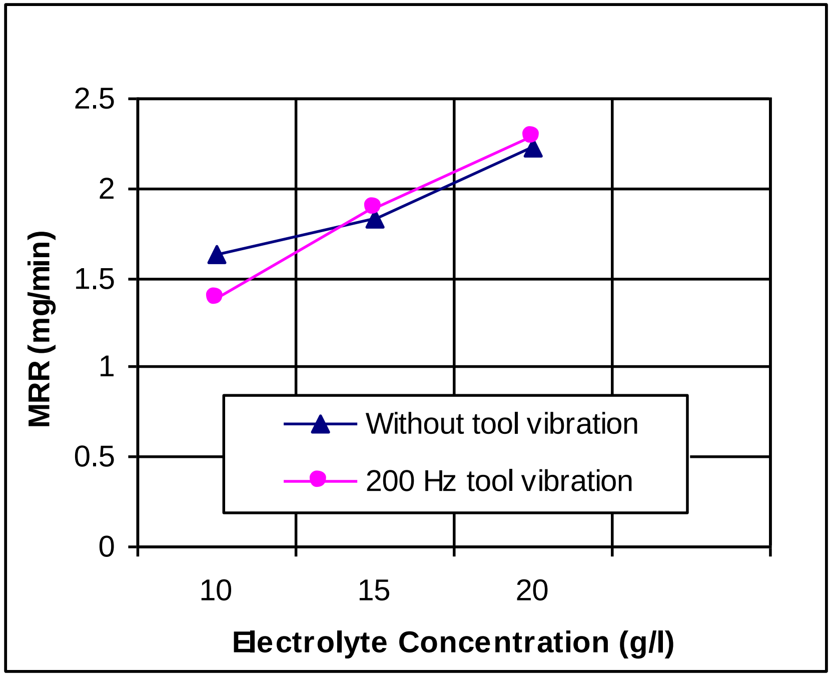


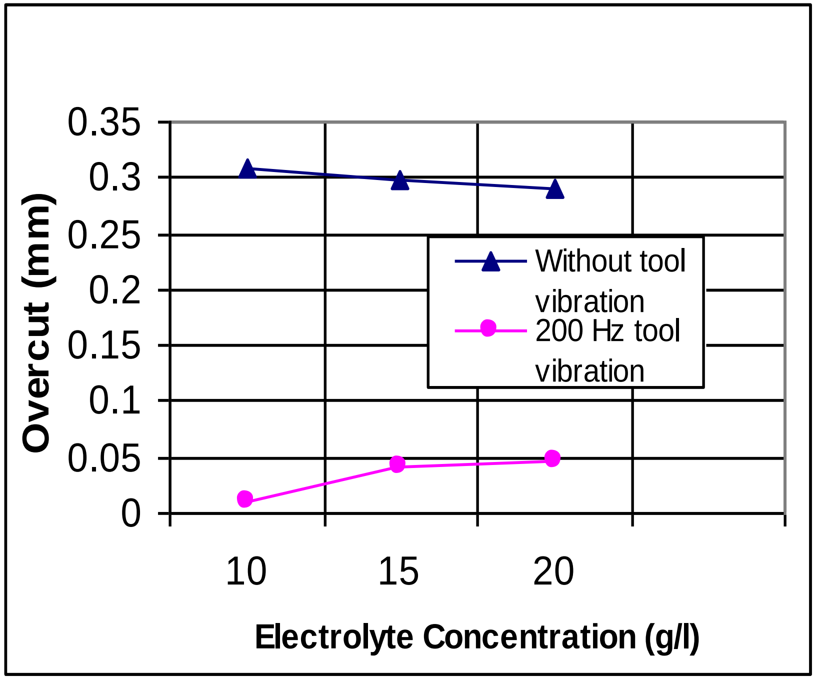
Accuracy (overcut) is improvement due to the micro tool vibration

At Mach. Voltage – 3 V, Mach. Frequency – 55 Hz

Tool vibrating frequency :

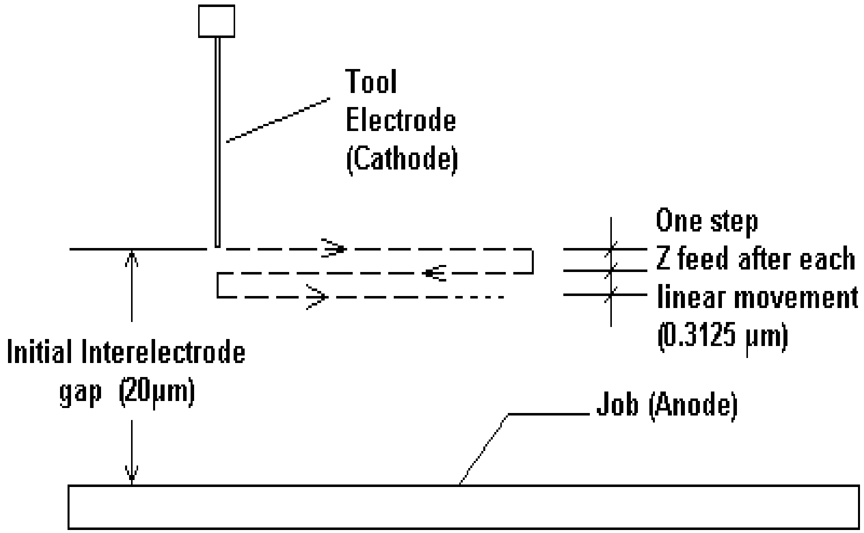
Range of frequency: Hz Range : 25 Hz to 300 Hz;



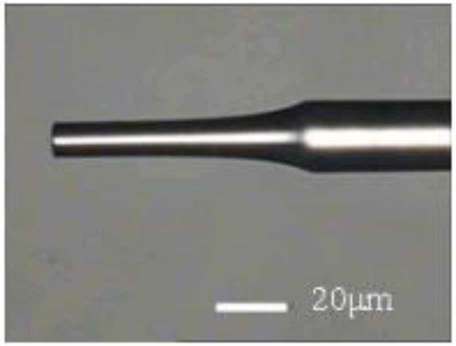


Accuracy (overcut) is improved due to the micro tool vibration, which creates pressure waves in the electrolyte and promotes better circulation of electrolyte and removal of sludge and precipitates from the narrow zone of micro machining

