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Reduction of undercutting in electrochemical micro-machining of micro-dimple arrays by utilizing oxygen produced at the anode

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ABSTRACT

Micro-dimple arrays are widely used as surface textures in tribology to improve friction performance. Through-mask electrochemical micro-machining (TMEMM) is a popular method to generate such arrays. However, machining accuracy is reduced by lateral undercutting of the micro-dimples. In this paper, we present that the oxygen bubbles produced on the workpiece surface during the machining could be employed to reduce undercutting. A thick mask was introduced to prevent escape of the oxygen bubbles from the micro-dimples. Oxygen bubbles accumulating at the micro-dimple edges might protect the edges from etching, thereby reducing undercutting and improving machining accuracy. The experimental results show an undercutting of only about 3 μm with a 250-μm-thick polydimethylsiloxane (PDMS) mask. In particular, there was no increase in undercutting when the applied voltage and machining time were increased. An interesting phenomenon was observed in which there was little increase in depth with increasing voltage, whereas the depth increased with longer machining time. Thus, direct or pulsed current can be used to generate different depths of micro-dimple arrays with low undercutting by simply controlling the machining time, regardless of the applied voltage.

1. Introduction

In materials manufacturing, the process of surface texturing is used to generate a specific groove or dimple pattern on a workpiece surface. As widely reported in the literature, surface texturing has become a popular method in tribology for improving the friction and lubrication performances of various mechanical components [1–3]. This is because a texture distributed over a workpiece surface can act as a fluid reservoir under boundary lubrication conditions, thus improving lubrication between mating components [4].

Among the various surface textures available, micro-dimple arrays have been widely used for improving tribological properties. A number of practical methods have been developed for generating micro-dimple arrays, including conventional micro-turning [5], micro-milling [6], electrical discharge micro-machining [7], chemical micro-etching [8], laser beam micro-machining [9], abrasive jet micro-machining [10], and electrochemical micro-machining (EMM) [11].

Among these, EMM is a promising machining technique that offers the advantages of high machining efficiency; independence of material hardness and toughness; absence of a heat-affected layer; and lack of residual stresses, cracks, tool wear, and burrs. Through-mask EMM (TMEMM) is a popular method used to generate micro-dimple arrays with controlled size, location, and density because thousands of micro-dimples can be generated at one time. In conventional TMEMM, the patterned mask is prepared by photolithography with photoresist at a thickness of 1–20 μm. Using this method, Wang et al. [12] generated micro-dimples with diameters as small as tens of micrometers. Landolt et al. [13] presented a new variation of TMEMM for titanium by using a laser-patterned oxide film. The patterned film was obtained by local irradiation using a long-pulse XeCl excimer laser. Electrochemical dissolution of the irradiated pattern on the workpiece yielded well-defined micro-dimples. However, both the photoresist and oxide film are single-use masks and must be prepared on the anode workpiece before each machining session, making the process time-consuming. Zhu et al. [14] developed a modified TMEMM technique to prepare micro-dimple arrays in which a sheet of insulation layer is coated with a conductive metal layer and perforated with through-holes for use as a mask to electrochemically etch micro-dimples. Compared with conventional TMEMM, the modified mask can be re-used, thus reducing both lead time and cost.

For applications in tribology, the different geometrical properties of micro-dimple surfaces, such as shape, diameter, depth, and area ratio, have been shown to have strong influences on tribological performance [15]. Therefore, the machining accuracy of a micro-dimple array is very important. In TMEMM, dissolution of the metal through the patterned mask always leads to an undercutting in diameter and greater depth. This undercutting enlarges the diameter of the micro-dimple, thereby decreasing the machining accuracy. Therefore, it is important to reduce the amount of undercutting in TMEMM. Usually, undercutting varies continuously with depth. Madore et al. [16] reported that to obtain

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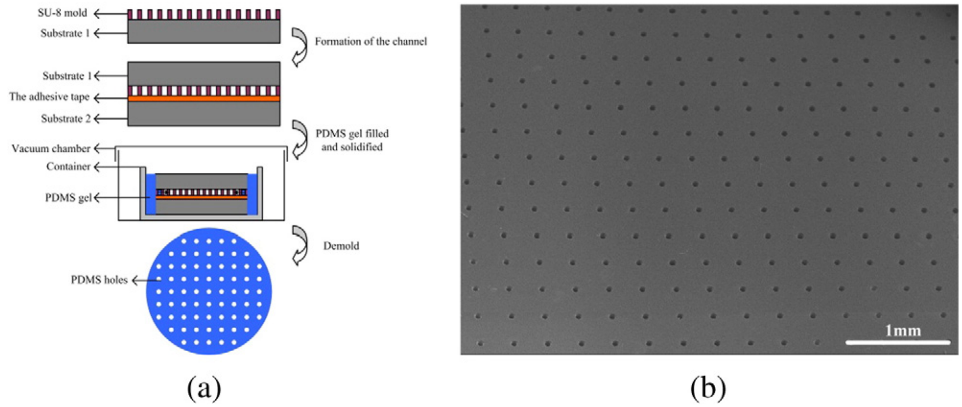

Fig. 1. (a) Fabrication procedure for (b) a PDMS mask with micro through-holes.

micro-dimples with the same diameter at different depths, it was necessary to use specially designed patterned masks of different dimensions, which added to the cost. Qian et al. [17] developed a low-cost modified TMEMM method using an auxiliary anode to reduce micro-dimple undercutting.

