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Removal of islands from micro-dimple arrays prepared by through-mask electrochemical micromachining

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ABSTRACT

Surface texture plays a fundamental role in tribology, allowing for the improvement of the friction and lubrication performances of various mechanical components. Through-mask electrochemical micromachining (TMEMM) is a feasible alternative for generating surface texture. However, in TMEMM the “island” phenomenon often occurs, which weakens the effect of micro-dimples on tribological properties. This study is the first to focus on removing islands by using a thick mask. Simulations were performed to analyze the distribution of current density on an anode surface and predict the anodic dissolution process under a thick mask. For reuse, the mask was fabricated from a PDMS layer measuring 200 μm in thickness. The simulations and experimental results verified that the island phenomenon can be avoided by use of a thick (200 μm) mask. In addition, the effects of the applied voltage and machining time on micro-dimple formation were experimentally investigated. The results indicate that the dimensions of micro-dimples are mainly determined by the applied voltage: the micro-dimple diameter increases with increasing voltage, and machining localization increases sharply. With prolonged machining time at constant voltage, only a slight increase in dimple diameter is observed. Moreover, because of a current valve in the electrolyte, micro-dimples with a flat bottom can be obtained at low voltage, whereas micro-dimples with a round bottom can be generated at high voltage.

1. Introduction

“Surface texturing” is a materials manufacturing process that is utilized to generate a specific groove or a dimple pattern on a workpiece surface. As reported in many studies, surface texturing has recently become a popular method in tribology for improving the friction and lubrication performances of various mechanical components. It has been observed that the tribological performance of piston rings with partial surface texturing may be enhanced. Typical surface textures include micro-dimple arrays, prism arrays, pyramid arrays, and micro-grooves. Compared with other textures, micro-dimple arrays have garnered more attention because they exhibit excellent tribological properties [1]. In sliding lubricated concentrated point contacts under linear reciprocating motion, at a high sliding velocity, the decrease in the coefficient of friction in the presence of surface texture is greater than that observed for the ground surface, and this is due to better retention of the lubricant in the micro-dimples [2]. In comparing a lapped smooth surface to a structured surface with a dimple size of approximately 100 μm at a density of 5–20%, it has been observed that the dimple surface reduced the friction coefficient from 0.12 to 0.10 [3].

To generate micro-dimple patterns on surfaces, various fabrication methods have been used, such as mechanical machining, electrical discharge machining, chemical etching, laser-beam machining, and abrasive jet machining. However, most of these approaches are unable to satisfy the demand for the industrial-scale manufacturing of inexpensive microstructures. For example, photolithographic processes are used in chemical etching, abrasive jet machining, and reactive ion etching, which are carried out through complex steps. With laser machining and electrical discharge machining, a heat-affected zone is generated and the “flanging” phenomenon is observed around the dimple rims, which require secondary processing or final lapping [4].

Electrochemical machining (ECM) has also been used for the surface texturing of metals. ECM is a process used to selectively

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remove material by an electrochemical reaction at the anode workpiece in an electrolytic cell with an appropriate combination of machining parameters [5]. Compared with other methods, ECM is a promising machining technique, offering 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 [6–9]. Hackert-Oschätzchen et al. [10] prepared microstructures in carbide metal alloys by jet ECM. The special characteristic of this technology is the restriction of the electric current to a confined area by a jet, which leads to a high localization of the removal area. Byun et al. [4] prepared dimples measuring 300 μm in diameter and 5 μm in depth on a workpiece by micro-ECM using a tool electrode with a diameter of 275 μm. However, the efficiency of this method is quite poor because the microstructure is generated point by point.

Through-mask electrochemical micromachining (TMEMM) is a common ECM method for generating micro-dimple arrays with controlled dimple size, location, and density. The TMEMM process involves several photolithographic steps, including soft baking to dry out the solvent after spin coating, exposure to UV light, post-exposure baking, and developing to produce micropatterns on photoresist-coated workpieces by the selective dissolution of metal from unprotected areas. Using this method, Madore and Landolt [11] fabricated arrays of hemispherical cavities on titanium. Hao et al. [12] fabricated microstructures on cylindrical workpieces. Chauvy and Landolt [13] presented a new variation of the TMEMM of titanium using a laser-patterned oxide film. Film patterning was achieved by local irradiation using a long-pulse XeCl excimer laser. 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. Zhu et al. [14] developed a modified TMEMM technique to prepare micro-dimple arrays in which an insulation sheet, coated with a conductive metal layer and perforated with through-holes, was used as a mask for TMEMM. However, in TMEMM, the problem of island formation is inevitable. Shenoy et al. [15] investigated island formation during TMEMM and observed that the problem was most likely to occur with a combination of a low aspect ratio and low film thickness ratio, which induce loss of electrical contact. Winkelmann and Lang [16] indicated that in TMEMM, because of the high aspect ratios of photoresist thickness to structure width, a non-uniform distribution of the applied electric field occurs over a workpiece, which leads to non-uniform material removal. Wang et al. [17] also observed a similar phenomenon and indicated that the problem of island formation can be solved by prolonging the etching time.

