Investigation into Suitability of Electrolytes during Fabrication of Micro Dimple Pattern by Electrochemical Micromachining

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Abstract

The textured surfaces improve the efficiency of engineering parts in different applications i.e. tribology, aerospace, defence, biomedical etc. Maskless electrochemical micromachining (EMM) is a promising method for micro dimple generation because no insulated mask is needed on every workpiece. The paper presents the systematic investigation of suitability of electrolytes for anodic dissolution of stainless steel (SUS-304) by maskless electrochemical micromachining. The dimple patterned tool having 600µm diameter is fabricated by UV lithography process on stainless steel wafer bonding with 230µm thick reusable SU-8 2150 negative photoresist. At a time, one dimple patterned tool with reusable mask can produce several samples with a short time and low cost. The set up consisted of EMM cell, power supply, vertical cross flow electrolyte system etc has been developed to study the performance of three different electrolytes i.e. NaCl (0.18M), $NaNO_3$ (0.26M) and NaCl (0.18M) + $NaNO_3$ (0.26M) in terms of the influence of process parameter i.e. voltage and inter electrode gap (IEG) on machined surface characteristics i.e. MRR and depth. Out of these three electrolytes, one electrolyte i.e. mixed electrolyte of NaCl+$NaNO_3$ has been selected as a better electrolyte based on the proper geometrical shape with controlled etching. The better mean depth of 53.5µm with proper geometrical shape has been achieved through the experimentations for NaCl+$NaNO_3$ electrolyte. Attempt has also been made for the analysis of SEM and atomic force microscopic images to study the micro-features of micro dimple pattern.

Keywords: Maskless EMM, micro dimple pattern, MRR, depth.

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1. INTRODUCTION

Micro-structured surfaces containing various patterns i.e. circular, square, rectangular etc. represent a new movement of promising micro-machining technologies for enhancing the functionality and performance of industrial components. Micropatterned surfaces can change the thermal, tribological, biological etc properties of the original surfaces. Many reviewers have been evaluated their theories on texturing and microtextured techniques [1, 2]. Micro circular patterned surfaces retain the lubricating substances in micro-impressions and act as lubricant reservoirs. These micro-textures reduce the shear stress in lubricated mating elements. Air-shielding electrochemical micromachining (AS-EMM) with electrolyte jet and air-film protection principle was used to generate the micro dimples with high precision and stability compared to electrochemical micromachining. In this process, the effect of process parameters i.e. machining voltage and feeding speed on dimple diameter and depth was investigated using 10% wt $NaNO_3$ electrolyte [3]. Air-shielding electrochemical micromachining is a very expensive process for dimple generation. The electro-etching conditions comprising voltage, machining gap, the formulation of the electrolyte, and current density were optimized for the generation of microstructures with a lower feature size using 10 wt% $NaNO_3$+10 wt% NaCl electrolyte by through mask electrochemical micromachining (TMEMM) method[4]. This method is costly process for masking of every workpiece. Electrochemical machining with continuous free jet and pulsed current (Jet-PECM) was used to fabricate the cross-sectional shape of straight-lined grooves on WC6Co carbide metal using 2.4 mol/l of $NaNO_3$ and 1.2 mol/l of NaOH [5]. This Jet-PECM is time-consuming process because it generates the grooves one by one and higher concentration of electrolyte is not economically suitable. The maskless EMM was used to investigate the generation of micro circular pattern with 800μm dimple diameter using electrolyte concentration of 2% (wt/vol) NaCl+$NaNO_3$[6]. But, the dimple diameter is large. Maskless electrochemical texturing process has also investigated the effect of important parameters such as the inter electrode gap, the applied voltage and the texturing time on diameter and depth for different texturing patterns containing dots, trace-dots and chevrons using a NaCl solution electrolyte of 200g/l [7]. Higher electrolyte concentration increases the overcut of the textured patterns and higher concentration is not more economical for this process.

Various micro-texturing techniques i.e. abrasive jet machining, laser micromachining, electro-discharge machining etc are used for fabrication of different textures. Compared with other methods, EMM is a promising machining technique with several advantages such as high machining efficiency, independence of material hardness and toughness, the absence of a heat-affected layer, a lack of residual stresses, cracks, tool wear and burrs and low production cost.

