Surface Texturing by Electrochemical Micromachining: A Review

Abhinav Kumar¹, Manjesh kumar¹, Anupam Alok¹, Manas Das*¹
¹Department of Mechanical Engineering, Indian Institute of Technology Guwahati, India

E-mail: manasdas@iitg.ac.in

Abstract. The study of surface texturing has been a great interest to the researcher over the last years. Surface texturing improves the property of the surface of the material in the working area. It creates a pattern of micron dimensions over the surface to influence the surface property in its working area. Several techniques are used to fabricate these micro dimensions. Electrochemical micromachining (EMM) emerges as a new technique with several benefits. This review paper highlights the advantages of EMM over other processes and discusses different methods to develop the micro-features. EMM process is capable of fabricating micron-size features without changing any surface property at a low cost.

1. Introduction
Texturing means to make a specific pattern of micro-dimensions like micro-holes, micro-slots, micro-asperities, etc. These are made over the surface to enhance its functionality [1]. It also increases the tribological performances of components having friction pair between them. It helps in reducing the friction and improve load-carrying capacity [2–5]. It finds its application in various fields of engineered surfaces like biomedical, tribology, wetting, optics, etc. Some of the specific patterns fabricated over the surfaces are an array of grooves, dimples, and pillars, etc. [6]. The micro-dimples have an advantage as it can act as a reservoir to intact lubricants on the surface to reduce friction between the sliding surfaces enhancing energy efficiency [7,8]. The micro-dimples is the most promising surface texture as it provides additional hydrodynamic pressure [9]. It also improves evaporation efficiency in spray cooling [10].

Surface texturing utilizes several techniques for the fabrication of micro-features such as laser surface texturing (LST), electric discharge (ED), nano casting and lithography, and chemical texturing. Most of them generate a heat-affected zone, which deteriorates surface property. Nano casting and lithography consumes a lot of time for the preparation of mask and not suitable for the large scale production. Chemical texturing is a good option for surface texturing, but controlling of process parameters is not efficient [1]. The most used one is the laser machining. Wang and Bai [11] fabricated micro dimples in a circular array over the silicon carbide surface by laser marking process. They concluded that the circular dimple texture improves the hydrophobicity of silicon carbide surfaces and the diameter of the dimple is the most influencing parameter which affects the contact angle. Petare et al. [12] fabricated a textured surface over the spur gear via laser. Textured gear is finished by abrasive flow finishing (AFM) process, which helps in achieving better surface finish, microhardness, wear-resistance, and microstructure.

Patel et al. [13] have compared laser surface texturing (LST) with electrochemical texturing (ECT). They found that the fabrication of large textured surface via laser is not economical. ECT has a lot of potential and economically feasible methods for texturing. Texturing via laser induces heat affected zone and rough surfaces. But these problems are eliminated via ECT.

2. Introduction to Electrochemical micromachining
Electrochemical machining (ECM) patented by Gussef in 1929 is a non-conventional machining process [14]. ECM is the macro form of EMM. In this process, an electrolytic cell is developed, having anode as a workpiece and cathode as a tool. The two electrodes are filled with an electrolyte, which forms the electrolytic cell. As the workpiece and tool are connected to the terminals of the electrolytic cell, they must conduct electricity for the machining process to take
place. In ECM, the workpiece dissolves which is connected to the anode, so it is also called anodic dissolution. The metal dissolution takes place in the form of ions from the anode and forms precipitates in the electrolyte when a voltage is supplied. The reactions which take place at anode and cathode are described below.