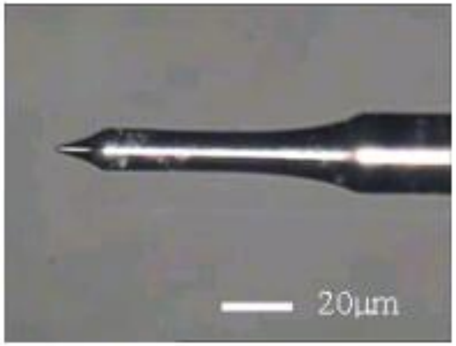
ECMM by Scanning Movement of Tool



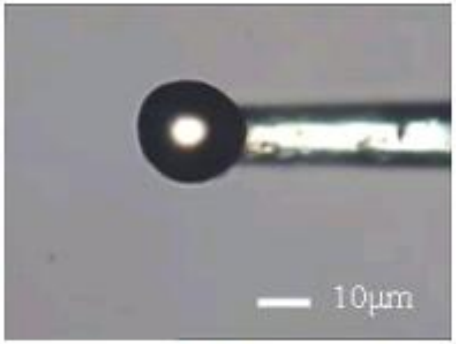
Scheme of micro-tool movement



(a) flat end

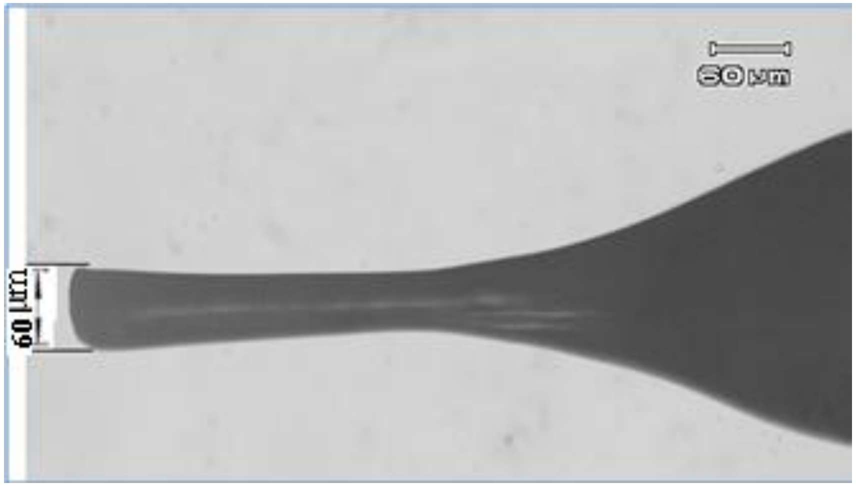


(b) conical end

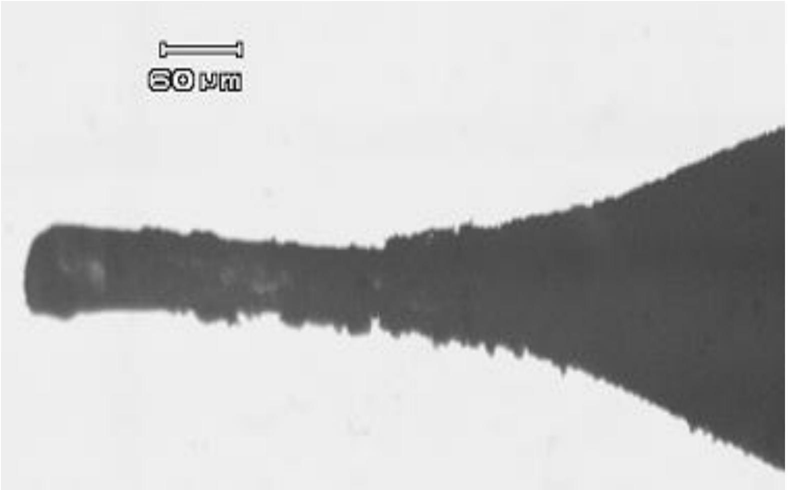


(c) spherical end

Negative Tool wear rate: Sludge deposition on the microtool

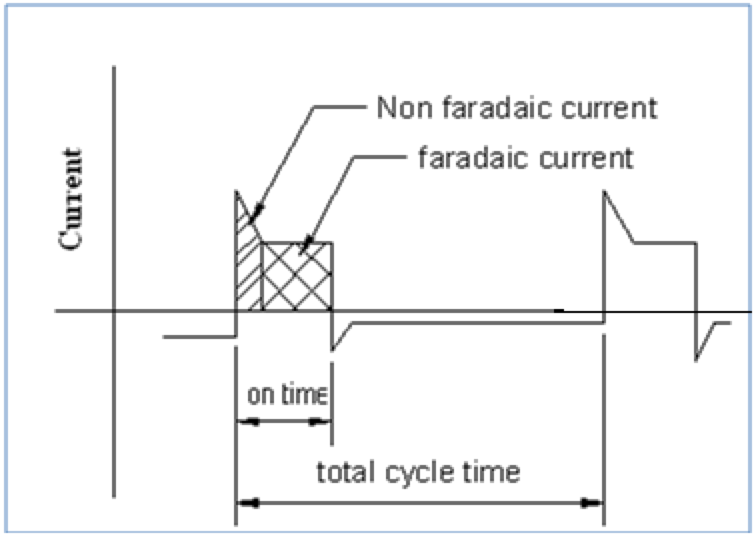


Fresh tool before EMM operation having taper angle 2^0 and tip diameter 60 μm

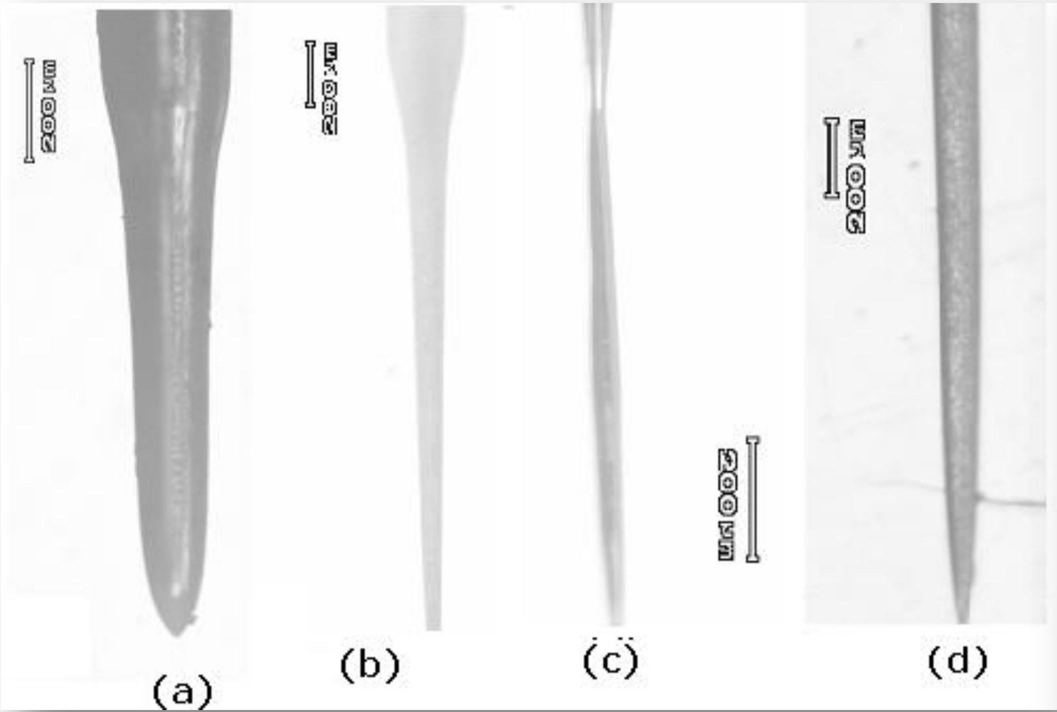


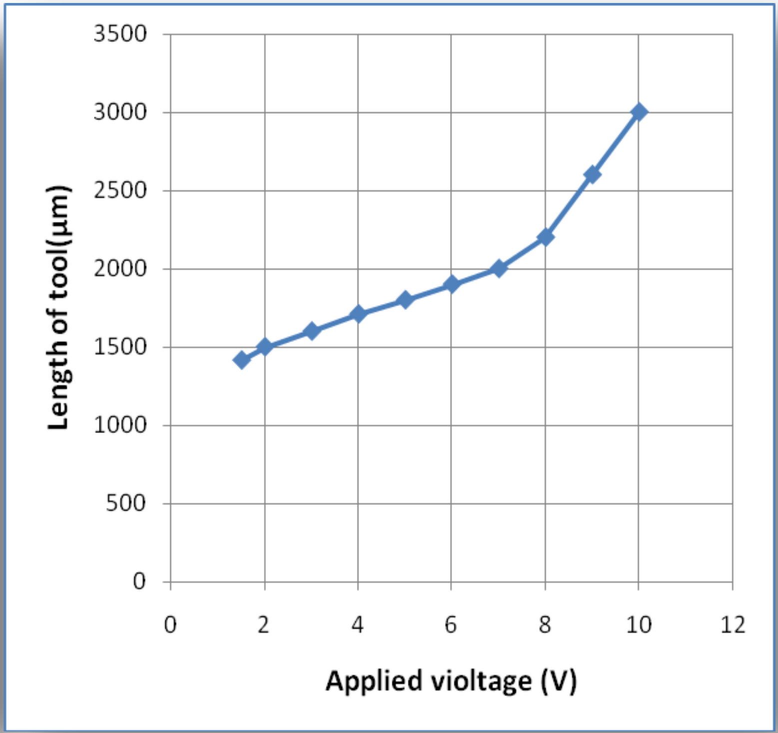
Sludge deposition on micro tool during EMM

It has been observed that positive base line potential not only increases overcut but also deposits metal on the micro tool during ECMM.



Shape evolution at high voltage and high amplitude of vibration





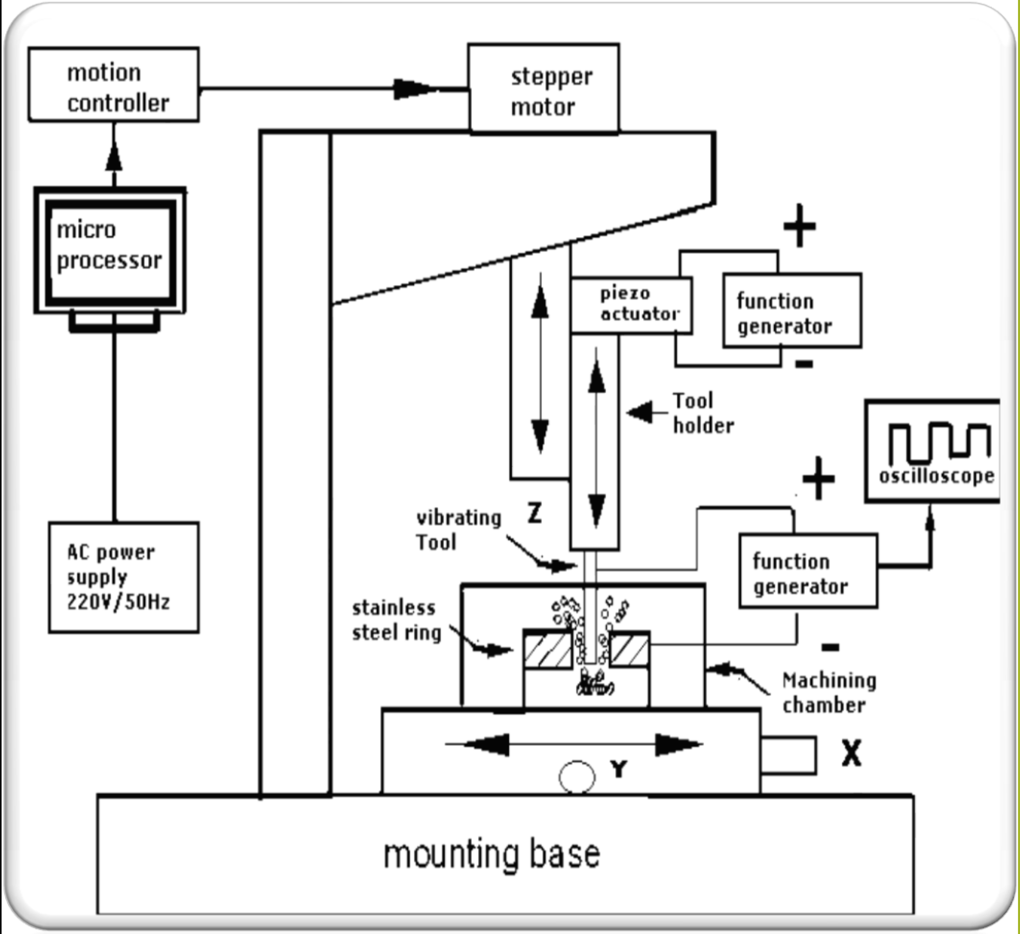
7 V applied voltage, 5 µm amplitude of vibration, 2 M/L NaOH, 900 µm dipping length and 228 Hz frequency of vibration

(a) 70 sec of machining, average dia. φ165 µm
(b) 100 sec of machining, average dia. φ131 µm
(c) 147 sec of machining, shank dia. φ30 µm and tip dia. φ 9 µm
(d) Increased voltage, sharp taper occurs having larger taper angle

Effect of voltage on the length of tool, maximum tool length 3 mm at 10 volt

Basic EMM setup

- ✓ECMM appears to be a very promising micro-machining technology due to its advantages, which include ***high MRR, better precision and control, short machining time, reliability, process flexibility.***
- ✓ It also ***permits the machining of chemically resistant materials*** like titanium, copper alloys and super alloys, which are widely ***used in biomedical, electronic and MEMS applications***
- ✓***The electrical conduction method maintaining the electrode gap distance between the tool electrode and work piece can be applied for sensing the voltage.***

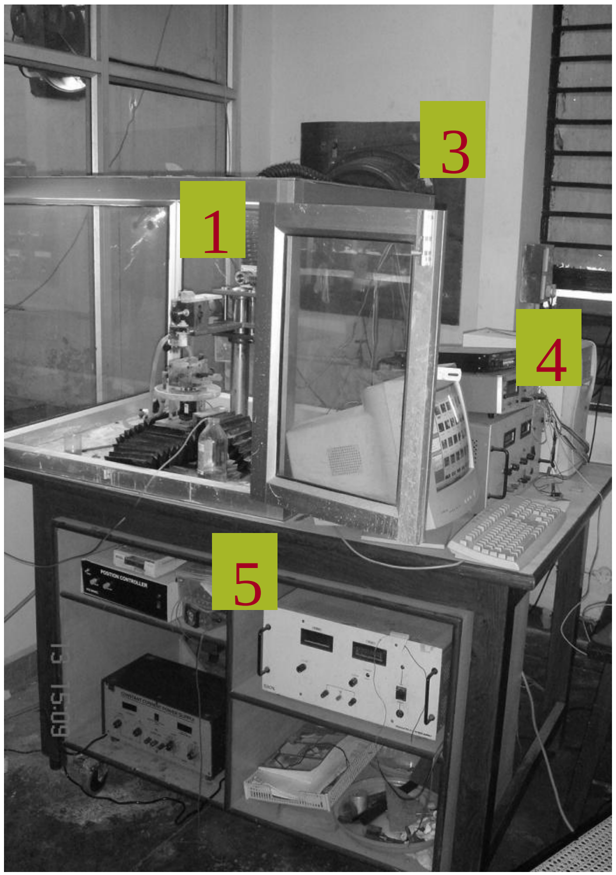


(Bhattacharya et al.)

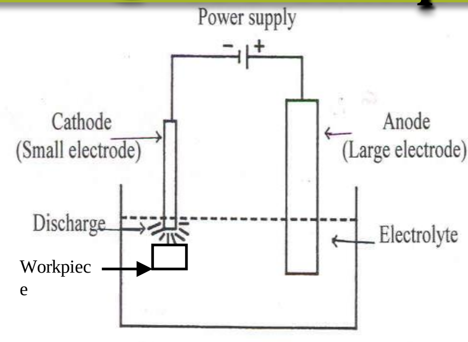
Electrochemical Micromachining (ECMM)

Electrochemical Micromachining (ECMM) setup

Experimental Set-up designed and developed @ IIT Kanpur

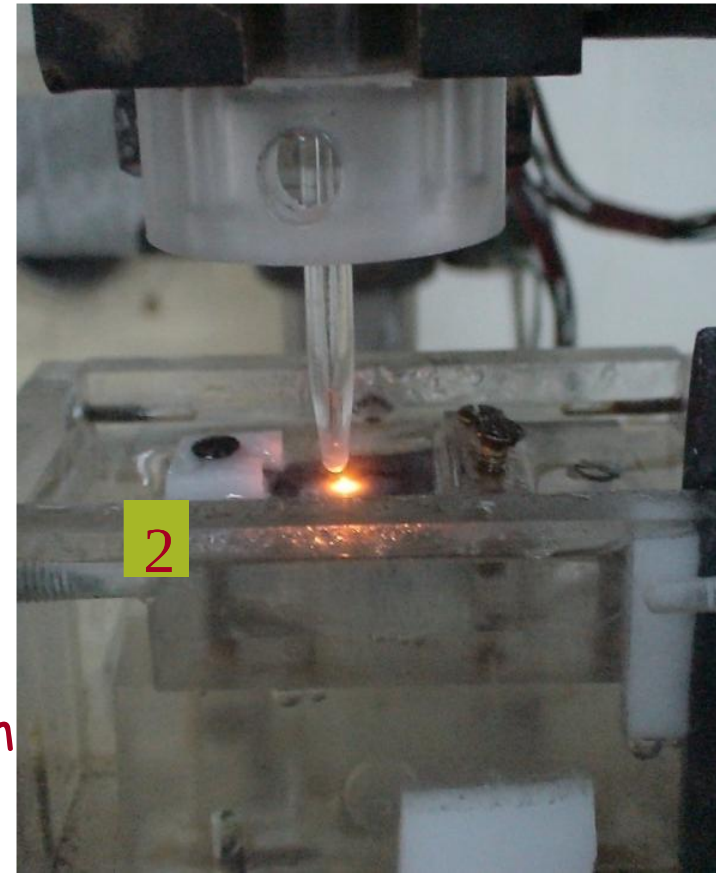


Experimental ECS Set-up



Process Schematic

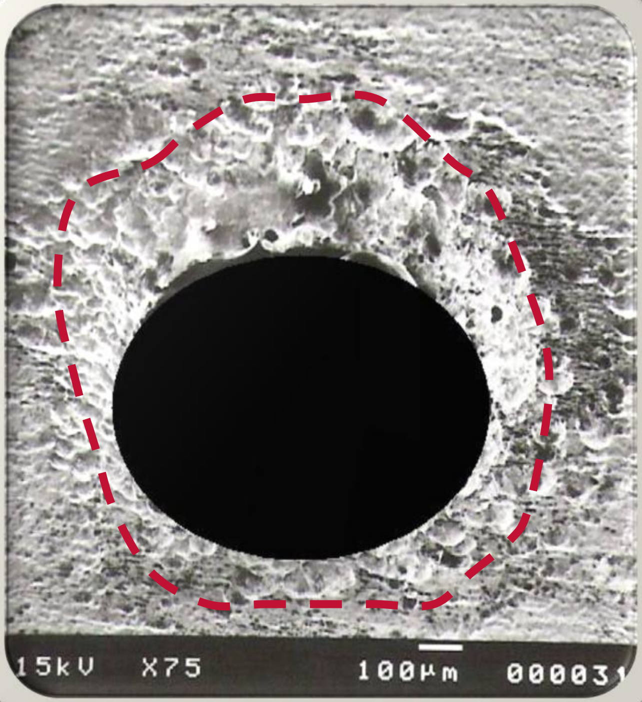
1. Machining Chamber
2. ECS Cell
3. Exhaust System
4. Control PC
5. Power Supply System



‘Spark’ at the tool tip

Micro-spark phenomena in ECMM

- **Micro cracks** occur in machining zone due to variation in machining parameters apart from tool feed rate, heat generation across IEG, accumulation of sludge and gas bubbles in the very small IEG
- **High speed storage digital oscilloscope** can monitor the nature of the pulse patterns.
- Causes of **change in gap resistance**: electrolyte heating, gas bubbles generation, sludge formation etc.