A novel method of maskless EMM has been developed to explore the possibility of micro circular pattern generation with lower cost and higher machining efficiency. One reusable patterned tool with mask can generate micro patterns on large number of samples. The developed EMM cell and setup with vertical cross flow system can generate good machined samples with better surface finish than other flow modes. The influence of machining parameters i.e. applied voltage and inter-electrode gap using three different electrolytes on material removal rate and mean machining depth of micro dimple pattern has been investigated.

2. EXPERIMENTAL PLANNING

Considering the influence of the predominant process parameters and texturing characteristics, a well-planned arrangement was considered for the indigenous development of maskless EMM setup. The developed setup consists of various sub-components and systems i.e. electrochemical micromachining cell, electrical power supply system, electrolyte circulation arrangement etc. for performing experimental investigations for micro dimple pattern generation of work samples. One important feature of electrolyte system is that flow system is vertical cross flow system, which maintains the better surface finish than other modes of electrolytes. Figure 1 shows a schematic diagram of the various sub-systems of the developed maskless EMM set-up.

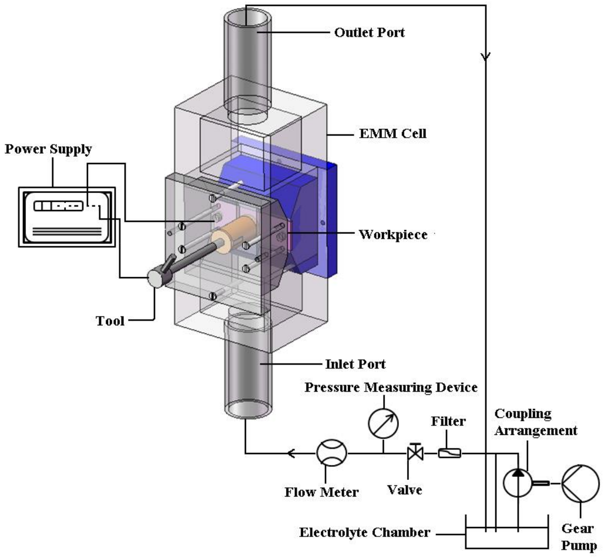

Fig.1. Developed EMM set-up

The micro circular patterned tool having 600μm diameter was fabricated by UV lithography process on stainless steel wafer bonding with reusable SU 8 2150 negative photoresist having thickness 230μm. The experimental clarification and research studies were designed in such a way so as to carry out the fruitful research analysis for deriving the effective research findings, which can be useful to the applied researchers and manufacturing industries in the area of micromachining domain achieved through maskless EMM. To analyze the control of the desired performance characteristics of the process parameters of the maskless EMM system, parameter settings were designed to utilize properly for the developed setup. The range of voltage and IEG is 10–16V and 100–400μm respectively. Other parameters are kept constant i.e. duty ratio of 40%, pulse frequency of 5kHz, current cut off of 3A, flow rate of 3.92 m^3/hr, concentrations of NaCl (0.18M), $NaNO_3$ (0.26M) and NaCl (0.18M) + $NaNO_3$ (0.26M), flow pressure 0.15 kg/cm^2 and time of 3 minutes. The characteristics of machined micro dimple pattern were examined with Optical Microscope (Leica DM2500, Germany), Three-dimensional (3D) Non-Contact Profilometer (CCI Sunstar, Taylor Hobson Ltd, UK), Atomic Force Microscope (Nanosurf Easyscan 2, Switzerland) and Scanning Electron Microscope (JEOL, JSM-6360, Japan).

3. RESULTS AND DISCUSSION

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For effective exploitation and industrial applicability of EMM, the process parameter settings must be decided while fabricating need-based structure to increase production rate, minimize wastage of material, and for quality production. The effect of EMM process parameters i.e. applied voltage and interelectrode gap using three different electrolytes is investigated for texturing characteristics i.e. MRR and depth.