At cathode:

\[
2H_2O + 2e^- \rightarrow H_2 \uparrow + 2OH^- \tag{1}
\]

At anode:

\[
M \rightarrow M^+ + e^- \\
M^+ + (OH)^- \rightarrow M(OH) \tag{2}
\]

Generally, the electrolyte is diluted with water. The different electrolyte has a different dissociation voltage. At a particular voltage, when the electrolyte dissociates, the hydrogen gas and hydroxide ion are produced. The hydrogen gas gets accumulated near the cathode, and the hydroxide ion combines with metal ions to form precipitates. Thus, the atom by atom removal from the workpiece takes place. ECM is also called a contactless electrochemical forming process. For machining to take place, the two electrodes should avoid contact with each other. The workpiece and the tool are separated by a distance called the interelectrode gap (IEG). This gap is generally less than 1 mm to achieve a high material removal rate (MRR) and high accuracy. Theoretically, there is no tool wear, but if they come in contact, a short circuit will take place and will deteriorate the shape of the tool. The final shape of the anode is the negative impression of the cathode, i.e. tool. Thus, short circuit protection is essential for accurate machining.

ECM is also considered as the reverse of the electroplating process. However, two significant differences that differ ECM with the later process are controlled machining of the workpiece and current density. The dissolution of the workpiece follows Faraday’s law of electrolysis. Some advantages which differ ECM from other non-conventional processes as described below.

- As there is no contact between workpiece and tool, no residual stress and no burrs are produced.
- Machining is independent of the workpiece properties like physical and mechanical.
- It gives good accuracy and good surface finish.
- Machining time is very less.
- Low volume of material is left as scrap.
- The heat generated during machining is also very less; thus, no thermal strain is induced.
- As no wear to the tool, the same tool can be reused for many components.

However, there are some limitations to the ECM process, which are described below.

- The workpiece must be electrically conductive.
- The final shape of the workpiece depends on the tool shape. Thus, designing the tool for complex shape is very important.
- The anodic dissolution depends on the electrolyte. Thus, electrolyte selection is very important.
- Maintaining small IEG is very challenging.
- Skilled workers are required to operate the machine.

EMM has all the qualities of being an extremely encouraging micromachining process because it incorporates high MRR, accuracy, and control, quick time to machine and it can easily machine titanium, copper amalgams, super compounds, and tempered steel [15]. Non-conventional machining strategies, for example, laser beam machining (LBM) and electric discharge machining (EDM) have been utilized for the machining of titanium and its amalgams. With the EDM procedure, one issue is that the by-products of machining can’t wipe out effectively, and the machining status is unsteady.
LBM has its disadvantages as it produces heat affected zone which degrades the surface property. [16]. Ultrasonic machining (USM), which has a more slender zone influenced by machining, is useful for hard and fragile materials. However, it has lower MRR, and also severe wear of tool takes place during machining [17].

Table 1 shows a range of parameters between ECM and EMM for the major machining characteristics. As the tool size is reduced to do micromachining, the value of the parameter is also reduced to do productive machining. The tool diameter is minimal, so the flow velocity of the electrolyte is negligible; otherwise, it will vibrate the tool, and the accuracy of the machining is reduced.

| Machining characteristics | Electrochemical machining (ECM) | Electrochemical micromachining (EMM) |
|---------------------------|----------------------------------|-------------------------------------|
| Applied Voltage           | 10–30 V                          | <10 V                               |
| Current density           | 20–200 A/cm²                     | 75–100 A/cm²                        |
| DC–Power supply           | Continuous/pulsed                | Pulsed                              |
| Pulse Frequency           | Hz–kHz range                     | kHz–MHz range                       |
| Electrolyte type          | Salt solution                    | Dilute acid/alkaline solution       |
| Electrolyte concentration | >20 g/l                          | <20 g/l                             |
| Tool Size                 | Large to medium                  | Micro                               |
| IEG                       | 100–600 µm                       | 5–50 µm                             |
| Surface finish            | Good, 0.1–1.5 µm                  | Excellent, 0.05–0.4 µm               |

3. Experimental set-up
The basic principle of machining for EMM is law established by Faraday for electrolysis, which is the same as ECM. The experimental set up for EMM is slightly different from ECM. The pictorial diagram of the EMM experimental set up is described in Fig. 1.

