RECENT DEVELOPMENTS IN ELECTROCHEMICAL MICRO MACHINING

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Abstract

Electrochemical Micro-Machining appears to be very promising as a future micro and nano machining technique since in many areas of applications it offers several advantages. In this paper, a review is presented on current research, development and industrial practice of micro-ECM for micro and nano fabrication. New developments in the area of electrochemical micro-machining e.g. micro-electrochemical milling, wire-ECM, solid electrochemical machining, surface structuring and OFLL etc. have also been reported. Future trend of research in the area of utilization of anodic dissolution method for manufacturing of nano range products are also highlighted. The Electrochemical micro machining can effectively be used for high precision machining operations. Further research activities of ECM will open up many challenging opportunities for effective utilization of ECM in the micro machining and nano fabrication domain.

Keywords: Electrochemical Machining, Micro-Machining, Nano- Fabrication.

1 Introduction

Electrochemical machining (ECM) has seen a resurgence of industrial interest within the last couple of decades due to its many advantages such as no tool wear, stress free and smooth surfaces of machined product and ability to machine complex shape in electrically conductive materials, regardless of their hardness. When this ECM process is applied to the micro-machining range for manufacturing ultra-precision shape, it is called electrochemical micro-machining (EMM). Micro-machining may literally mean the machining of the dimension between 1 and 999 mm. However, as a technical term, it also means the smaller amount of machining that cannot be achieved directly by a conventional technique.

Advanced micro machining may consist various ultra precision activities to be performed on very small and thin work pieces in large numbers. Sometimes, when these things are performed with conventional machining techniques, the problem one usually encounters is high tool wear, rigidity and heat-affected zone [1]. In non-conventional machining most of the machining processes are thermal oriented, e.g. Electro Discharge machining (EDM), Laser beam machining (LBM), Electron beam machining (EBM) etc [2,3]. Chemical machining and Electrochemical machining are thermal free processes, but chemical machining cannot be controlled properly in the micro-machining domain. ECM process is applied to the micro machining range of applications for manufacturing ultra precision shapes; it is called Electrochemical micro machining (EMM). EMM appears to be a very promising micro machining technology due to its advantages that include high MRR, better precision and control, rapid machining time, reliable and environmentally acceptable. In recent years, ECM has received much attention in the fabrication of micro parts [4-8]. Fig.1 shows the schematic view of EMM system set up, which consists of pulsed DC power supply, machine controller, micro tool drive unit, mechanical machining unit and electrolyte flow system etc. Recent research establishes the fact that electrochemical process of metal removal can also be effectively utilized for nano machining [9]

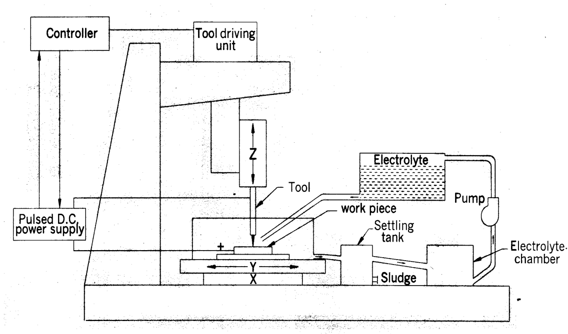
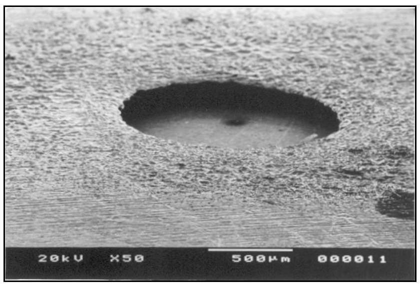


Fig.1 Schematic View of EMM

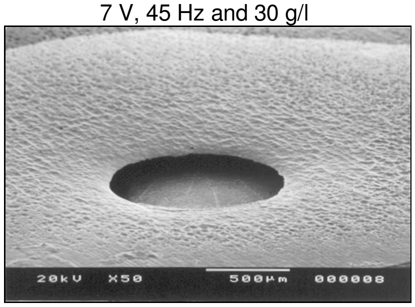
Research attempts have been made by the electromechanical consumer product industries as well as T.J.Watson research center of IBM apart from other research institutions [7,10]. To exploit full potential of EMM, research is still needed to improve accuracy and compactness. In this paper, a review is presented on current research, development and industrial practice in micro-ECM. An attempt has also been made to report the latest development of ECM in the field of nano-fabrication.

