Fabrication of Island-Free Micro Dimple Arrays by Through Mask Electrochemical Micromachining

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Abstract

Micro-dimples are among the basic microfeatures that are indispensable in improving the tribological performance and reliability of various mechanical components. Through mask electrochemical micromachining (TMEMM) is a feasible process for fabricating micro-dimple arrays with controlled size, location and density by maintaining surface texture. However, "Island formation" is one of the major barriers which not only hampers the surface quality but, in turn, weakens the effect of micro dimples on tribological properties. In this paper, optimal machining parameters along with suitable electrolyte combination are utilized for achieving island-free micro dimple array. AZ-4903 PR is being introduced as a mask due to its availability, low cost, chemical resistance and high flexibility. Pattern of micro-dimples with an average diameter of 65µm imprinted on the mask are being replicated over SS 304 substrate with considerable repeatability. The effect of two major electrochemical micromachining parameters, pulsed duty cycle and machining time on the machining accuracy as well as surface properties of the micro-dimples is analyzed. It was experimentally established that formation of islands could be avoided even after using a thin mask of 20µm thickness and well controlled shapes with smooth surface geometry can be achieved by prolonging the machining time.

Keywords: Through Mask Electrochemical Micromachining, Micro-Dimple Array, Island, Machining Accuracy, Surface Integrity.

1. INTRODUCTION

Nowadays, surface texturing at the micrometer scale, such as in the use of micro-dimples, micro-grooves, micro-pillars and micro-prisms, has represented an advanced technology in many engineering fields. Micro-dimple arrays are capable for improving the performance and consistency of mechanical systems by increasing in efficiency through reducing friction. It was found that a surface possessing micro-dimples with optimized dimension is more effective for reducing the friction coefficient as compared with the smooth surface [1]. A number of techniques are available for generating micro-dimple patterns, such as milling, electrical discharge machining, chemical etching, laser beam machining, abrasive jet machining, and electrochemical machining (ECM). Compared with other methods, ECM has the advantages of a lack of residual stress, tool wear, and heat-affected layer [2-3] and is quite popular for fabrication of dimples in micron range. Electrochemical Micromachining (EMM) makes it possible to remove materials selectively by electrochemical reaction at the anode workpiece. Metal is dissolved at the anode, and oxygen bubbles are produced. Micro-dimple array measuring 300µm were prepared on the AISI 440C specimen with a cylindrical tool electrode of diameter 275µm and focused on improvement in the friction coefficient However, the efficiency of the said method is quite poor because point to point microstructures are generated[4]. Through-mask electrochemical micromachining (TMEMM) is a common ECM method for generating micro-dimple arrays with controlled dimple size, location, and density. Using this method, arrays of hemispherical cavities were fabricated on titanium [5]. In another study, a new variation of the TMEMM of titanium was presented using a laser-patterned oxide film. Film patterning was achieved by local irradiation using a long-pulse XeCl excimer laser [6]. Electrochemical dissolution of the irradiated lines on the oxide film yielded well-defined grooves. Using this method, unusual cavity shapes can be generated by multistep mass-transport-controlled dissolution [7]. A similar phenomenon also indicated that the problem of island formation can be solved by prolonging the etching time [8].

Previous studies have shown that thick mask was introduced to remove islands by optimizing the current density distribution during TMEMM [9]. In TMEMM, the electrical field intensity at the mask edge is much larger than that of the feature centre because of the marginal effect of the electrical field, which leads to a high current density at the edge. As such, the amount of material removal at the edge is more as compared to that at the centre of the dimple. As a result of which, non-uniformity in the dimple surface could be noticed leading to formation of "island". The problem of island formation is treated as a certainty in TMEMM. It was experimentally investigated that when TMEMM was carried out with a combination of a low aspect ratio and low film thickness ratio, island formation occurred due to loss of electrical contact [10]. Island removal by employing masks of comparatively higher thicknesses i.e. 250µm PDMS mask for generation of micro-dimple array free from islands have been studied upon the profiles of the generated micro-dimple arrays [11]. Since, the phenomenon of island formation possess to be a hurdle towards sound machining, so achievement of island-free micro dimples is always a challenging task. While utilization of a 250µm mask involves a considerable amount of expense, PDMS mask being hydrophobic in nature may restrict the electrolyte flow into the mask's micro-holes, preventing ECM. This may lead to non generation of a sound dimple surface. Hence, there is an urgent need to investigate TMEMM process utilizing thin mask of such material which retains sufficient adhesiveness with the workpiece so as to withstand the electrolyte flow during machining.