![Figure 1. Pictorial diagram of EMM experimental set-up [19]](image)

The equipment which helps in machining in the micron range is the X, Y, and Z-axis movement having a resolution of 0.1 µm. The movement of these axes is controlled by a CNC controller. Pulsed DC provides better machining as it gives time to remove the debris particles after machining as compared to continuous DC power supply. A digital oscilloscope is utilized to store digital data and display the pulse power. The tool is upheld in a tool assembly unit which is controlled by the Z-axis controller. The machining chamber made of Perspex material is used to hold the workpiece. Another
essential part of EMM is an electrolyte. The electrolyte flows between the electrodes through gravity. As debris particles are generated while machining and mixed with the electrolyte, it has to be purified before reuse. The XY table along with the machining chamber is kept over a strong base to avoid vibration and rigidity to the fixture.

In EMM, anodic dissolution to the microscopic domain is controlled with a pulse power supply of high frequency and three-axis stage controller. These provide accurate control measures of the workpiece as well as microtool. There are methods to fabricate micro-features via EMM. Some of them are discussed below.

3.1. Maskless EMM

In maskless EMM, jet-electrochemical micromachining (Jet-EMM) dissolves metal in a controlled way by current density in a highly localized way. Here, the photoresist mask is not prepared; however, high aspect ratio micro dimensions are fabricated by this process. In this, an electrolytic jet from the nozzle acts as the cathode and helps in removing debris and bubbles and the passive layer over the workpiece [20,21].

The passive electrolyte is used because it forms an oxide film of transpassive nature and evolves oxygen in the stray current zone. Lu and Leng [22] fabricated micro-features on titanium workpiece surface using both through mask-EMM (TMEMM) and Jet-EMM. It was concluded that TMEMM is suitable for regular surfaces; however, Jet-EMM can fabricate any curvature on an irregular surface. Any 3D profile can be easily fabricated by Jet-EMM. However, the machining rate is slow. Compared with TMEMM, maskless EMM provides less accuracy, less flexibility and less process control [23]. Patel et al. [13] fabricated micro-dimples on the flat and curved surfaces using maskless EMM. Tool insulated from the surrounding with tip open used to fabricate micro-dimples, as shown in Fig. 2(a). For a flat surface, the tool has not been given any feed to generate the hemispherical shape due to current density distribution between the electrodes. A fixture has to be developed for a curved workpiece such that IEG is maintained constant during indexing of the workpiece as shown in Fig. 2(b).

Patel et al. [24] experimentally investigated the tribological behavior on hypodermic needles. They created textured surfaces on the needles using EMM, as shown in Fig. 3. Micro-dimples, circular grooves, and linear channels are machined on a curved metallic hypodermic needle. It was observed a 5.6% reduction in insertion force due to the lower contact area. They also found that micro-dimples are more capable of holding lubricant as compared to micro-channels.
Figure 3. Schematic view of (a) micro-dimple, (b) linear micro-groove and (c) circular micro-groove

3.2. Through-mask EMM (TMEMM)

It is one of the most effective methods for generating microstructures via EMM. In this process, a pattern made of the mask generally photoresist or other materials is pasted over the workpiece surface (i.e., anode) for restricted material removal as shown in Fig. 4. The metal will dissolve from the surface where the photoresist mask is not present [25]. As IEG is very small, the selection of electrolytes is very critical in the case of through-mask EMM (TMEMM) [23].

Figure 4. Schematic of TMEMM

The advantage of using a mask is that the complex structure can be easily prepared but to a limited area. There are various processes by which the mask is prepared. Some of them are described below.

3.2.1. Dry film mask. A GPM200 dry film (DuPont, USA) was fabricated using photolithography and then placed over the workpiece for selective etching [26]. The through-hole mask is fabricated in a sequence of steps which follows as described and shown in Fig. 5.