Previous studies have shown that the typical micro-dimple dimensions required to reduce the coefficient of friction are 2–10 μm in depth and 50–600 μm in width [18]; therefore, prolonging the etch time is an unsuitable method for removing islands during TMEMM because the depth of dimples will be simultaneously increased. Generally, in TMEMM the patterned photoresist layer used as the mask is 5–20 μm in thickness. In this paper, a thick mask was introduced to remove islands by optimizing the current density distribution during TMEMM. Simulations were performed to analyze the effects of using masks with different thicknesses on the current density distribution over a workpiece and predict the evolution processes for micro-dimples on the workpiece. Experiments were conducted to study the effect of the thick mask on the profile of micro-dimples. In TMEMM, the patterned photoresist is a single-use mask and must be cleaned from the anode surface after machining. In this study, a mask was fabricated from a PDMS layer measuring 200 μm in thickness, which has the advantages of chemical resistance, low cost, flexibility, and high molding capability. The PDMS mask is reusable because no damage is caused to the mask during TMEMM due to the mask's good chemical resistance.

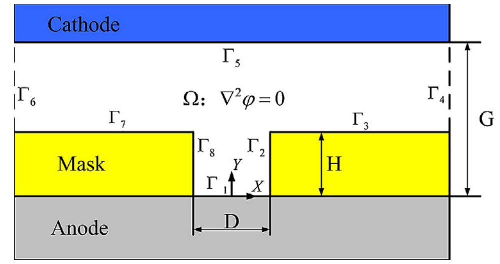

Fig. 1. Schematic and mathematical model of the TMEMM process.

2. Physical model and numerical method

2.1. Model definition

In TMEMM, a workpiece is covered by a patterned mask and only the metal exposed to the electrolyte is removed because the electric field is restricted by the mask. Fig. 1 gives a diagrammatic representation of the TMEMM process used for model analysis, where H is the thickness of the mask, D is the diameter of the exposed anode surface, and G is the distance between the cathode and anode.

In order to investigate both the current density distribution on the workpiece with different thicknesses of the mask and the evolution process of micro-dimples during TMEMM, the following conditions and assumptions were made:

(i) The conductivity of the electrolyte, σ, is constant.
(ii) The temperature of the electrolyte, T, is constant.
(iii) The concentration gradient in the bulk electrolyte is negligible.
(iv) The current efficiency, η, is constant.

The electric potential φ in the interelectrode gap can be approximately described by Laplace's equation [19]:

$$\nabla^2\varphi = 0 \tag{1}$$

The corresponding boundary conditions are as follows:

$$\varphi|\Gamma_1 = U_R\,(\text{At the anode surface}) \tag{2}$$

$$\varphi|\Gamma_5 = 0\,(\text{At the cathode surface}) \tag{3}$$

$$\frac{\partial\varphi}{\partial n}\Big|\Gamma_{2,3,7,8} = 0\ (\text{Insulation boundaries}) \tag{4}$$

$$\frac{\partial\varphi}{\partial n}\Big|\Gamma_{4,6} \approx 0\ (\text{Virtual boundaries}) \tag{5}$$

The current density, i, is provided by Ohm's law, as expressed through Eqs. (6) and (7):

$$I = \frac{U_R}{R} = \frac{U_R\sigma A}{\Delta} \tag{6}$$

$$i = \frac{I}{A} = \frac{U_R\sigma}{\Delta} = \sigma\nabla\varphi \tag{7}$$

where U_R is the applied voltage, R is the equivalent resistance, and Δ is the inter-electrode gap between the cathode and the anode.

According to Faraday's Law, the metal removal rate v can be expressed as follows [20]:

$$v = \eta\omega i \tag{8}$$

where ω is the volumetric electrochemical equivalent of the material. Thus, according to Eq. (8), the metal removal rate depends on the current density distributed over the workpiece during TMEMM.