- Some of the major factors related to ECMM setup which influence the phenomenon of the occurrence of **micro-sparks** are identified as;

1. **Micro tool movement**
2. **Electrolyte circulation**
3. **Inter electrode gap control and monitoring**

Micro-spark phenomena in EMM

1. **Micro tool movement**

- **μ-tool feed rate should always be less than the linear MRR**, for performing micro-machining.
- **Maintaining constant feed rate** to any operation increases the **possibilities of occurrence of micro sparks**.

2. **Electrolyte circulation**

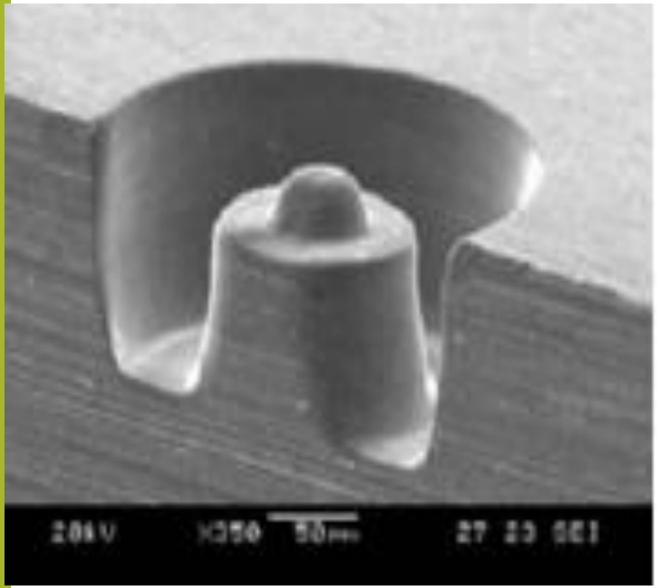
- Hydrogen gas generation and evaporation of water may **change the electrolyte concentration and viscosity.**
- **Highly concentrated viscous electrolyte may not be able to remove all the reaction products from the IEG, leads to micro sparks.**
- These sparks can be controlled by selecting proper electrolyte (acidic electrolyte does not produce any insoluble reaction products).

3. **IEG control and monitoring**

- IEG should be maintained effectively in the range of 5-15 .
- **By products of reactions may stick between micro tool and workpiece and might lead to micro spark generation.**
- **These sparks may be avoided by vibrating micro-tool and using stepper motor controlled mechanism for tool movement.**

Applications of ECMM

Micro Electrochemical Milling



Micro hemisphere on the top of cylinder

- Layer-by-layer machining is applied with dilute and less toxic electrolyte, 0.1 M H_2SO_4.
- Micro structures with good surface quality (R, 0.28 µm)

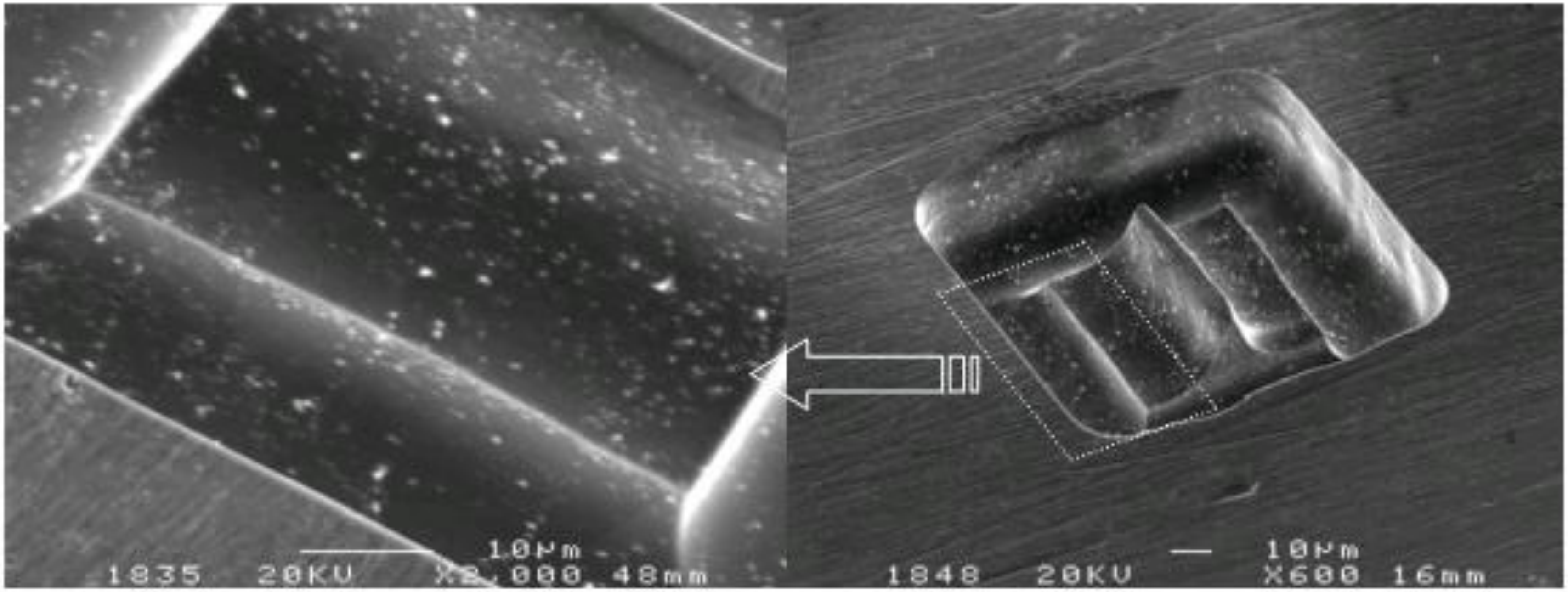
Steps in Micromachining-

Rough cut- the cylinder & the hemisphere with 100 µm diameter on the cylinder.

Finish cut with very fast feed rate - the hemisphere with 60 µm diameter.

Dissolution can be localized by not only short pulses but dissolution time.

Milling of 3D structure with plane surfaces

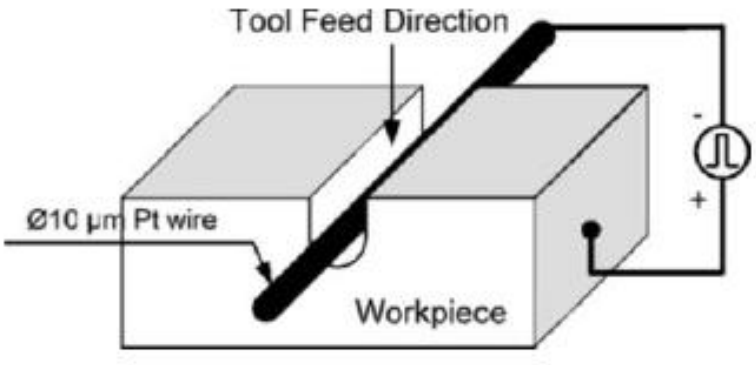


Regular 3D structure with planes which was machined layer by layer using a flat tip electrode with diameter of 10 µm on a 300 µm thick nickel base superalloy (GH3030) plate. Pulses with 4.5 V and 90 ns pulse on-time were applied in 0.2 M H2SO4.

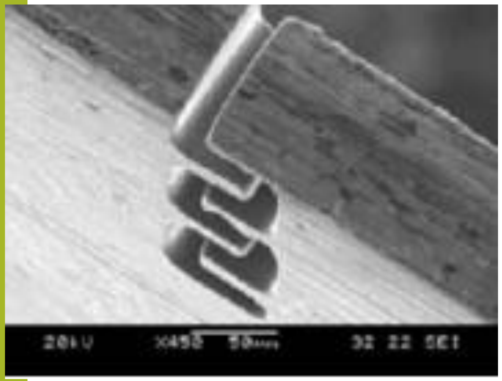
ECMM processing can achieve a good surface quality and machining precision by using the type of flat tip electrode.

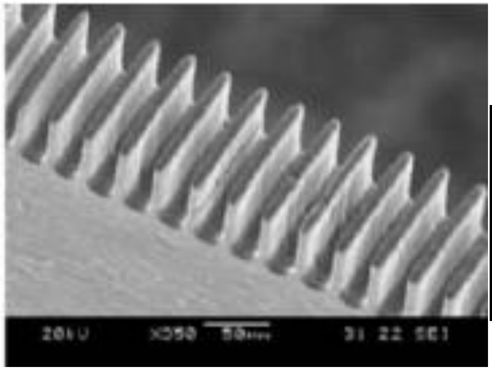
Wire Electrochemical Machining

- A **micro wire** is used as a tool electrode in Wire ECMM.
- Wire is not worn out, thinner wire can be used. Wire ~~feeding~~ **traveling** **is not necessary.**
- Applied to the fabrication of **micro grooves**.



Wire ECM





Platinum wire with 10 μm diameter. Micro grooves with 20 μm width.

Wire ECMed micro grooves

NANO-FABRICATION USING ECMM

- Attempts have been made to utilize micro and nano scopic anodic dissolution of metals for fabrication of Nano features. Principles of ECMM have already been successfully demonstrated to machine nano scale features using ultra short pulses.

- Research is going on around the world to improve the performance characteristics of ECMM for utilizing it more effectively in Micro and Nano fabrication.
- Some of the latest research directions in this area:

(i) Solid electrochemical machining ,

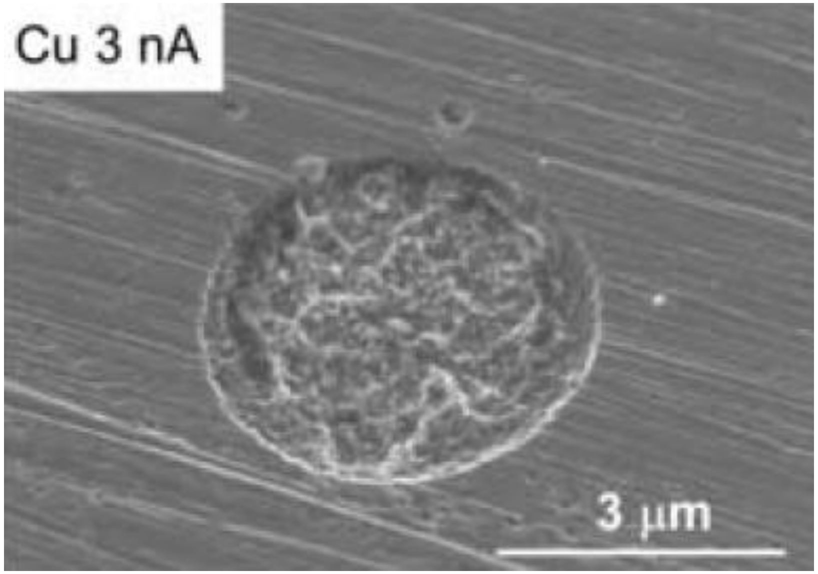
* ECMM with no liquid electrolyte,
* ECMM with polymer electrolyte coated micro-electrode,

(ii) **Wet Stamping**

(iii) **Nanometer Scaled Surface Structuring** ,

(iv) **Nano ECM**

SEM images of machined metal surfaces under various conditions for 60 min

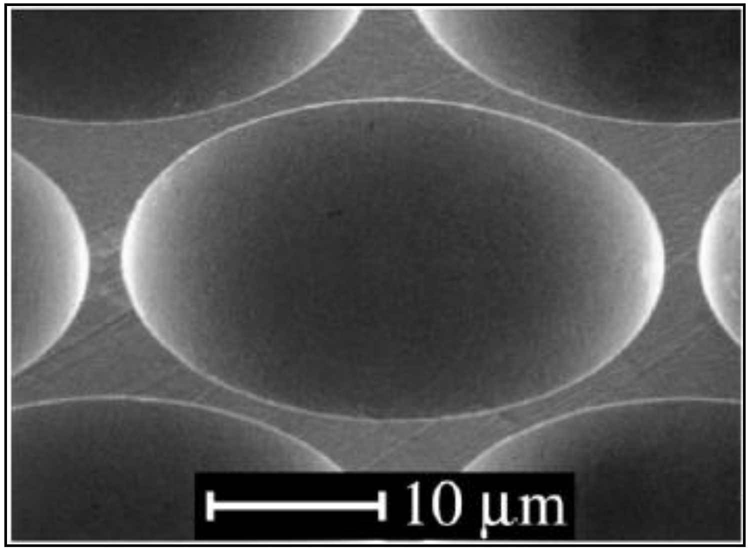


The aspect ratio of the machined surface can be easily designed by the apex configuration of the polymer layer.