This study utilizes a patterned mask of a negative PR (AZ 4903) of very low thickness i.e. 20µm, possessing strong adhesiveness with the substrate. Micro-dimple arrays without island formation are generated over the sample covered with a mask with patterned micro holes. The exposed areas on the workpiece undergo anodic dissolution upon machining. The mask needs to be removed after completion of the machining. The developed TMEMM set up with vertical cross flow electrolyte system generates micro-dimple array within a short period of time with improved dimensional uniformity. The effect of duty ratio and machining time on undercut (U_c), dimple depth (d_d), etch factor

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(f_e) and especially on surface roughness (R_a) were investigated during this process.

2. EXPERIMENTAL SET UP

A well planned research program has been taken up for experimentation in the developed TMEMM set up as shown in Fig.1. The set up has main three components (i) EMM cell with tool and workpiece fixture devices (ii) electrical power supply connections (iii) electrolyte flow guiding scheme with vertical cross flow electrolyte system. The EMM cell is made of Perspex and the inlet and outlet arrangements are made of stainless steel. The gear pump is used to flow the electrolyte throughout the system. The sludge is settled at the bottom of the tank and can be easily drained out.

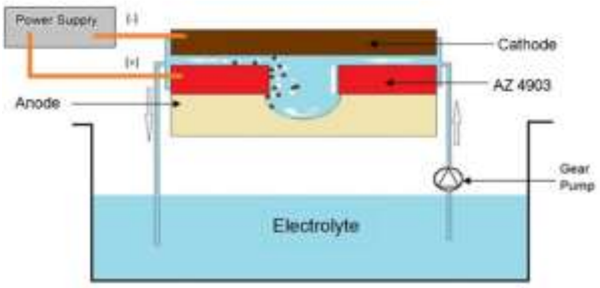


Fig. 1. Schematic of the developed TMEMM set up

3. EXPERIMENTAL PLANNING

Based on literature survey and trial experiments, two significant parameters i.e. duty ratio and machining time are considered as the influencing factors for TMEMM. The range of duty ratio is chosen from 20-50%, whereas, two different machining times i.e. 90s and 120s are considered for the experiments. The frequency of 2KHz in the form of square pulses and electrolyte concentration of NaCl (5.8M) and $NaNO_3$ (8.5M) are fixed. Other process parameters i.e. flow velocity of 3.8 m/s, back pressure of 0.04Kg/cm^2 are also kept constant. In the following experiments, a 20µm thin mask containing patterned micro-dimples is employed. Each experiment is repeated three times.

In TMEMM, metal gets dissolved in both Z as well as Y directions, which results in undercutting as well as increase in micro-dimple depth. The Etch Factor (f_e), which is equal to the ratio of the etching depth of the generated micro-dimple to the undercut can be calculated from equation (1), is computed to evaluate the machining localization of the micro-dimple:

$$f_e = d_d/U_c \qquad ....(1)$$

Where d_d is the depth and U_c represents the undercut in the micro-dimples generated after TMEMM. Undercut, U_c can be calculated as the difference of the radius of the generated micro-dimples to the radius of micro-holes patterned on the mask. A high f_e reflects high machining localization.

Approximately 40 micro-dimples for each sample were measured during analysis. Optical microscope (Leica DM2500, Germany), Talysurf CCI Non-Contact Profilometer (Taylor Hobson) and Scanning Electron Microscope (JEOL JSM 6360) were utilized to measure the machined surface characteristics and analyze the profiles of the generated micro-structures.

Table 1

Machining parameters for the experiments

Average diameter of micro-holes on the mask	65µm
Thickness of patterned mask	20µm
Workpiece Material	SS 304
Workpiece thickness	200µm
Mask Material	AZ 4903
Applied Voltage	12V
Duty Ratio	20%,30%,40%,50%
Machining Frequency	2 KHz
Inter Electrode Gap	2000µm
Electrolyte Concentration	NaCl (5.8M) + $NaNO_3$ (8.5M)
Machining Time	90s, 120s

4. RESULTS AND DISCUSSIONS

4.1. Influence of duty ratio on undercut (U_c)

From Fig. 2, it can be observed that, with the increase in duty ratio, undercut increases gradually up to a certain value, and then decreases. With increase in duty ratio, current density increases and results in more material removal and causes increase in Uc. When duty ratio exceeds 40 %, due to decrease in the pulse-off time, the oxygen bubbles generated on the anode surface due to dissolution, gets entrapped under the mask. The slowing down of escape of oxygen bubbles results in increase in the inter-electrode resistance. As a result of which, the current decreases rapidly resulting major reduction in the undercut. Moreover, as the machining time (t) increases, the exposure time of the bare material (in between the mask opening) increases resulting in the rise in undercut.