Figure 2 depicts the effect of voltage from 10V to 16V on MRR for three types of electrolytes i.e. NaCl, $NaNO_3$ and NaCl+$NaNO_3$ and other parameters are kept constant i.e. IEG of 100µm, duty ratio of 40%, pulse frequency of 5 kHz, flow rate of 3.92 m^3/hr, machining time of 3 minutes and concentrations of NaCl (0.18M), $NaNO_3$ (0.26M) and NaCl (0.18M) +$NaNO_3$ (0.26M). From the figure, it has been clearly observed that MRR rises with the increase in voltage for three electrolytes. The highest MRR is observed for NaCl than other two electrolytes except 10V. This is due to the higher mass transfer dissolution of stainless steel in NaCl. The mass transfer dissolution is the mass of the workpiece that dissolves, is transferred away from it, resulting in flow of mass transfer current. Mass transfer occurs due to migration, diffusion and convection. Overall, the mass transfer is also higher for NaCl+$NaNO_3$ due to availability of higher conductive ions than other two electrolytes. The lowest curve of MRR is observed for $NaNO_3$ because it has moderate capability of electrical conductivity. This mixed electrolyte of NaCl+ $NaNO_3$ always upholds the uniform etching from the whole micro dimple pattern.

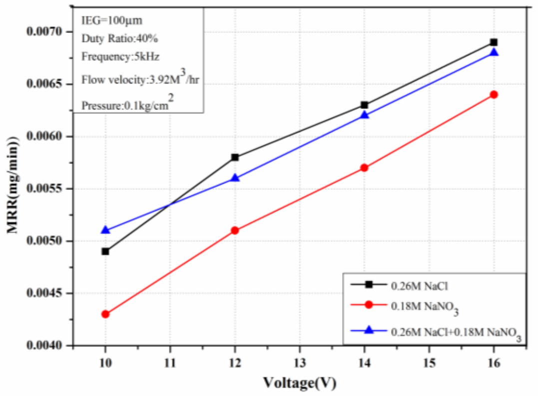

Fig.2. Effect of voltage on MRR for NaCl, $NaNO_3$ and NaCl +$NaNO_3$

Figure 3 represents the effect voltage on average depth of micro dimple pattern for three different electrolytes. The controlled machining depth i.e. 53.5µm has been observed in the micro dimple pattern machined with NaCl+$NaNO_3$ electrolyte for 10V. The depth increases with increase in voltage. Higher depth occurs due to higher localization effect, but stray current density also affects on the circularity of holes resulting the machining accuracy deteriorates. The increase in depth almost lies for $NaNO_3$ in between two other electrolytes i.e. NaCl and NaCl+$NaNO_3$. The effect of stray current density is less compared to NaCl. The depth is higher for NaCl due to controlled machining. The depth of NaCl + $NaNO_3$ is more or less same or higher than NaCl and $NaNO_3$ because the mixed electrolyte performs the controlled machining.

The dimensions of standard deviations in depth with a range of 0.701-2.696µm for NaCl, 0.566-2.205µm for $NaNO_3$ and 0.481-2.611µm for NaCl + $NaNO_3$ at the range of machining voltage of 10-16V using pulse current power supply at constant voltage mode have been formed. The almost lower standard deviation in depth with regular shape and size has been shown at applied voltage of 10V for NaCl + $NaNO_3$ than other three voltages using reusable SU-8 2150 flexible mask. Below 10V, the micro dimple patterns were not formed properly with good geometrical shape and size. Above 16V, the micro dimple patterns were generated with irregular shape and lower surface quality.