2 Material Removal and Machining Accuracy in EMM

Various predominant process parameters such as current density, Inter Electrode Gap (IEG), electrolyte and also the anode reactions etc influence the machining performance of EMM. Experimental results proved that the addition of the magnetic field causes increase in material removal rate (MRR) and accuracy. When inter-electrode current is 6A, MRR is 37 mg/min but by the addition of magnetic field, MRR increases to 55 mg/min [11]. The MRR is expressed in terms of unit removal (UR) in micro machining domain [2]. UR is defined as a unit of work piece removed during one cycle/pulse of machining action. UR is basically dependent on three important factors (i) mass transport effect, (ii) current distribution and shape control, (iii) passive oxide films and transpassive dissolution. For achieving higher accuracy, pulsed power supply with small IEG, passivating electrolyte and dual pole tool is preferred. [12]. Experimental investigation on the influence of EMM parameters on material removal rate and accuracy recommends machining voltage range of 3-7 V, which gives an appreciable amount of MRR at moderate accuracy [13] as shown in Fig. 2. Further investigations are still needed in the area of EMM for better understanding of the metal removal mechanism and parametric optimization for attaining high machining accuracy.



7 V, 45 Hz and 30 g/l



3 V, 55 Hz and 30 g/l

Fig. 2 Micro-holes at different parametric conditions

3 Power Supply for EMM

EMM using pulsed current offers considerable potential for enhancement of ECM process. The high current density required for proper operation of EMM process, may give high concentration of reaction products, which can only be partly removed by the electrolyte, especially if the inter electrode gap is narrow. The increasing contamination can cause a deposition to form on the tool, so the work piece material no longer dissolves uniformly. This type of problems can be largely avoided by applying a pulsed voltage [14]. The anodic electrochemical dissolution occurs during the short pulse on-time, each ranging from 0.1 to 5 ms. The dissolution products can be flushed away from the inter electrode gap by the flowing of electrolyte during the pulse off-times. For further improvement of micro machining accuracy, piezoelectric transducer is used to retract the tool from the work piece during pulse off time to enlarge the gap by means of vibration so as to intensify the electrolyte flushing [15]. Fig. 3 shows the block diagram of a typical power supply utilized for the EMM system. However, short duration pulses have great potential to achieve higher dimensional accuracy due to small amount of material removal per pulse as shown through test results in Fig. 4 and 5. For full acceptance of pulsed machining system by industry, a low cost power supply with outstanding performance needs to be developed. In this area, lot of research is going on and still it needs more.

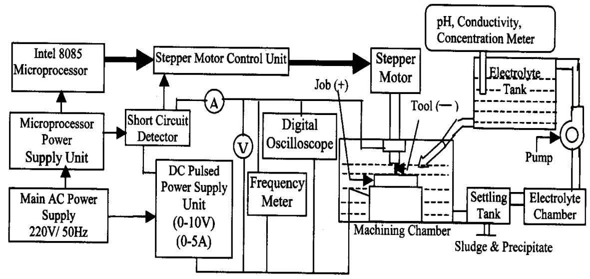


Fig. 3 Power supply unit For EMM

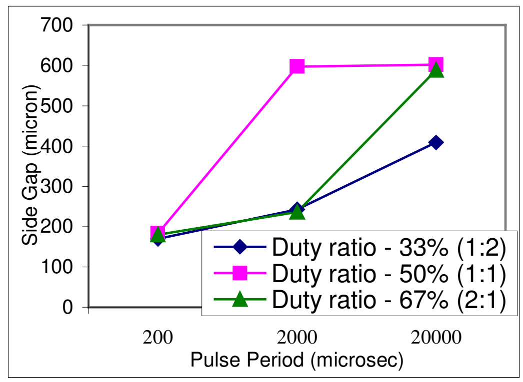


Fig. 4 Effect of pulse period on accuracy

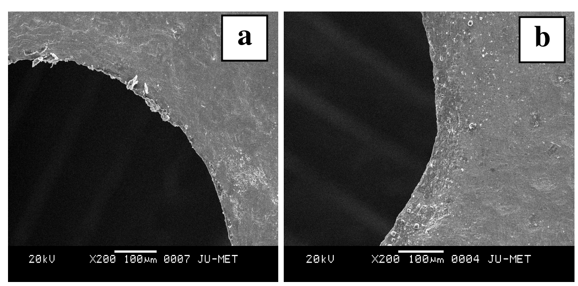


Fig. 5 Micro holes periphery at (a) 20 g/l, 3V, 33% & 2000 µsec, (b) 20 g/l, 3V, 33% & 200 µsec