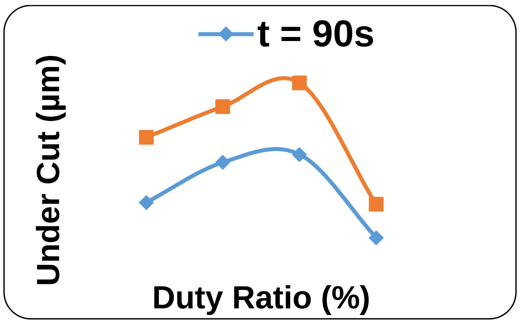


Fig. 2. Effect of duty ratio on Undercut

4.2. Influence of duty ratio on dimple depth (d_d)

Fig.3 shows the depth variation in micro dimples at different duty ratios with changing machining times. It could be observed that as the duty ratio changes from 20% to 50%, the depth of the micro-dimples gradually decreases. At lower duty ratio, as pulse-off time is higher, the removed material gets sufficient time to leave the machined surface. As a result, the dimple depth is on the higher side. As duty ratio increases, the pulse-off time proportionately decreases causing hindrance in electrolyte exchange mechanism. This leads to reduction in depth of the micro-dimples. The dimple depths achieved while machining for 90s is comparatively lower than that of the depths attained when the machining time was 120s.

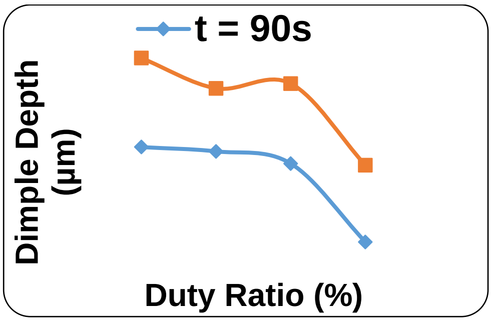
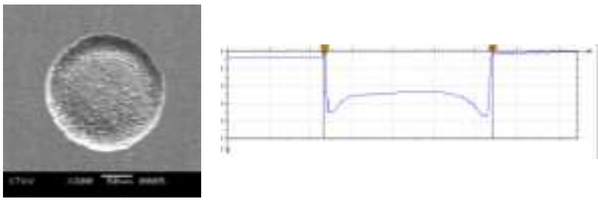


Fig. 3. **Effect of duty ratio on depth of the dimple**

4.3. Influence of duty ratio on etch factor (f_e)

Machining localization is an influencing factor for micro-dimple formation and can be defined by etch factor (f_e). It is the sole way to determine the anisotropy of the TMEMM process. An etch factor of 1.0 indicates ideal isotropic material removal. A large f_e implies small undercut and a controlled material removal could be observed beneath the mask opening, whereas a smaller etch factor implies large undercut where lateral material removal under the mask is much more. Fig.4 shows the profile geometry of the micro-dimple fabricated at 90s, where (a) represents SEM micro-graph and (b) highlights the geometry of the generated micro-dimple showing uneven material removal from the dimple surface.



(a) (b)

Fig. 4. **Island formation at the centre of the micro-dimple (a) SEM Micrograph (b) dimple profile**

Fig.5. plots the etch factors at different duty ratios. It could be noticed that f_e reduces with increase in duty ratio. This aspect could be explained by the fact that as the pulse-on time increases, the stray current density also increases resulting in the increase in undercut (U_c), which decreases f_e. When TMEMM was carried out for 90s, etch factor gradually decreases from 1.37µm to 1.03µm. Whereas, in case of t = 120s, f_e was found to be lowest at 40% duty ratio and thereafter, a slight increment of 0.028 µm could be noticed when the duty ratio was increased to 50%.