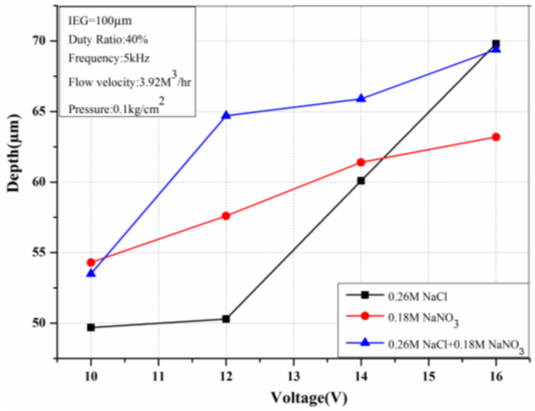

Fig3. Effect of voltage on depth for NaCl, $NaNO_3$ and NaCl +$NaNO_3$

Experimental investigations have been conducted to explore the effect of interelectrode gap on MRR for micro dimple pattern experiments by varying the interelectrode gap (IEG) in the range of 100-400µm. It is observed that MRR decreases with increase in interelectrode gap for three different types of electrolytes because the resistivity of electrolyte increases, resulting the current density decreases at constant voltage. The decrease of MRR is lower for $NaNO_3$ than other two electrolytes with increased interelectrode gap because it has moderate capability for material removal for the availability of less number of metallic ions. For NaCl, MRR is lower than NaCl+$NaNO_3$ except IEG of 300µm and higher than $NaNO_3$ because the electrolyte concentration is lower than the combined concentration of NaCl+$NaNO_3$ because combined electrolyte increases the current density which leads to more MRR. In IEG of 300µm, the MRR is lower due to less localized machining of material for NaCl+$NaNO_3$. The MRR for NaCl is lower than NaCl+$NaNO_3$ and higher than $NaNO_3$ due to availability of more conductive ions than $NaNO_3$. In lower inter electrode gap, the uniform and controlled etching takes place at NaCl+$NaNO_3$ electrolyte than NaCl and $NaNO_3$ and stray current distribution is also controlled across the micro dimple pattern.

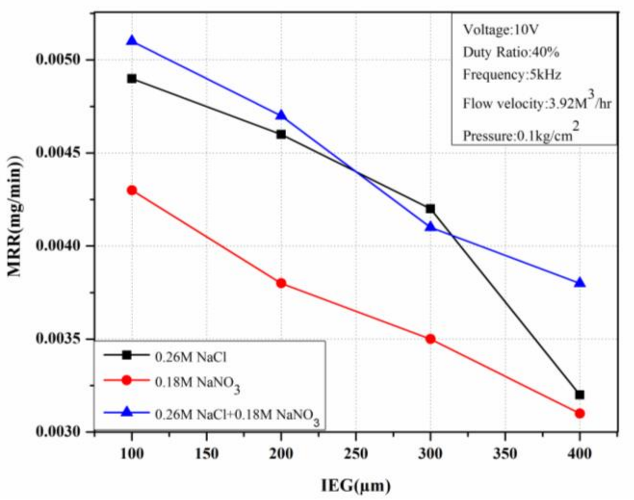

Fig.4. Effect of IEG on MRR for NaCl, $NaNO_3$ and NaCl +$NaNO_3$

Figure 5 represents the effect IEG on average depth of micro dimple pattern for three different electrolytes. The machining depth is lower for NaCl from 100µm to 400µm than other two electrolytes because NaCl has higher stray current density due to the availability of more metallic ions. The more material is removed from the periphery of micro dimple pattern due to higher stray current density distribution. The change of depth for $NaNO_3$ is almost same or higher than NaCl+$NaNO_3$ due to higher localization effect and less stray current density. The effect of stray current density for $NaNO_3$ is less compared to NaCl. As a result, the depth is higher due to controlled machining comparison to NaCl. The depth of NaCl + $NaNO_3$ is more or less uniform than NaCl and $NaNO_3$ because the mixed electrolyte performs the controlled machining with good geometrical shape.

The dimensions of standard deviations in depth with a range of 0.796-1.590µm for NaCl, 0.403-0.961µm for $NaNO_3$ and 0.018-1.739µm for NaCl + $NaNO_3$ at the IEG of 100-400µm using pulse current power supply at constant voltage mode have been formed. The almost lower standard deviation in depth with proper geometrical shape has been shown at IEG of 100µm for NaCl + $NaNO_3$ than other two electrolytes. Below 100µm, the micro circular patterns were not formed properly with good geometrical shape and size. Above 400µm, the micro circular patterns were generated with improper geometrical shape with uncontrolled etching.