4 Development of Micro Tools

Development micro-tools remains a major challenge for manufacturing micro-feature by EMM [16]. Tool design mainly deals with the determination of tool shape. Prediction of the tool shape is a formidable inverse boundary problem of Laplace equation [17,18, 19]. In addition to tool design, suitable development of micro tool is required for successful machining. In general material for micro tool should consists of a chemically inert material, good electrical conductivity and easily machinable. Micro-tools can be developed by applying small hall ECM, EDG, ELID grinding and WEDM. Fig. 6 shows micro-tool manufacture by Electrolytic in-process dressing (ELID) grinding [20]. For reducing the effect of stray current, the micro tool should be insulated with SiC / Si_3N_4 by means of a chemical vapour deposition (CVD) process so that current only flows through the front face. Further research is still needed in the area of micro tool design and development.

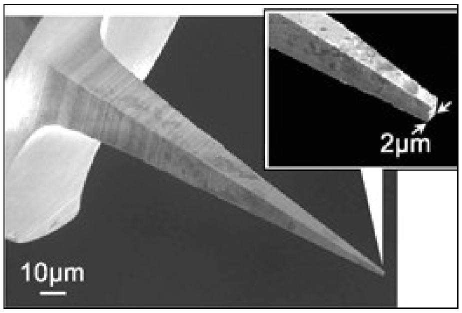


Fig. 6 Micro-tool manufacture by ELID grinding [20]

5 Role of Inter Electrode Gap (IEG)

If the inter-electrode gap is narrowed down to a bare minimum level then the resolution of machined shape becomes better and the possibility of applying ECM to micro machining increases. Maintaining the specific IEG uniformly is an important requirement to achieve high accuracy and surface finish. Around 1V can be applied between the tool and the work piece, for measuring the current in such a way that the electrical contact of the micro tool with the work piece can be checked [21]. In pulsed EMM system, the IEG and tool position monitoring can be conducted during pulse off time. A unique hybridized EMM set-up has been developed with a micro-tool vibration system. Piezo-electric transducer (PZT) has been used for vibrating micro-tools, which creates acoustic waves and cavitation in narrow IEG and improves the circulation of electrolyte that may result in reduction or elimination of micro-spark generation. The influence of micro-tool vibration frequencies on accuracy is shown in Fig. 7 during EMM operation [22]. Attention to be needed in the area of dynamic gap measurement and control for effective metal removal.

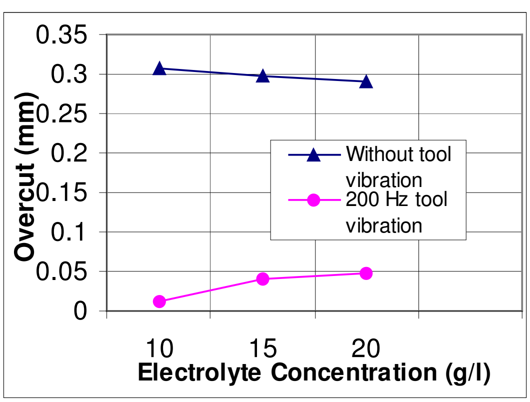


Fig. 7 Machining accuracy with and without tool vibration

6 Electrolyte for EMM

Electrolytes play a vital role for precise control of metal removal in microscopic domain. Generally anodic films are allowed to form on work piece surface which helps to achieve anodic smoothing, finally some times it may cause for short circuiting during EMM due to smaller IEG. Hence it is advisable to use fresh and clean electrolyte for micro machining. The electrolyte carries away the heat and reaction products from the zone of machining. Electrolyte must possess less throwing power apart from basic properties, to increase the accuracy. ECM electrolytes are classified into two categories: passivating electrolytes containing oxidizing anions i.e. sodium nitrate, sodium chlorate and non-passivating electrolytes containing relatively aggressive anions such as sodium chloride. Passivating electrolytes are known to give better machining precision [23]. It may be observed during micro holes generation on the metallic foils by EMM process that the lower value of electrolyte concentration with higher machining voltage and moderate value of pulse on time will produce a more accurate shape with less over cut at moderate MRR [13]. Research is to be done to increase the EMM machining accuracy by acquiring proper knowledge in the area of fluid kinematics and hydrodynamics, type and concentration of electrolyte, etc.