- A substrate was dressed with oxygen plasma treatment for 3 minutes.
- The dry film of the desired thickness was laminated onto the substrate.
- The prepared dry film was exposed to a UV oven keeping a photomask having micro holes over it.
- The cured dry film was put in sodium-potassium carbonate diluted with water 1% by weight at 30°C for 60 sec.
- The dry film mask with patterns was removed off the substrate and pasted to the upper surface of the workpiece.
- The dry film was exposed at a dose of 70 mJ/cm². A negative photoresist, GPM200 dry film, chemically reacts during UV exposure and cure the photoresist, which makes it insoluble. The alkaline sodium potassium carbonate solution dissolves the uncured areas of the photoresist.
Figure 5. (a) Fabrication of patterned dry film (b) hole in dry film and (c) fabricated dry film over workpiece [26]

Qu et al. [6] proposed a novel EMM technique in which a dry film mask having an array of micro-dimples is carried by the tool and is placed between the tool and the workpiece. This mask can be reused and can allow for mass production. In this, the substrate does not undergo photolithography, but a dry film mask is laminated over the substrate by the application of 2 bar pressure. They analyzed the current density distribution over the workpiece using ANSYS to verify with the experiment results and concluded that film thickness does not affect the etching profile of micro-dimple. They took a 50 µm thick dry film mask. They fabricated micro-dimple arrays on SS 304 to get a diameter of 109.4 µm with a depth of 15.1 µm in 4 min of machining time. They got many accurate dimples with the ratio of etched micro-dimple to micropattern on the mask is 1.09.

Madore et al. [27] made several microfeatures on the titanium sheet using TMEMM. The negative polyamide-based photoresist is coated on the titanium surface for UV exposed to make a pattern. The desired cavity shape has been determined by the amount of electric current passed. They used 3M methanol-sulfuric acid electrolyte. The regular grid channel was formed and a spiral-shaped channel to analyze the performance of TMEMM. They concluded that TMEMM could be employed to machine highly corrosion resistance material like titanium. Using photoresist, it is difficult to mass-produce micro-dimples array as a photoresist mask has to remove after EMM and it is also difficult to make a large size of the mask as the bed of photolithography is small. Thus, it restricts the production of micro-dimples over a large area [28].

3.2.2. PDMS (Polydimethylsiloxane) mask. This mask is very popular as it is resistant to chemicals, low cost, and flexible. For the creation of this mask, initially, the Su-8 mold is fabricated. SU-8 mold is fabricated from negative photoresist BN308-150, SU-8, and a resin propylene-glycol-methyl-ether-acetate (PGMEA). PDMS gel was used to replicate the pattern of the molds. The major advantage of
The PDMS mask is that it can be reused because it is not damaged during machining as it is a polymer material. The process of making SU-8 mold with an array of micropillars has been shown in Fig. 6.

![Fabrication Process Diagram](image)

**Figure 6.** The fabrication of the SU-8 mold with an array of micropillars (a) Cleaned substrate surface. (b) BN308-150 casting and prebake. (c) UV exposure with no mask and postexposure bake. (d) SU8-2050 casting and prebake. (e) UV exposure with the mask. (f) Postexposure bake and development

The several steps involved in the making of SU-8 mold with micropillar are as follows:

- A polished silicon wafer substrates of thickness 3 mm and 2-inch diameter disks were cut to apply for the photomasks.
- To clean the substrate surface, it is immersed into acetone solution with the ultrasonic cleaner to wash oil from the substrate.
- The substrate is layered with a BN308-150 negative photoresist up to 2.5 μm thick.
- The photoresist is then baked at 90 °C for 20 min and then exposed to UV without the mask and again exposure for 30 min at 120 °C.
- SU-8 photoresist covers the substrate by spin-coated, and then it is placed over a hotplate. Its temperature is steadily increased from 65 °C to 95 °C at a rate of 10 °C/min and maintained for 90 min. Then it is cooled at normal temperature.
- Now the UV is exposed over the SU-8 photoresist via a traditional mask aligner.
- Acid washing is followed by dipping into sodium hydroxide to eliminate metal ions.
- Again it is dipped into acetone to eliminate any acid or alkali and then it is rinsed by deionized water and kept over a hotplate at 150 °C for 15 min for removal of leftover water.
- Postexposure bake process is done for the substrate from 65 °C to 95 °C for 30 min, followed by room temperature cooling.
- Then using a photoresist solvent, PGMEA (propylene-glycol-methyl-ether-acetate) with little ultrasonic agitation for 10 min is performed and followed by a rinse with the deionized water.
- At last, it is baked for 10 min at 50 °C to evaporate the leftover water and finally, SU-8 mold with micro-pillars is fabricated.