Different kinds of metal substrates can be machined and submicron resolution can be achieved at room temperature.

Surface structuring by ECMM

The surface topography of biomedical implants plays an important role for cell attachment and differentiation.



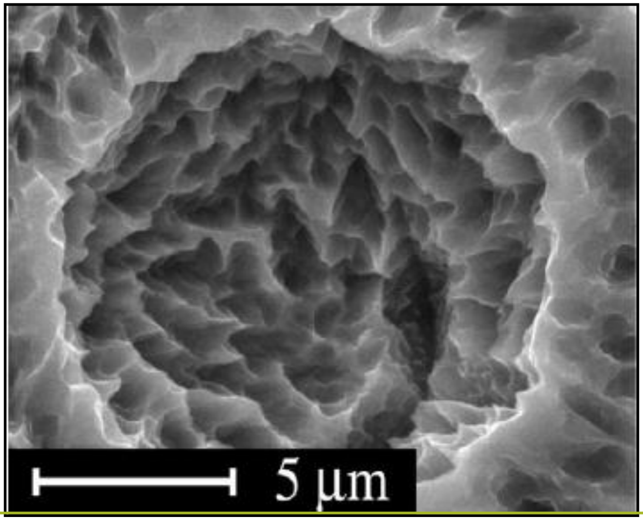
Electro-polished cavities and mechanical polished surface

Using an optimized voltage function well defined regular surface structures on 1.5 cm diameter polished disks were made.

Nanometer Scaled Surface Structuring

Surface topography at the nanometer scale is thought to be at least as important for cell response as micrometer scale topography.

For titanium, chemical etching in hot sulphuric and hydrochloric acid based electrolytes can produce roughness on a submicrometer scale. By superposing this type of nano-roughness with electrochemical microstructuring one can produce surfaces with controlled roughness at two different scales.

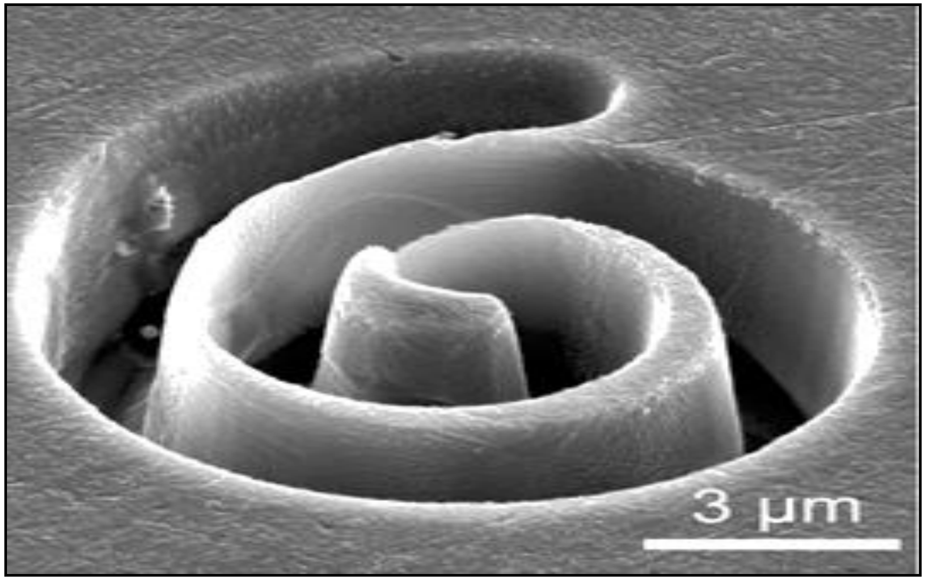


Superposition a sub-micrometer roughness produced by chemical etching on a 10 µm cavity produced by ECMM.

Nano ECM

In Scanning Tunneling Microscope (STM) based ECMM, reactions are confined to the tunneling region due to depletion of electrolyte in the tip-surface gap.

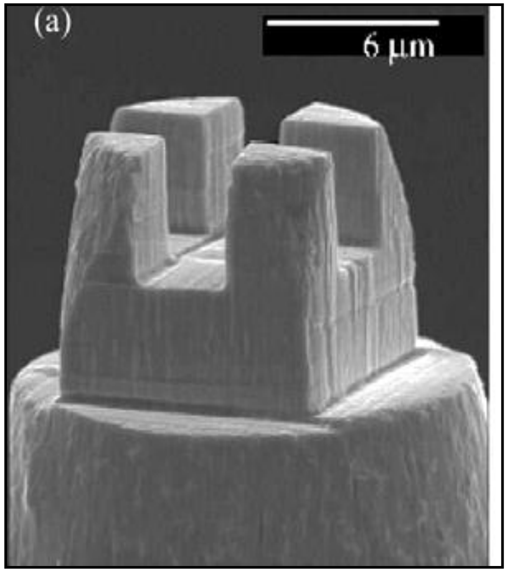
Using STM based ECMM micro-grooves with sub micron width can be fabricated with machining precision below 100 nm. STM has also been used as tool for nano-structuring of electrode surface by the application of 500 ps voltage pulses [30, 31].



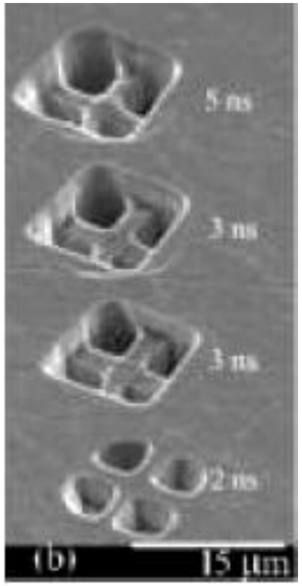
5 µm deep spiral machined in Ni sheet.

Nanomachining by ECM

A tungsten tool of complex shape with rounded features was produced by focused ion beam milling and utilized for single step electrochemical machining for generating nano-structures in Nickel using ultra short voltage pulses.



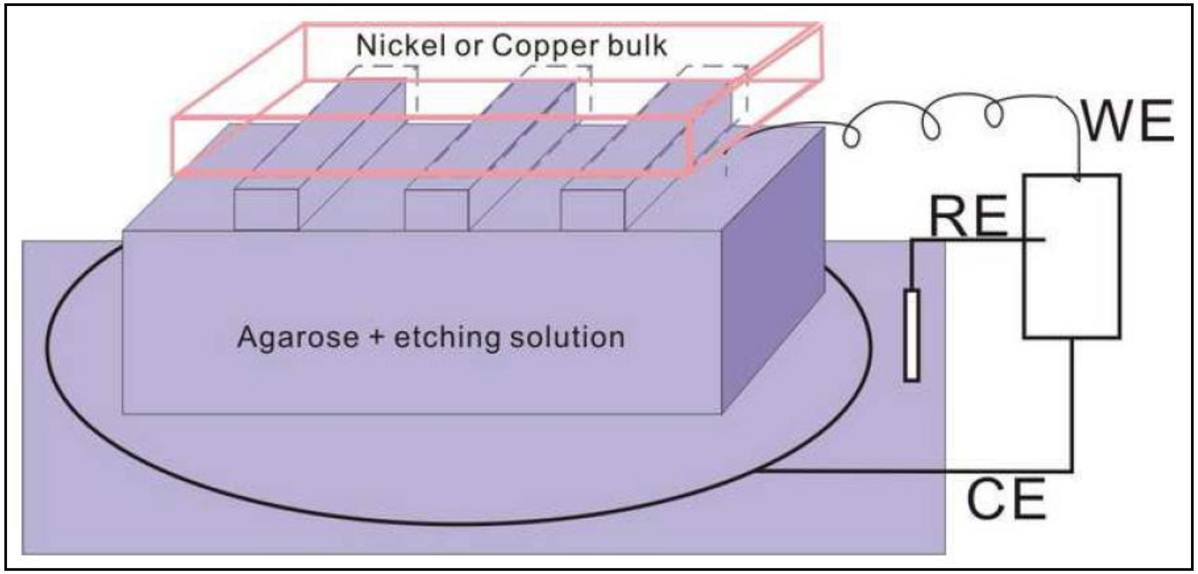
(a) Tungsten Tool



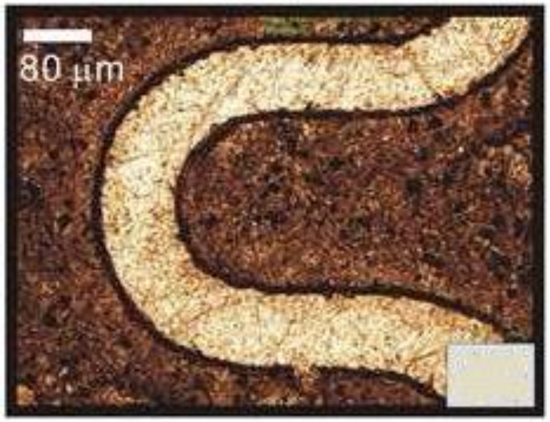
(b) Structure in Ni

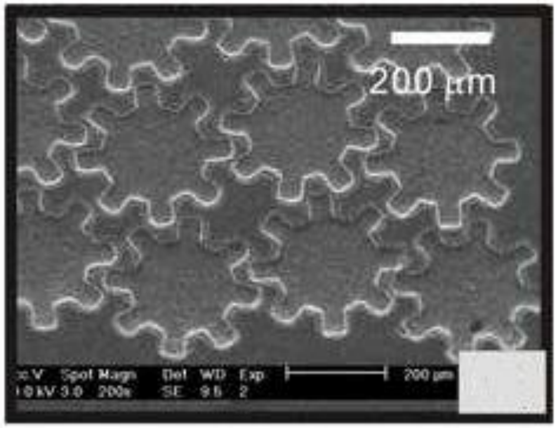
The structure of 400 nm was machined into the nickel surface in 105 seconds which is much faster than the time required to machine the tool itself.

Electrochemical Wet Stamping



- Pre patterned agarose with a high gel strength soaked in a etching solution acts as a stamp.
- Electrolyte comes into contact with the workpiece through the agarose stamp.
- Anodic dissolution will take place only to the preferential parts of the conductive substrate.

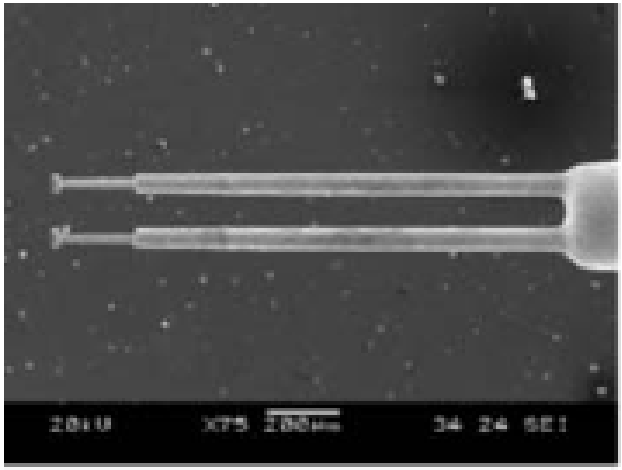




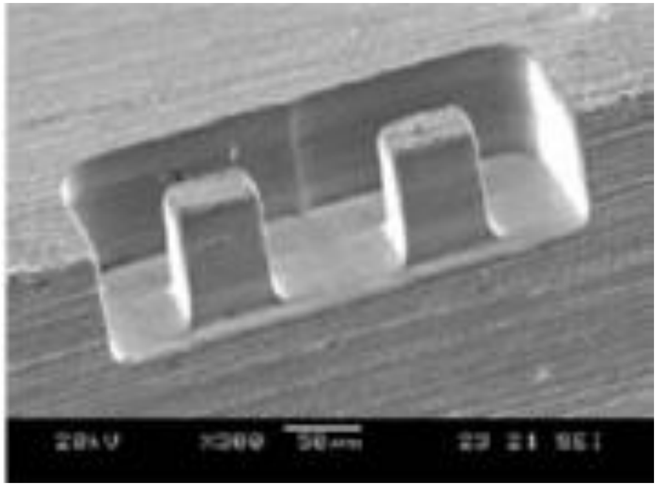
Microstructures fabricated on the bulk metal

Multiple Disk-type Electrodes

Disk-type electrodes can be applied to machine micro structures without taper.
Application of multiple electrodes increases productivity of micro ECM.
For the multiple machining without taper, multiple disk-type electrodes are machined by Reverse ECM (You can make the tool by reverse ECM, and then without disturbing it, use it as a tool in ECMM).