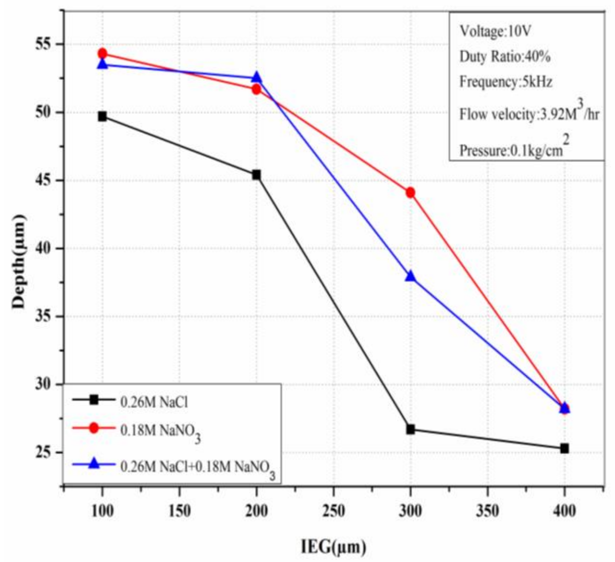

Fig.5. Effect of IEG on depth for NaCl, $NaNO_3$ and NaCl +$NaNO_3$

From the experimental investigations of micro circular pattern generation, the best parameter combination are voltage of 10V, electrolyte concentration of NaCl(0.26M)+$NaNO_3$(0.18M), duty ratio of 40%, pulse frequency of 5kHz, IEG of 100µm, flow rate of 3.92 m^3/hr and machining time of 3 minutes using SU-8 2150 flexible mask as shown in figure 6. One perforating mask has more capability to produce several samples without rupturing of mask material at higher velocity. Figure 6 shows the SEM image of micro circular pattern with minimum overcut of 21.124µm, depth of 53.5µm and surface roughness of 0.0512µm. This proper geometrical shape has been formed due to good flushing conditions and uniform current distribution.

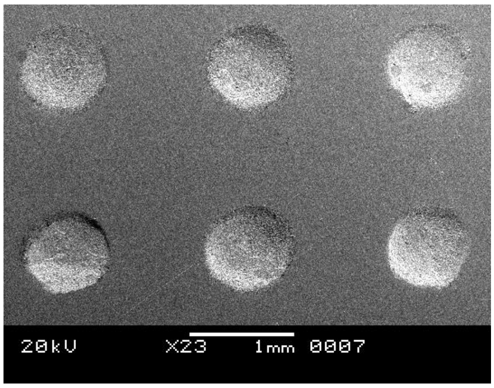

Fig.6. Micro dimple pattern machined with NaCl +$NaNO_3$

Figure 7 shows a 3D image of the micro circular impression and the detail of depth measurement with 64.9µm.

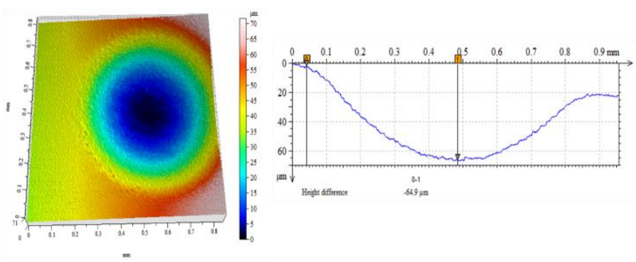

Fig.7. 3D view and 2D profile of depth of micro circular impression for NaCl +$NaNO_3$ electrolyte

A small segment of machined circular impression is analyzed by Atomic Force Microscope (AFM) as shown in figure 8. Figure 8 shows 3D view with 2D profile of small segment of machined circular impression inside one of the dimple patterns. The value of root mean square (R_q) is 0.913µm and it represents the standard deviation of surface heights. The value of maximum profile peak height (R_p) is 0.180µm and it shows the height of the highest peak above the mean line in the profile. The value of maximum profile valley depth (R_v) is -0.205µm which shows the depth of the deepest valley below the mean line in the profile. Surface roughness (R_a) is 0.275µm which signifies the arithmetical average value of all absolute distances of the roughness profile from the center line within the measuring length.