7 Control of Micro-Spark and Stray-Current Machining

Micro-sparking and stray-current machining during EMM process are to be controlled for effective utilization of this process in practice in the area of micro-fabrication. The increment in gap resistance due to various causes, e.g. electrolyte heating, gas bubble generation, sludge formation, etc., leads to an occurrence of micro-sparks, causing larger radial overcut as well as micro- spark affected zone that result in poor quality of final products as shown in Fig.8. Better quality of the workpiece in EMM can be generated through combinational/simultaneous control of various process parameters. The development of comprehensive analytical model is an important research contribution for correlating the interactive and higher-order influences of the various predominant machining parameters, such as, pulse on/off ratio, machining voltage, electrolyte concentration, voltage pulse frequency and tool vibration frequency on the micro-spark and stray-current affected zone (MSAZ) for higher precision and better surface quality products [24]. The developed model can be used for various process parametric conditions for achieving the minimum MSAZ with effective material removal.

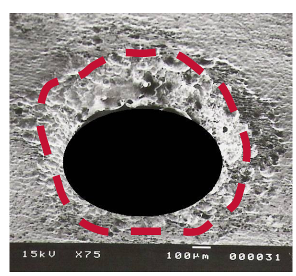


Fig. 8 Micro-spark and stray-current affected zone (MSAZ)

7 Applications

In this section, typical applications of EMM technologies for microfabrication of components are introduced.

(i) Nozzle Plate For Ink Jet Printer head

Pulsating current/voltage permits a better control over electrochemical micro machining of thin films and foils for applications in micro fabrication. Through mask EMM was used to fabricate series flat-bottomed v-shaped nozzles in a metal foil as shown in Fig. 9 [25]. The process is applicable to various materials including high strength corrosive resistant materials such as conducting ceramics [26].

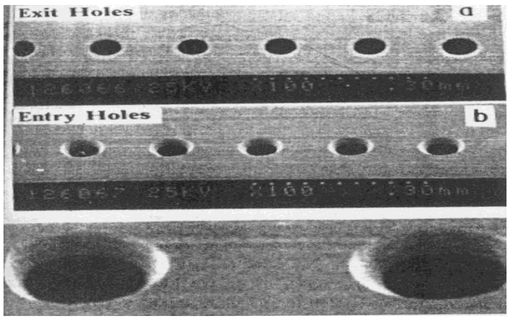


Fig. 9 An Array of V Shaped Nozzles

(ii) Production of High Accuracy Holes

EMM method can be used for the accurate production of holes [8]. An SEM micrograph of machined micro hole by EMM at a particular machining condition i.e. machining voltage 10V, electrolyte concentration 15 g/l, pulse on time 12.5 ms and frequency of pulsed power supply 50Hz is shown in Fig. 10. At this parametric condition, the over cut of the machined hole produced by the EMM is comparatively less [13]. A typical application is the production of micro holes in turbine blades for generating cooling effect, where its advantages are fully exploited. [27]. It has also found many applications in other industries like automobile, medical and defense industries. It has also been used to produce the micro grooves for self-acting fluid film bearings, which can be controlled precisely without distorting the other surfaces [6].

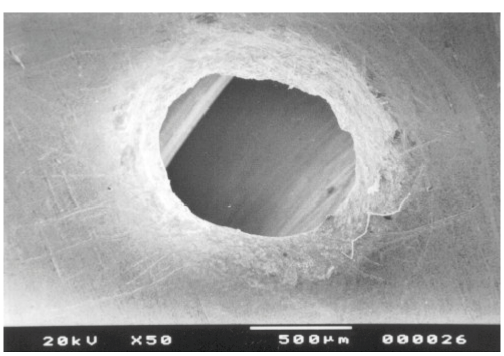


Fig. 10 SEM Micrograph of Machined Micro Hole

(iii) 3D Micromachining

3-dimenional EMM is shown in Fig. 11, SEM micrograph of a machined component of an electronic circuit board in which platinum wire of 10-µm diameter was used as a tool on the copper sheet by the application of 2 MHz frequency of 50 ns, 1.6 V pulses. To obtain delicate 3D copper structure i.e. 5µmX10µmX12µm in the middle of the hole sitting on a base, i.e. 15µmX15µmX10µm, the microtool is first fed vertically 12 µm deep into the work piece. After this vertical machining, the microtool is moved laterally along the prescribed path in the copper sheet. The outer rectangular trough is dissolved to a dimension of 22µmX14µm. During the process, the microtool feed rate is adjusted to 0.5µm by monitoring the peak current transient of the inter electrode gap [28].