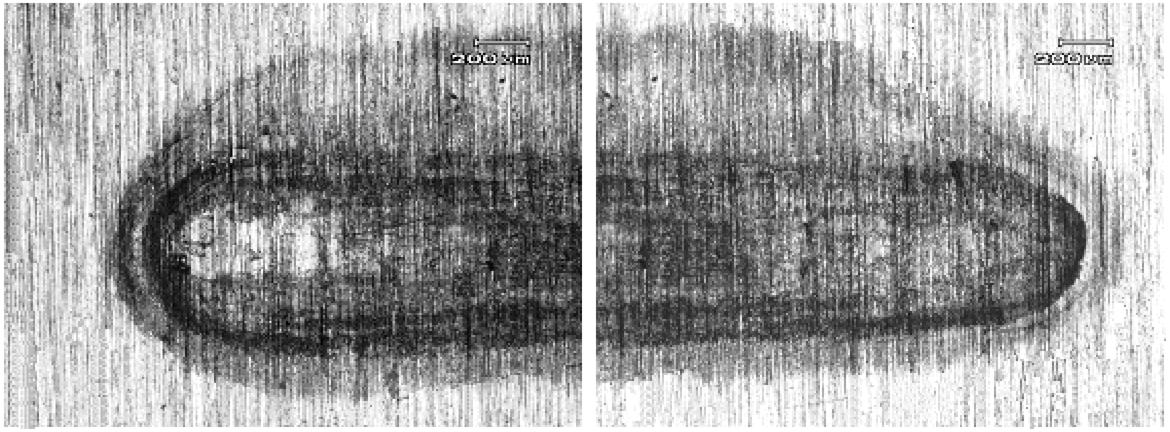
Dual disk-type electrodes
(WC, 45μm disk dia. and 20 μm neck dia.)



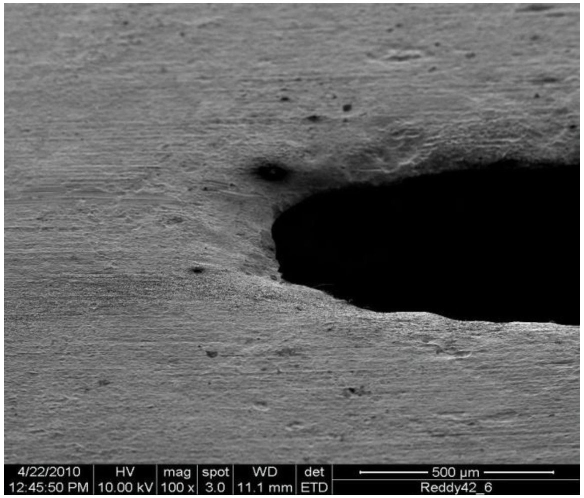
Dual micro columns

Experimental Observations

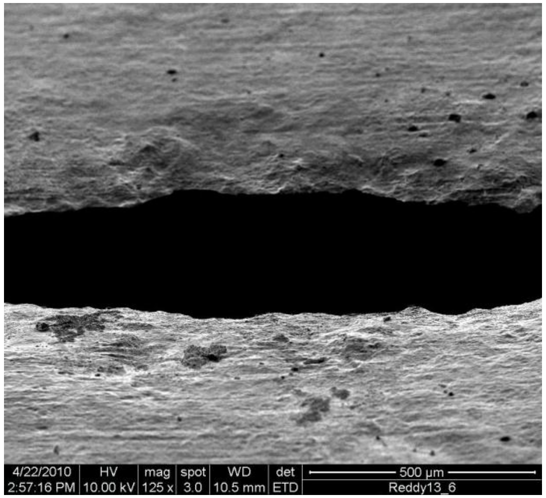
Some Experimental Observations during ECMM



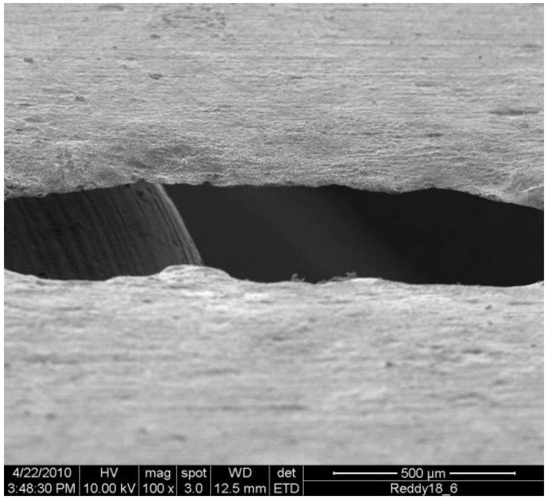
optimum parametric setting i.e. 30 kHz, 7 V, 15%, 50 g/l and 312.5



50 kHz, 10V, 40%, 60 g/l, 175 µm/sec

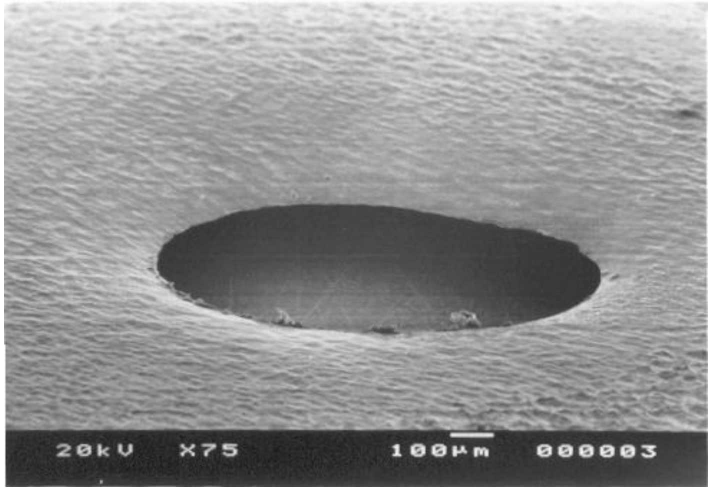


60 kHz, 9V, 50%, 70 g/l, 150 µm/sec

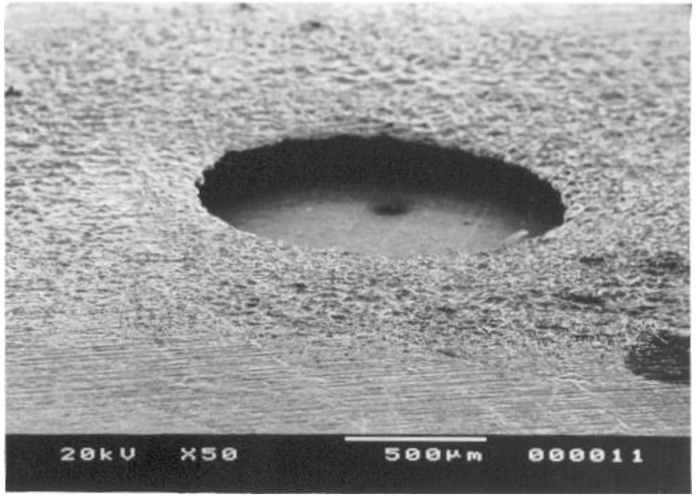


50 kHz, 10V, 70%, 80 g/l, 200 µm/sec

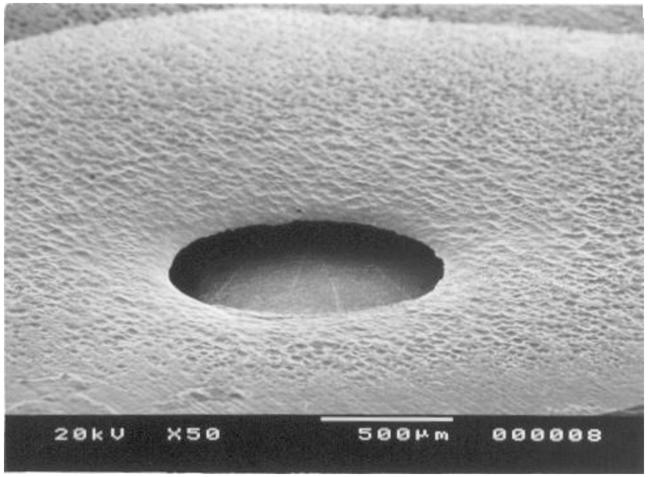
SEM Micrograph of micro hole at, 0.144 mm/min Tool feed rate and Pulse on-off ratio 2:1



3 V, 30 g/l, 45 Hz



7V, 30 g/l, 45 Hz

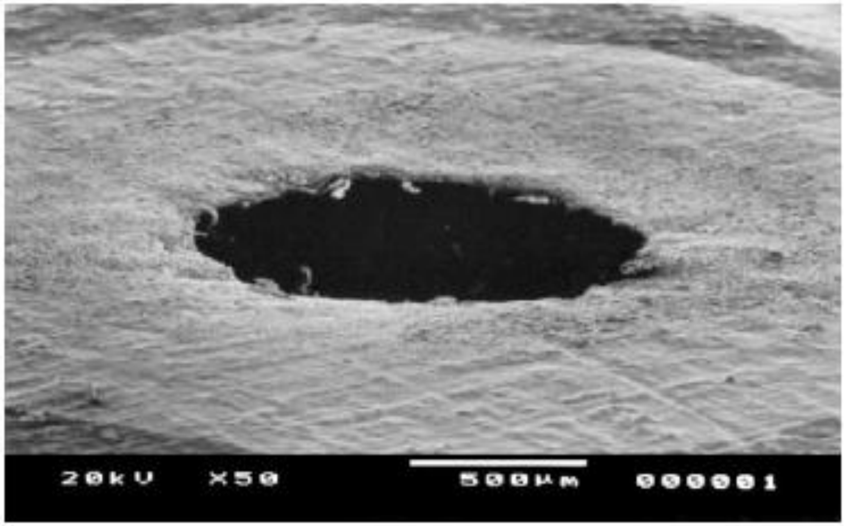


3V, 30 g/l, 55 Hz

Accuracy and surface integrity for the micro holes

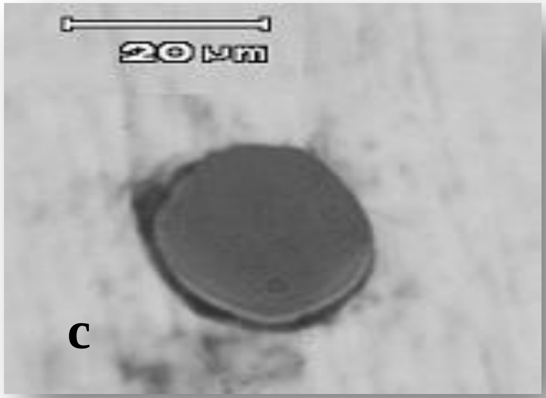
EXPERIMENTAL RESULTS

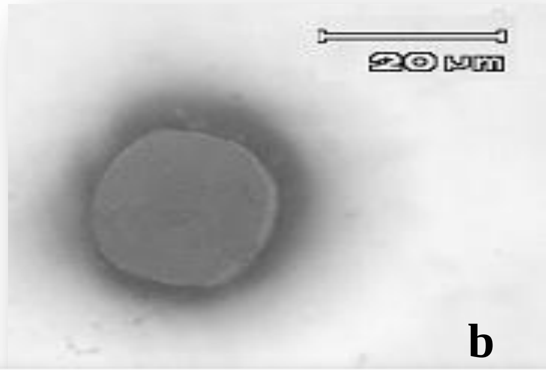
Small burrs can be identified over the periphery of the micro hole due to the possibility of occurrence of micro sparks.