Now for the fabrication of the PDMS mask, the flat substrate 2 is aligned with substrate 1 having the micro-pillar array, with the help of double-sided tape. Now PDMS gel is filled to the mold by the vacuum-aided process, and PDMS has cured afterward. Finally, cured PDMS mask having through-holes were removed from the vacuum chamber [29–31]. The fabrication of PDMS mask with through-holes is described schematically in Fig. 7.
Qu et al. [30] have fabricated PDMS mask through-holes for TMEMM. From the experimental results, it was found that the optimum curing temperature is 70 °C. The PDMS mask through-holes were fabricated with a diameter of hole 50 µm at a thickness of 200 µm. The micro-dimples were fabricated at low voltage to get a smaller diameter. The machining accuracy of the mask of diameter 50 µm and 100 µm are 59 µm and 109 µm diameters of micro-dimples.

Chen et al. [29] have introduced one new technique to fabricate PDMS mask. The photoresist BN308-150 is sandwiched between the substrate and SU-8 mold to enhance the adhesion of the micro-pillars to the substrate. The micro-pillars were fabricated of 50 µm diameter of 300 µm depth with adhesion, and it is attached to the SU-8 mold even after peeling off the PDMS through-hole mask. An array of the micro-circular hole, micro-cross hole, and micro-half ring hole was successfully formed. The PDMS mask undergoes corona treatment for 10 s to improve adhesion property and then attached to the workpiece with rubber roller laminating machine. The PDMS mask of thickness 200 µm and diameter 50 µm is fabricated, and the micro-dimple array was prepared to have diameter 61.5 µm and depth 3 µm. By making a workpiece as a cathode, PDMS mask is used for micro-electroforming. The micro-cross-embossment was fabricated having a width and a height of 100 µm and 25 µm respectively.

3.2.3. Sandwich-like EMM (SLEMM). Zhang et al. [32] proposed a new methodology which is sandwich-like EMM (SLEMM) to decrease the sidecut of micro-dimples to improve accuracy. The line sketch of the SLEMM process is shown in Fig. 8.
In this process, a dry film mask made of GPM220 is laminated over the workpiece surface with the help of hot rolling, and the tool is made in contact with the mask such that IEG is almost negligible. After the experiment, it was observed that the mean diameter of micro-dimples using SLEMM is small as compared to TMEMM due to the uniform distribution of current density in SLEMM. Also, it was found that the etch factor is as high as 2.5 for SLEMM as compared to TMEMM, i.e., 0.9. For deeper micro-dimples, porous metal cathode gave good results compared to the solid metal cathode as it allows gases to escape [33] from the machining zone. Further, Zhang and Qu enhanced the micro-dimples accuracy by allowing the flow of electrolyte in the lateral direction through porous metal cathode [34].

4. Conclusions
The paper describes electrochemical micromachining (EMM) as one of the most promising techniques for surface texturing. It offers several advantages like no heat generation, no surface residue, machining accuracy, better surface finish at low cost. The micro-features like micro-dimples, micro-channels, etc. can be easily fabricated over flat as well as curved surfaces. Several techniques which include mask as well as maskless EMM. The higher aspect ratio of micro-dimples can be achieved with the maskless EMM whereas high accuracy can be achieved with TMEMM. Fabrication of the mask takes several steps. Researchers are trying to make the process more feasible and customized.

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