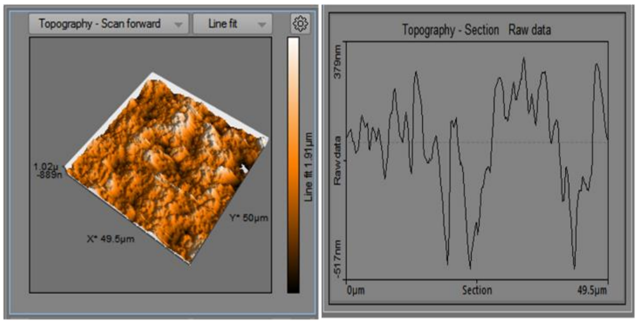

Fig.8. 3D view and 2D profile of surface roughness of the segment of dimple pattern for NaCl +$NaNO_3$ electrolyte

4. CONCLUSIONS

This paper reports on the influence of EMM process parameters i.e. voltage and IEG on the MRR and depth of micro dimple pattern fabricated by maskless electrochemical micromachining. Based on the results of experimental investigations, the recommendations of this research work can be summarized as follows:

(i) Compared with through mask EMM, the present approach of maskless EMM is capable to achieve higher machining accuracy of circular pattern generation. Single textured tool using SU-8 2150 flexible mask can generate more than several samples using developed EMM setup with vertical cross flow electrolyte system.

(ii) For higher MRR, machining with higher voltage and lower IEG is suggested for three electrolytes, but for controlled depth with regular shape, machining with lower voltage and lower IEG with NaCl + $NaNO_3$ electrolyte is recommended than other two electrolytes.

(iii) From the experimental investigations for micro dimple pattern generation, the best machining parametric combination is applied voltage of 10V, NaCl(0.26M/L)+$NaNO_3$(0.18M/L), pulse frequency of 5 kHz, duty ratio of 40%, interelectrode gap of 100µm, flow rate of 3.92 m^3/hr and machining time of 3 minutes.

The presented research work is very helpful for better understanding of the maskless EMM process to achieve better machining quality of micro dimple pattern. Lower concentration, higher frequency and proper electrolyte supply to the micro-machining zone enhance the machining conditions, which in turn improve shape control and surface quality. The higher accuracy of dimple pattern is a challenge and essential requirements for generation of better shape and size of the micro textured patterns during EMM operation.

References

[1] Evans C. J., Bryan J. B. "Structured," "Textured" or "Engineered" Surfaces," CIRP Annals-manufacturing Technology, 48(2):541–556, 1999.

[2] Bruzzone A.A.G., Costa H.L., Lonardo P. M., Lucca D. A., Advances in Engineered Surfaces for Functional Performance, CIRP Annals-manufacturing Technology, 57(2):750–769, 2008.

[3] Wang M., Bao Z., Qiu G., Xu X., Fabrication of micro-dimple arrays by AS-EMM and EMM, International Journal of Advanced Manufacturing and Technology, DOI 10.1007/s00170-017-0538-0, 2017.

[4] Wanga Q., Xiaob J., li Y., Experimental Study on the Through-Mask Electrochemical Micromachining (EMM) Process, Advanced Materials Research, 189-193:692-696, 2011.

[5] Martin A., Eckart C., Lehnert N., Hackert-Oschätzchena M., Schubert A., Generation of Defined Surface Waviness on Tungsten Carbide by Jet Electrochemical Machining with Pulsed Current, Procedia CIRP, 45: 231 – 234, 2016.

[6] Kunar, S., Bhattacharyya, B., Experimental Investigation into Surface Structuring by Electrochemical Micromachining, Proc. 6th International and 27th All India Manufacturing Technology, Design and Research Conference (AIMTDR-2016). Pune, India, 1438-1442, 2016.

[7] Parreira, J.G., Gallo, C.A., Costa, H.L., New advances on maskless electrochemical texturing (MECT) for Tribological purposes, Surface & Coatings Technology, 212:1–13, 2012.