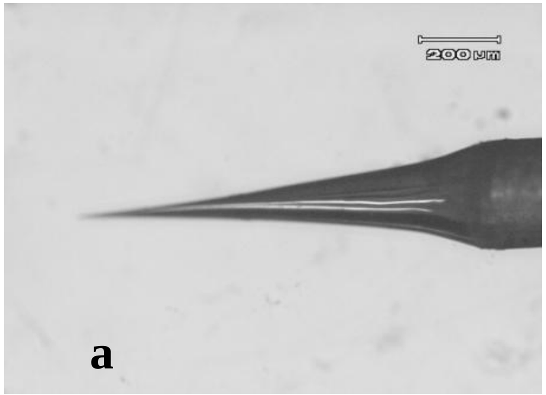


Effect of stray current and sparking

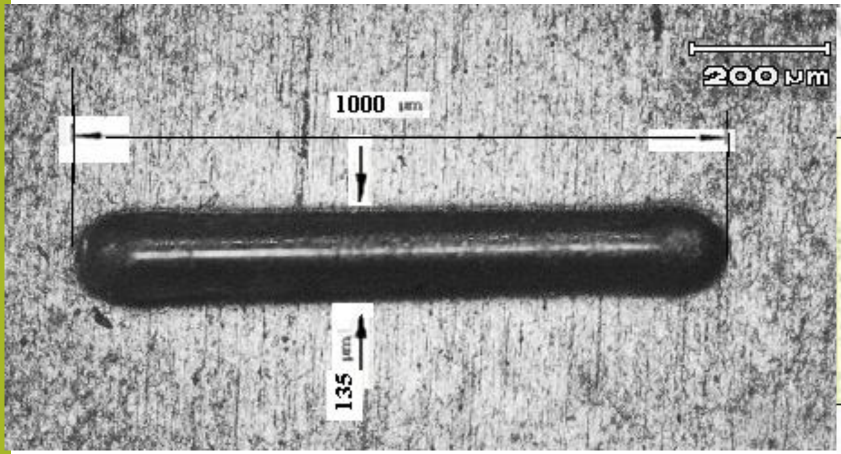
From the analysis of test results and SEM micrographs it may be observed that optimum value of machining voltage is about 3V, Machining frequency is about 55 Hz and electrolyte concentration is about 20 g/l which will produce accurate micro holes



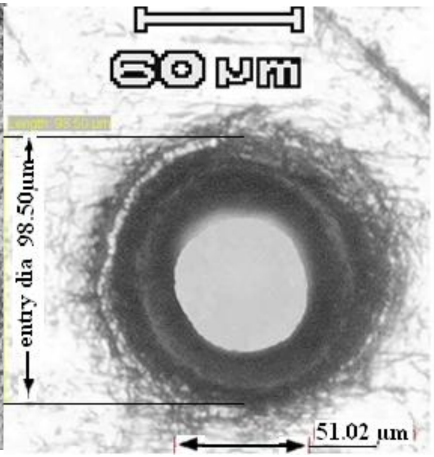


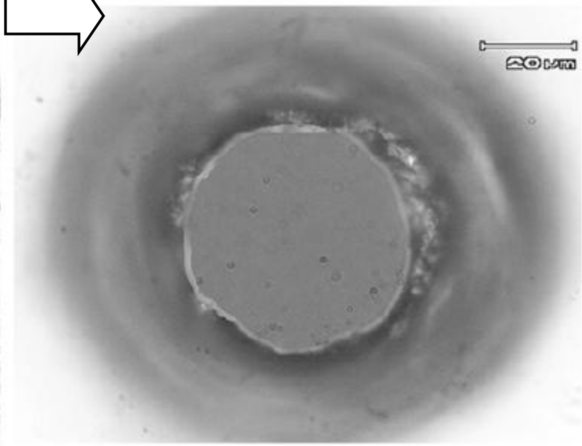


Micro hole of entry dia. 21 µm (c) and exit dia. 20 µm (b) on stainless steel plate (SS 304) of thickness 35 µm with the fabricated tool of 12 µm diameter shown at (a)



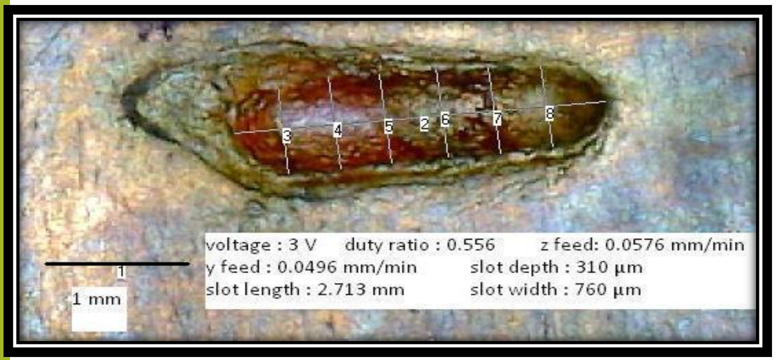
Blind micro channel of 50 µm depth generated on 60 µm thick SS 304 plate

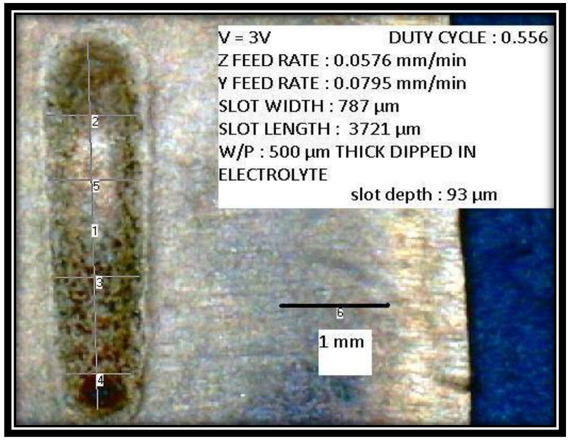


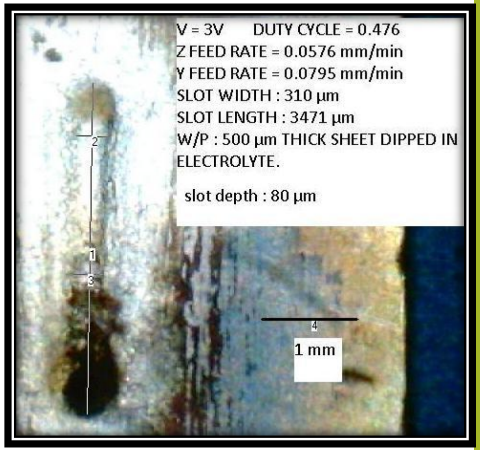


Nozzle generated at medium feed rate

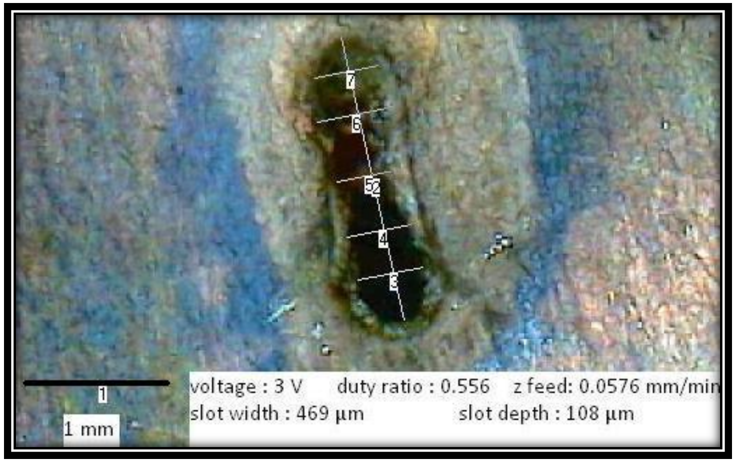
Photographs of the slots (Iitk)