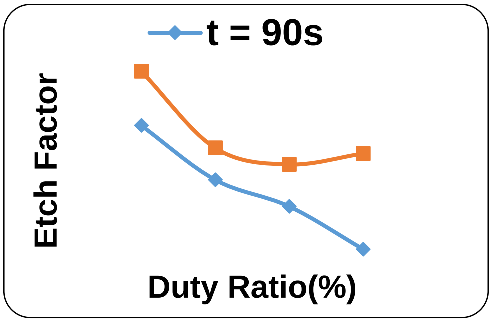


Fig. 5. **Effect of duty ratio on Etch Factor**

4.4. Influence of duty ratio on Surface Roughness (R_a)

After complete execution of the TMEMM process, the machined surfaces were held under the CCI Non-Contact Profilometer (Taylor Hobson) to investigate about the surface roughness (R_a) inside the periphery of the generated dimples.

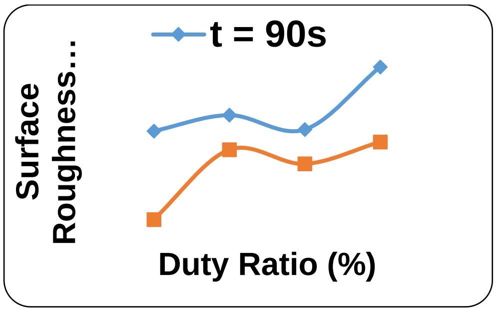


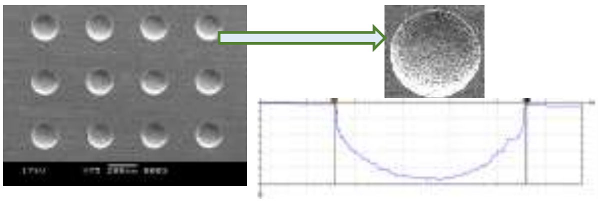
Fig. 6. **Effect of duty ratio on surface roughness**

Figure 6 explains about the nature of the machined surface at different duty ratios. As duty ratio increases, the surface roughness (R_a) value showed an increasing trend. This is because the current efficiency and the total amount of electricity do not change when the same applied voltage and effective machining time are applied. As a result of which, the volume of material removed remains the same. However, the relaxation time to zero current is longer at a low duty cycle and the reaction products are removed more thoroughly by the flow of electrolyte.

As the duty ratio increases, the time of removal of the reaction products decreases gradually and hence, the surface integrity of the dimples machined at lower duty ratios are much finer than that machined at higher duty ratios. Therefore, a low pulse duty cycle is more suitable for generating micro-dimples with a better three-dimensional topography.

4.5. Fabrication of Island-free micro dimple array based on experimental analysis

Based on the experiments conducted along with the thorough investigation of the results, it is obvious that fabrication of island-free micro-dimple array is quite feasible with this methodology of TMEMM. Fig. 7 shows the optical micrographs of the developed island free micro-dimple array fabricated under particular parametric combination i.e. machining voltage 12V, frequency 2 KHz, duty ratio 20%, Electrolyte concentration 10% NaCl + 10% $NaNO_3$ and Machining time 120s.



(a) (b)

Fig. 7. **Island Free Micro-dimple (a) SEM Micrograph (b) dimple profile**

Fig. 7(a) represents the SEM micrograph of an array of micro dimples while sound dimple geometry is found from Fig. 7(b).

5. CONCLUSIONS

A simple process for fabrication of micro-dimple array free from islands by TMEMM has been demonstrated. Based on the experimental investigations, the following conclusions can be obtained:

(i) Island free micro-dimples are successfully generated by utilizing very thin mask of 20μm thickness and machining for 120s.

(ii) With the increase in duty ratio, while the value of undercut and the surface roughness rises, the depth of the micro dimples and the etch factor decreases.

(iii) Formation of islands in the centre of the dimples could be restricted by enhancing the machining time and applying the mixture of NaCl and $NaNO_3$ as electrolyte. Moreover, utilization of thick masks for elimination of the island inside the dimples could be avoided by employing very thin masks resulting cost-effectiveness.

(iv) Micro-dimple arrays measuring 97μm diameter and 43.1μm depth were successfully prepared with an applied voltage of 12V, frequency 2 KHz, duty ratio 20% and a machining time 120s.

TMEMM can be effectively utilized for micro-pattern generation with various geometries during various surface structuring operations. Other significant factors could be investigated to sort out many challenges in the engineering scenario and increase the acceptability of TMEMM.

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