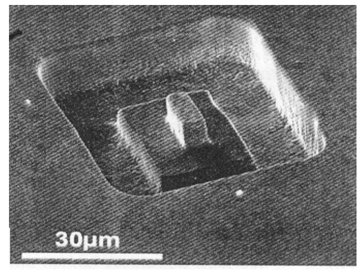


Fig. 11 3D-electronic circuit board component [28]

8 Present State of Research in Electrochemical Micromachining

Attempts have been made to utilize micro and nanoscopic anodic dissolution of metals for fabrication of micro and nano features. Principles of ECM have already been successfully demonstrated to machine micro scale features using ultra short pulses. Some of the latest developments in this area are presented here in under.

(i) Micro electrochemical Milling

Layer by layer micro machining can be achieved for fabricating 3D structure with good surface quality by utilizing controlled movement of the cylindrical micro tool in dilute acidic electrolyte. Fig. 12 shows a micro hemisphere on the top of a cylinder, machined in three steps e.g. rough cut for fabricating cylinder and hemisphere with 100 µm diameter on the cylinder and finally finish cut with very fast feed rate for fabricating final shape of the hemisphere with 60 µm diameter [29]. Finish cut should be applied at high speed with short pulse on-time. Not only short pulses but also dissolution time can localize electrochemical dissolution.

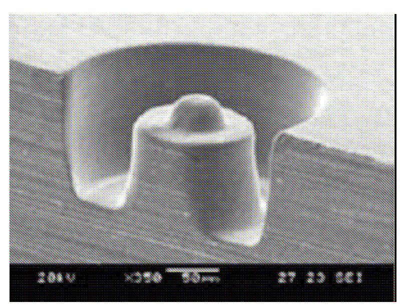
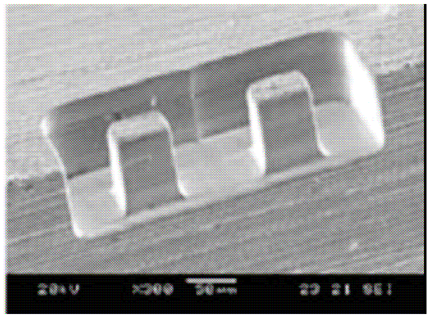


Fig. 12 Micro hemisphere

Disk-type electrodes can be applied to machine microstructures 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 EDM. Fig. 13 (a, b) shows dual micro columns fabricated on SS 304 work piece by dual disc type electrodes of WC, 45µm disc and 20 µm neck [30].



(a)

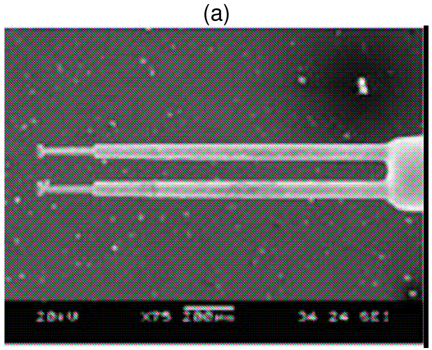
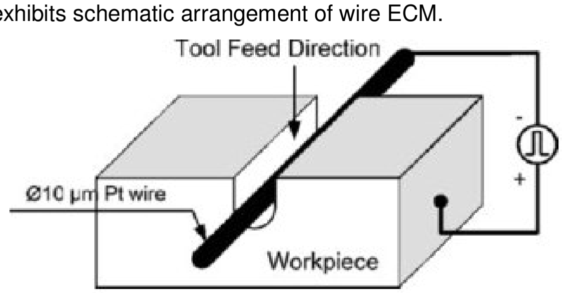


Fig. 13 (a) Dual micro-columns on SS 304, (b) Dual disc type micro-electrodes

(ii) Wire Electrochemical Machining

Microwire of less than 10 µm can be utilized as tool in wire ECM. In ECM, there is no tool wear during machining. Hence wire is not worn out and very thinner wire can be used and also wire feeding is not essential. Fig. 14 (a) exhibits schematic arrangement of wire ECM.