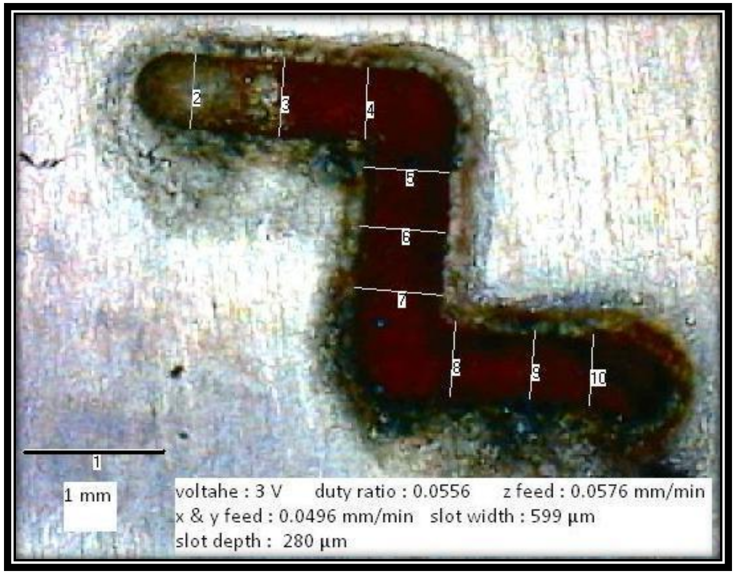






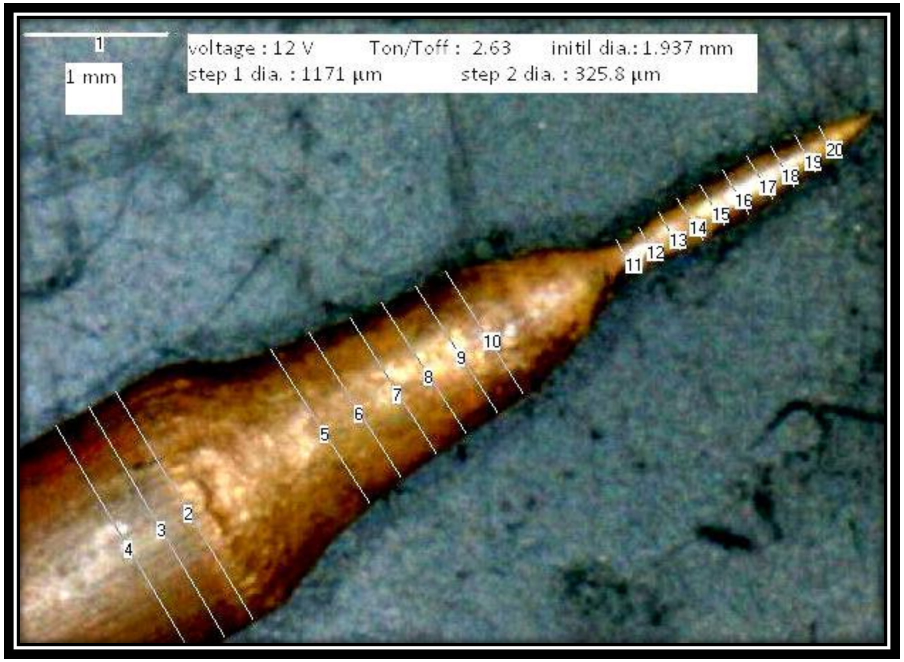
Slots machined with uncoated tool

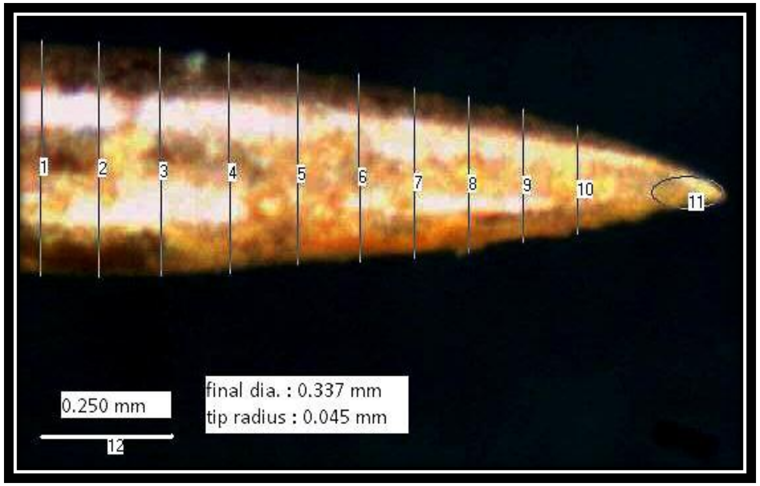


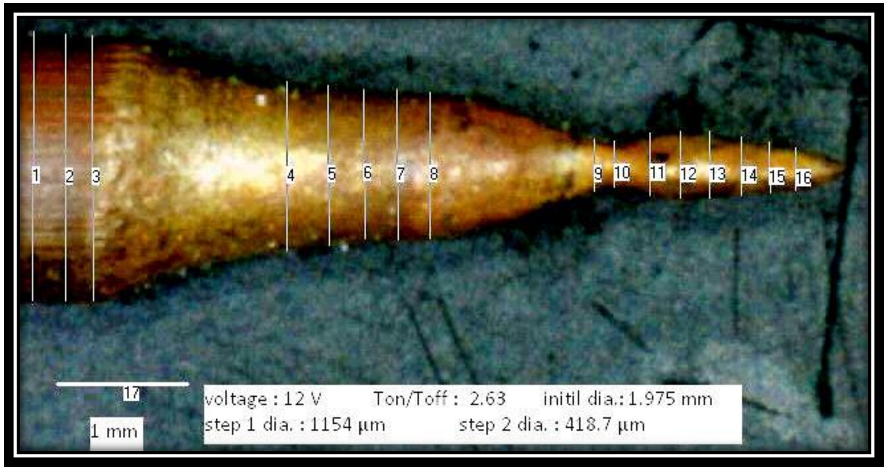


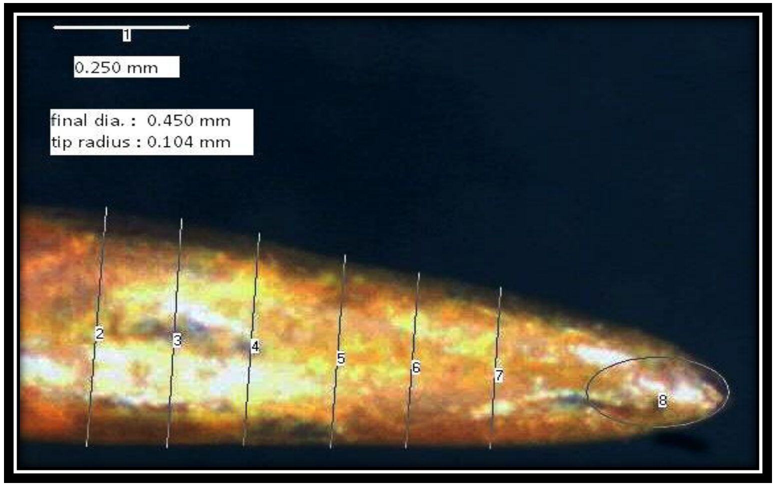
Slots machined with coated tool

PHOTOGRAPHS OF STEPPED MICRO TOOLS (IITK)



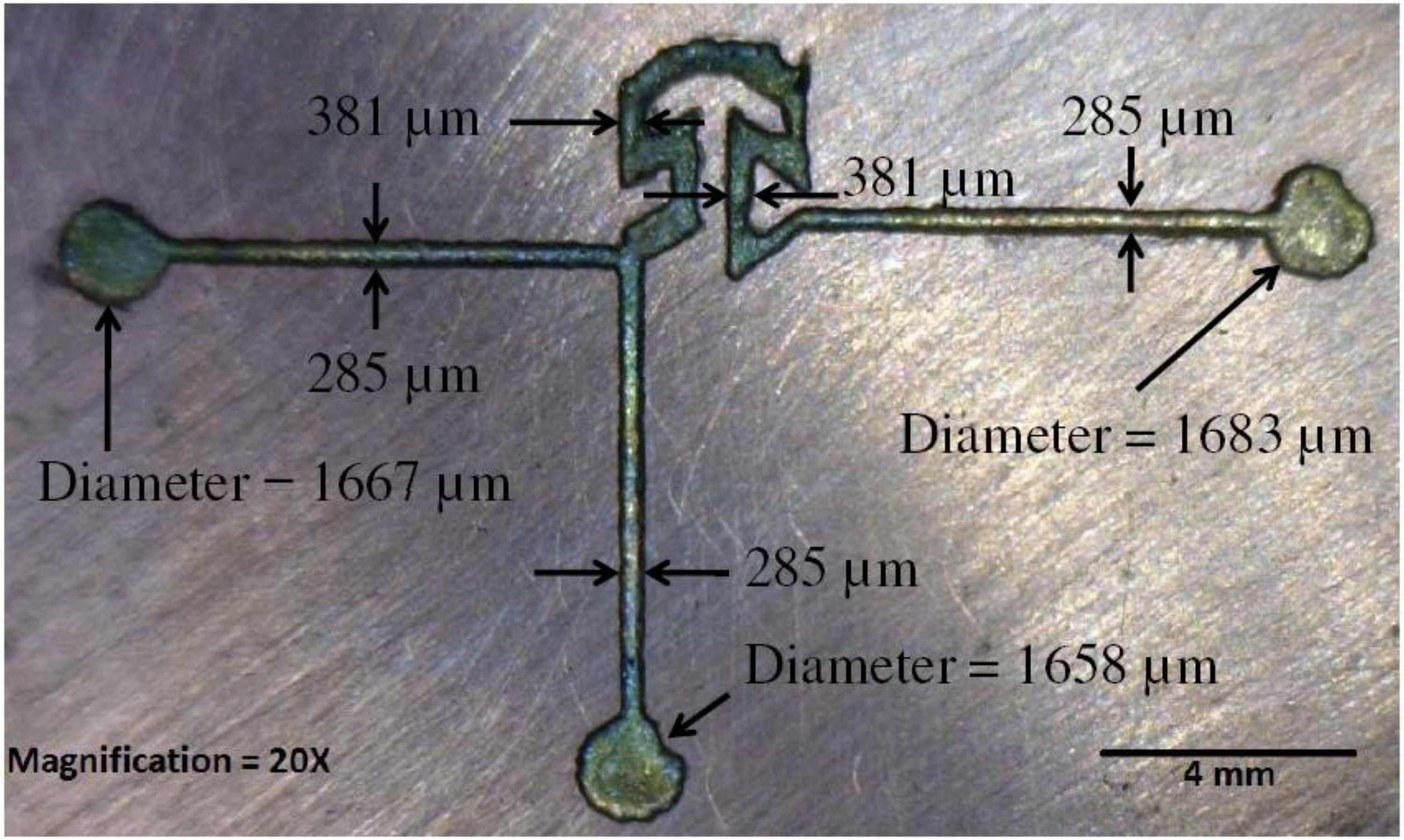






Fabrication of µ-mixer (Kalia-IITK)

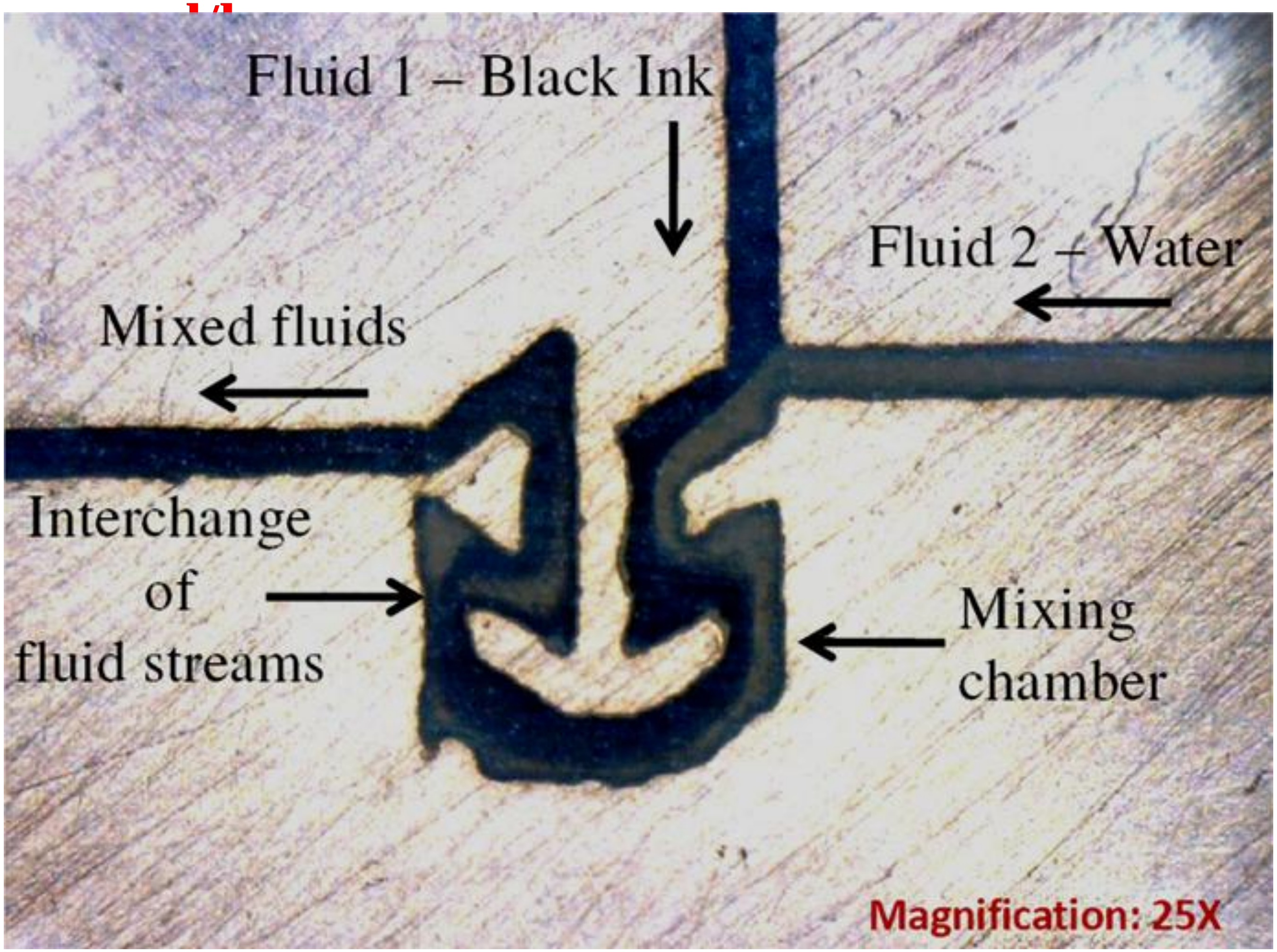
Adhesion of mask on work piece using water insoluble glue



Pulsed voltage = 5 V, T_{on} = 1000 µs, T_{off} = 400 µs, Electrolyte = $NaNO_3$ with concentration = 15 g/L of water and IEG = 1000 µm.

Testing of µ-mixer (Kalia-IITK)