Generally, in electrochemical machining (ECM), the oxygen generated on the workpiece surface affects machining efficiency and is usually promptly removed by a flowing electrolyte with high velocity. In this paper, we present that the oxygen bubbles produced on the workpiece surface could be employed to reduce undercutting when micro-dimples are machined using TMEMM. A 250-μm-thick mask was introduced to prevent escape of the oxygen bubbles from the micro-dimple. The resulting accumulation of oxygen bubbles at the micro-dimple edges might protect the edges from etching, thereby reducing undercutting and improving machining accuracy. Experiments were performed to investigate the reduction of the undercutting with this presented method.

2. Material and methods

The procedure of fabricating patterned polydimethylsiloxane (PDMS) masks for generating micro-dimple arrays was described in detail in our previous paper [18]. The main fabrication procedure is shown in Fig. 1(a): (1) the micro-pillar arrays were prepared using photolithography with an SU-8 resist on substrate 1, (2) substrates 1 and 2 were stuck together using a binding agent to form a closed micro-pillar array channel, (3) PDMS gel was injected into the channel in a vacuum chamber and solidified at 70 °C for 0.5 h, and (4) the cured patterned PDMS mask was smoothly peeled from the SU-8 mold. As shown in Fig. 1(b), micro through-holes with diameters of 50 μm were prepared in PDMS masks with thicknesses of 50 and 250 μm.

The TMEMM system shown in Fig. 2 was constructed to generate micro-dimple arrays on a workpiece surface. A cathode was designed with a multi-slit structure to ensure that the electrolyte vertically flowed onto the entire PDMS mask, with the aim of enhancing adhesion between the mask and workpiece during the machining process. A timing switch was used to control the machining time, and a current sensor was used to acquire the current signal. The experimental conditions are shown in Table 1.

Generally, in TMEMM, the metal is dissolved in both the X and Y directions, which results in undercutting as well as increased micro-dimple depth, as shown in Fig. 3. The etch factor EF, which represents the ratio of the etched depth to the distance of undercutting of the micro-dimple, is introduced to evaluate the machining localization of the micro-dimple:

$$EF = \frac{h}{\Delta r} = \frac{h}{r - r_0} \tag{1}$$

where h is the depth of the micro-dimple, Δr is the undercutting of the micro-holes in the mask, r is the radius of the micro-dimple, and r_0 is the radius of the micro-holes in the mask. A high EF reflects a high machining localization.

In this experiment, the dimension of the micro-dimples was measured using a three-dimensional profilometer (DVM5000, Leica, Germany), and a scanning electron microscope (SEM; S-3400N, Hitachi, Japan) was used to examine the micro-dimple arrays.

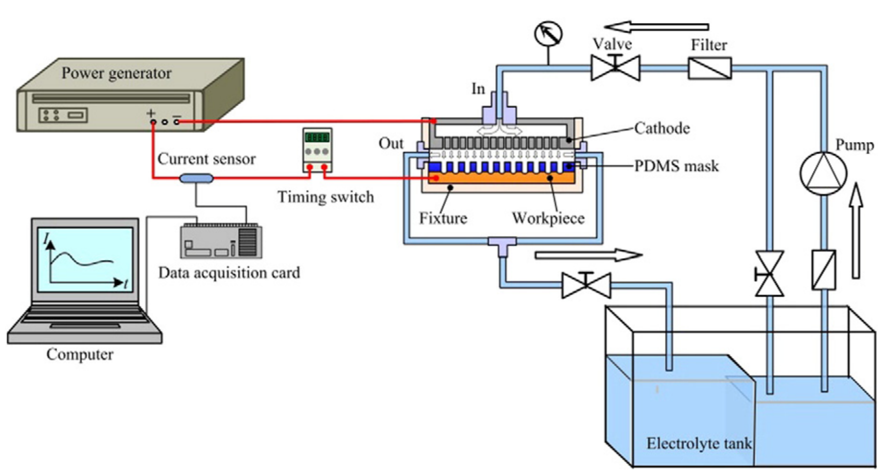

Fig. 2. Schematic diagram of the experimental system.