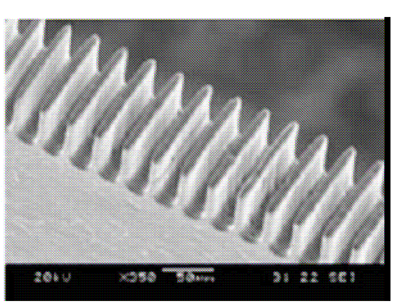


Fig.14 (a) Scheme of wire-ECM, (b) Micro-grooves by wire-ECM

Wire ECM can be applied to fabricate micro grooves. Fig. 14 (b) shows microgrooves machined by wire ECM [30]. Complex profile of micro-grooves can also be generated by wire-ECM.

(iii) Solid electrochemical machining

Solid electrochemical machining 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 [31]. Solid electrochemical machining has also been performed using an ion conducting polymer coated tungsten needle microelectrode at ambient temperature. As is well known, Nafion has high proton conductivity at room temperature. Moreover, a variety of metal ions can travel in Nafion in place of protons [32]. In contrast, the present development employs a tungsten (W) microelectrode coated with a polymer electrolyte layer, as depicted in Fig. 15.

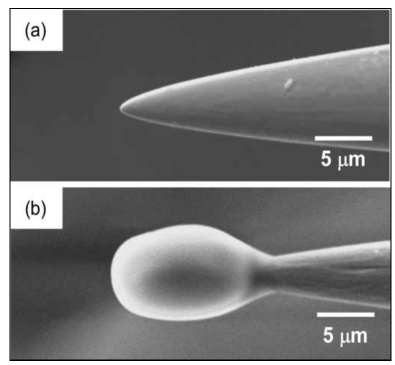


Fig. 15 W micro-electrode before (a) and after Nafion coating (b)

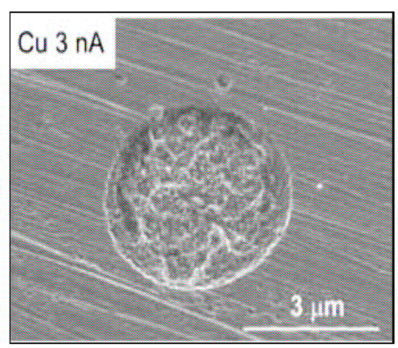


Fig. 16 Machined surfaces under various conditions for 60 min

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 microcontact of the polymer and target metal plate. Hence, the aspect ratio of the machined surface can be easily designed by the apex configuration of the polymer layer. It has been demonstrated that many different kinds of metal substrates can also be machined and submicron resolution can be achieved at room temperature as shown in Fig. 16.

(iv) Oxide film laser lithography (OFLL) by EMM

Complex photo resist masking process in lithography can entirely be eliminated by the application of laser hybrid ECM. Titanium is anodized using sulfuric acid electrolyte. The oxide film is irradiated using a well-focused laser beam (10µm) to form a pattern on the oxide film of thickness 200-300nm on titanium base. Dissolution is localized at the irradiated areas, the remainder of the oxide film acting as a mask. The photo resist could be entirely eliminated. After anodic dissolution, the freestanding oxide film at the edge of machined cavities is removed by ultrasonic cleaning [33] as shown in Fig. 17. The OFLL technique is better adapted for fabricating multi-level structures since it does not require application of a photoresist. After fabrication of the first level, the sample is anodised again and the second level pattern is produced by selective laser irradiation of the oxide, followed by anodic dissolution of the irradiated areas.

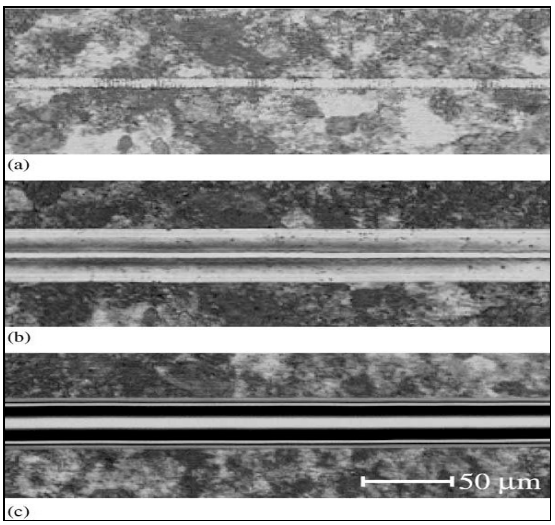


Fig. 17 (a) Laser trace on irradiated oxide on Titanium (b) after anodic dissolution (c) after ultrasonic cleaning