Mixing at volume flow rate (Q) = 20



Calculations

Q = 20 ml/hr

w = 0.2857 mm

h = 0.0511 mm

A = w x h

Q = A x V

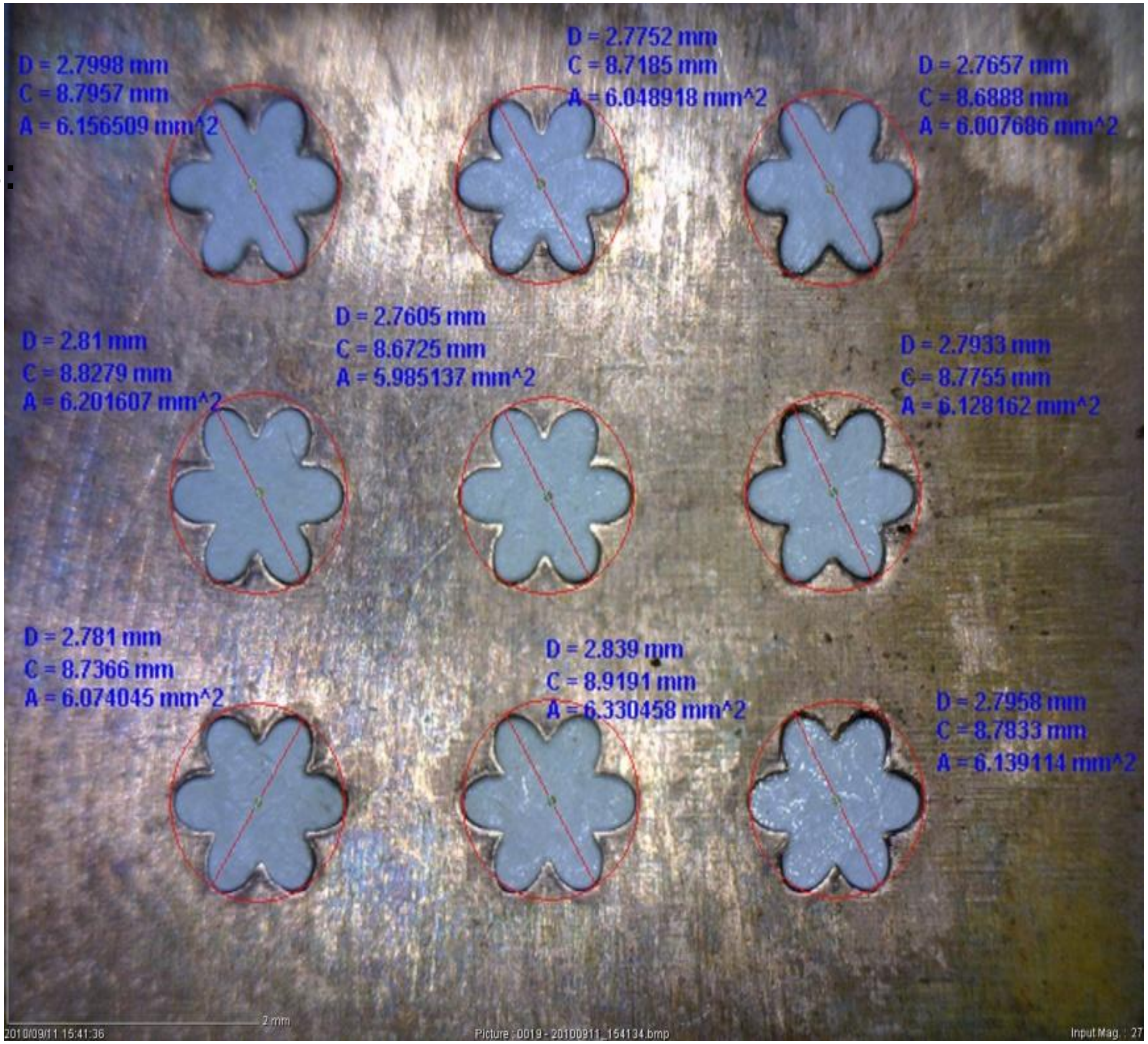
D = 4A/P

R_e = 32.89

Patterning of features (IITK-Thakur)

Operating parameters:

Applied voltage	4V
Electrolyte Concentration	20 g/L ($NaNO_3$)
IEG	1 mm
Duty Cycle	0.476



Conclusions

- ✓Further research will open up many challenging possibilities for effective utilization of ECMM in the micro and nano-scale domain of machining.
- ✓Extensive research efforts and continuing advancements in the area of ECMM for effective utilization in micro fabrication leading towards nanofabrication require improvements in:

(i) Microtool design and development and coating,

(ii) Monitoring and control of the IEG,

(iii) Control of material removal and accuracy,

(iv) Power supply,

(v) Selection of electrolyte, and

(vi) Elimination of micro sparks generation in IEG, etc.

- ✓The increasing demands for precision manufacturing of micro parts and nano-features for biomedical components, automotive components and IT applications will lead modern manufacturing engineers to utilize ECMM technique more successfully considering its advantages, i.e. quality, productivity and ultimately cost effectiveness.


THANK
YOU

Mechanism of material removal

Faraday's introduced two fundamental laws, which governs electrolysis:

1. The amount of any substance deposited or dissolved is proportional to the quantity of electricity that is passed through electrolyte.
2. The amount of substance dissolved or deposited by the flow of same quantity of electricity are proportional to their gram equivalent weight.

$$Q_{th} = \frac{Ita}{vF}$$

Where, I = Applied current, t = Machining time, F = Faraday's constant, v = Valence of metal dissolution and a = Molecular weight of the metal

The material removal rate or unit remo9val basically depends on the following factors,

1. Anodic reaction and current efficiency.
2. Mass transport controlled anodic dissolution, and
3. Current distribution and shape evolution.

Mechanism of material removal

Anodic reaction and current efficiency

- Rate of different anodic reactions are dependent on the ability of the system to remove the reaction products as soon as they are formed and supply of fresh electrolyte yo the inter electrode gap.
- The machining performance can be governed by:

❖ Dissolution rate
❖ Shape control
❖ Surface finish of the workpiece

The current efficiency of the metal dissolution, ‘η’ is related to the actual weight loss or material removed, $'Q_{act}'$, and can be expressed as:

$$\eta = \frac{Q_{act}}{Q_{th}}$$

Q_{th}= Theoretical weight loss

Material removed per unit time or MRR is related to current efficiency as:

$$MRR = \frac{Q_{act}}{t} = \frac{Ia\eta}{vf}$$

A= molecular weight, I = applied current, v = voltage and f = Faraday’s constant

Mechanism of material removal

Mass transport controlled anodic dissolution

- Mass transport rate depend on the hydrodynamic condition for a given metal-electrolyte combination.
- distribution and accuracy of the job can be affected by mass transport condition.
- In acceptor mechanism, the rate of transport towards the anode of acceptor type such as complexing ions or water is rate limiting and salt film precipitation occurs at the surface of anode.
- In EMM, smooth surface finish can be achieved only at limiting current density.

$$J = \frac{\nu f D C_{sat}}{\delta}$$

Current distribution n and shape evolution

- The nature of current distribution pattern will also influence the shape generation and degree of levelling in ECMM.
- In through mask ECMM, three different scales must be considered with respect to current distribution, i.e. work piece scale, pattern scale and feature scale

- **At micro tool (cathode), the reaction having the smallest oxidation potential will take place**
- **At workpiece (anode), the reaction having the largest oxidation potential will occur first**

ECMM power supply

Basic theoretical and fundamental research work and preliminary industrial practice have indicated that ECMM using pulsed current offers considerable potential for enhancement of ECM process.

- **Figure shows the current efficiency against the current density for continuous and pulsed voltage for an interval of 10 ms with a pulse duration of 1 ms, the efficiency decreases gradually with an increase in current density beyond a limit..**

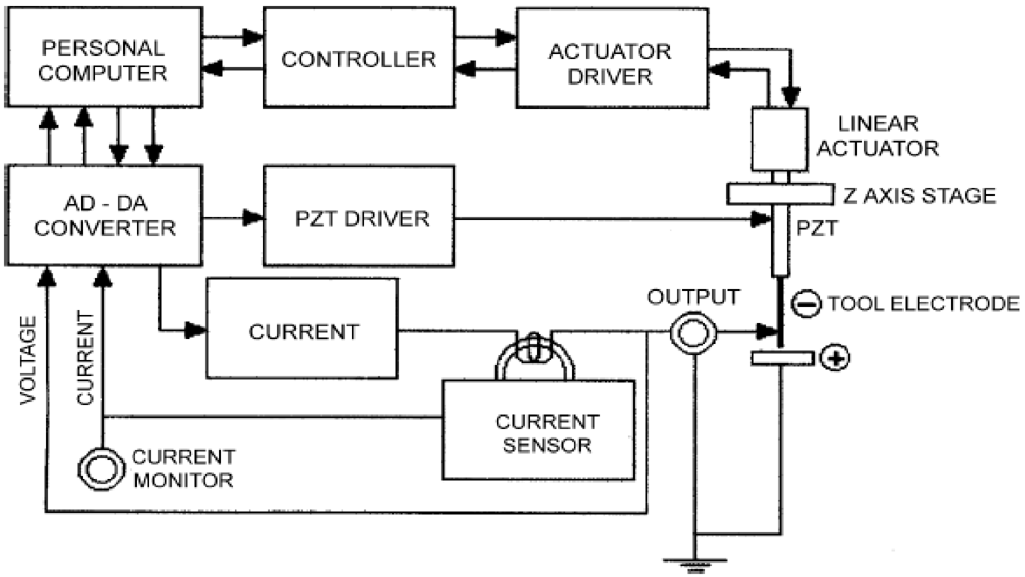
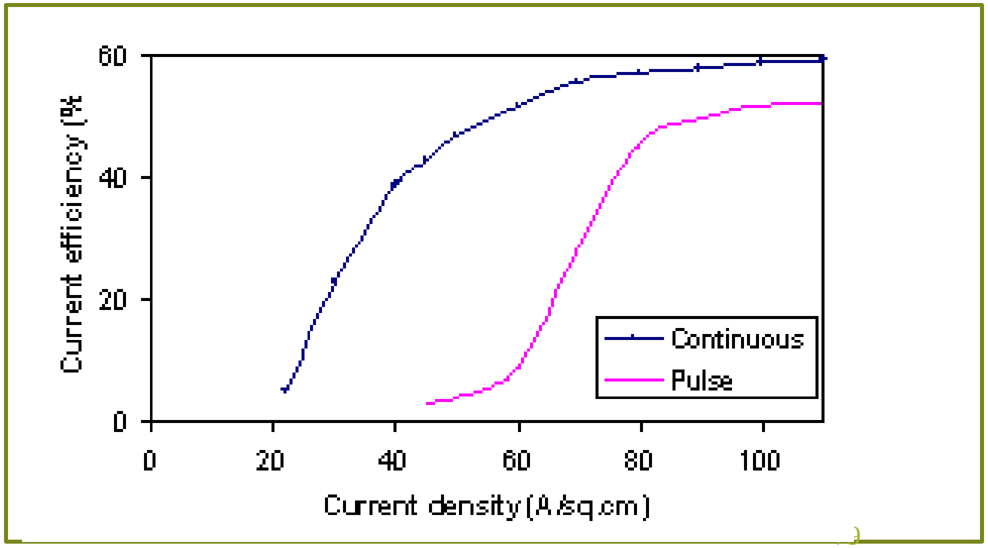


Fig. 3. Power supply system of EMM [31].



EMM electrolyte

Add Fig. 12

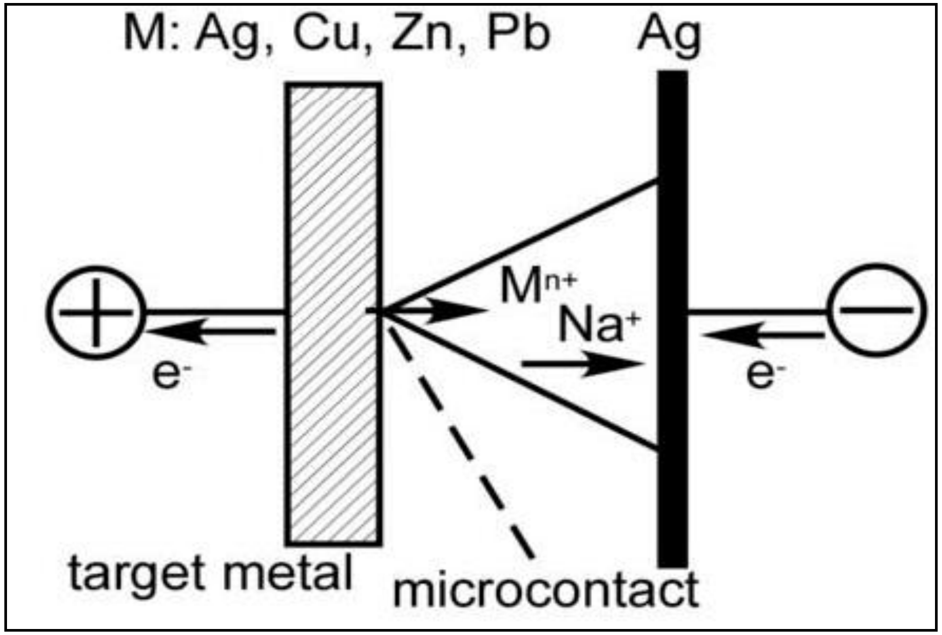
Add Fig. 12

- EMM can be improvised through modifying electrolyte flow distribution.
- An EMM with an eccentric orbital movement can enhance the uniformity of electrolyte flow and to eliminate the flow field disruption processes.
- The electrolyte flow is passed through the settling tank and micro-filters, which removes foreign particles and makes it enable for recirculation towards the IEG (machining zone).

Solid State Electrochemical Machining

ECMM with no liquid electrolyte

SSEM involves an anodic electrochemical reaction at the micro-contact between the metal substrate and ion conductor i.e. Na-β”-Al_2O_3 pyramid. The metal substrate is locally incorporated into the ion conductor in the form of metal ions via the micro-contact under a DC bias source at 523 ~ 873 K below the melting temperature of the target metal.



Ion migration model for SSEM

Influence of Process parameters on Micro Spark Affected Zone (MSAZ)

Parameters	Symbols	Levels				
		-2	-1	0	+1	+2
Pulse on/off ratio	x_1	0.5	1.0	1.5	2.0	2.5
Machining voltage (V)	x_2	2.5	3.0	3.5	4.0	4.5
Electrolyte conc. (g/l)	x_{-3}	10	15	20	25	30
Voltage frequency (Hz)	x_4	35	40	45	50	55
Tool vibration frequency (Hz)	x_5	100	150	200	250	300