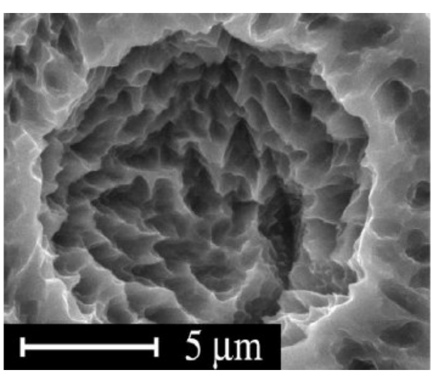


Fig. 18 Superposition a submicrometer roughness produced by chemical etching on a 10µm cavity produced by EMM [34]

(v) Micro and Nanometer Scaled Surface Structuring

The surface topography of biomedical implants plays an important role for cell attachment and differentiation. 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 [34]. An example of such a surface is exhibited in Fig. 18. The ability to fabricate well-defined surface topographies will be useful for better under- standing of the complicated interactions of living cells with implant materials.

(v) EMM for nano-fabrication

In Scanning Tunneling Microscope (STM) based ECM, reactions are confined to the tunneling region due to depletion of electrolyte in the tip-surface gap. Using STM based ECM micro-grooves with sub micron width can be fabricated with machining precision below 100 nm as shown in Fig. 19.

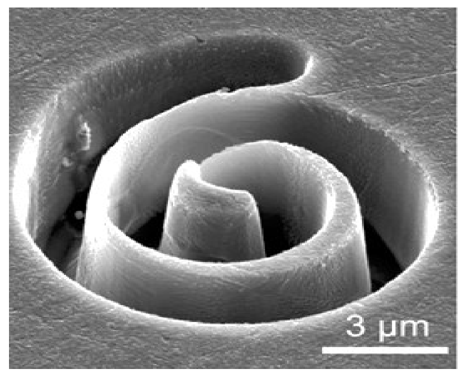
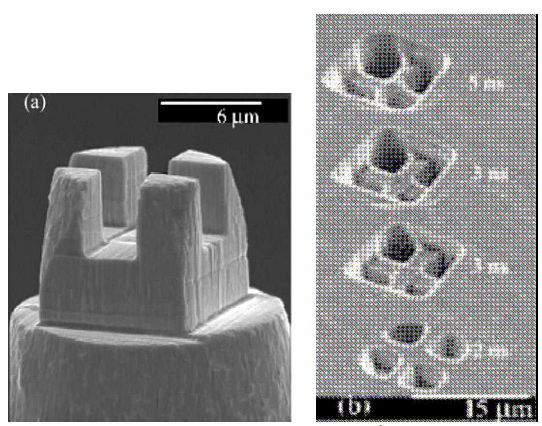


Fig. 19 5 µm deep spiral machined in Ni sheet [35]

STM has also been used as tool for nano-structuring of electrode surface by the application of 500 ps voltage pulses [35, 36]. 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 Nickle using ultra short voltage pulses as shown in Fig. 20. 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 [37].



(a) Tungsten Tool (b) Structure in Ni

Fig. 20 Nanomachining by ECM [37]

9 Conclusions

The paper presents research achievements and industrial applications created in micro and nanoscale machining using ECM. Results of recent research indicate the applications of electrochemical metal removal in micro and nano-machining offers many opportunities that have been unexplored till now. Further research activities in the area of ECM for effective utilization in micro and nano-fabrication require improvements in tool design and development, monitoring and control of the inter electrode gap, control of material removal and accuracy, efficient power supply, elimination of micro sparks in IEG and selection of suitable electrolyte which are expected to enhance the applications of ECM technology in modern manufacturing industries engage in ultra precision machining. Extensive research efforts and continuing advancements in this area will make the process more efficient and effective. The increasing demands for precision manufacturing of microparts and nano-features for biomedical components, automotive components and IT applications will lead modern manufacturing engineers to utilize ECM technique more successfully considering its advantages. Electrochemical micro-machining will be more popular in the near future in the area of micro and nano fabrication due to its quality, productivity and ultimately cost effectiveness.

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