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Pulsed electrochemical micromachining for generating micro-dimple arrays on a cylindrical surface with a flexible mask

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ABSTRACT

Micro-dimple arrays play an important role in improving the performance and reliability of mechanical systems, and micro-dimples on the surfaces of piston rings and sliding bearings may reduce friction. Although many methods can be employed to create micro-dimples on cylindrical surfaces, it is still a challenge to generate micro-dimple arrays on cylindrical surfaces with high efficiency and low cost. In this paper, a patterned polydimethylsiloxane (PDMS) mask with good flexibility is introduced as a mask in through-mask electrochemical micromachining (TMEMM) for generating micro-dimple arrays on a cylindrical surface, in which thousands of micro-dimples can be fabricated in tens of seconds. In addition, the reusability of the PDMS mask is experimentally verified. To enhance removal of the product, the use of a pulsed current is introduced into TMEMM of micro-dimples. The experimental results show that the pulse duty cycle plays a significant role in enhancing the removal of product and improving the uniformity of the micro-dimple arrays. And the effect was weakened with increasing pulse duty cycle. Compared with duty cycles of 40, 60, and 80%, the highest current efficiency with a duty cycle of 20% is obtained at a frequency of 10 kHz. Finally, micro-dimple arrays with a diameter of approximately 110.6 μm and a depth of 11 μm are successfully generated on the cylindrical surface.

1. Introduction

In recent years, surface texturing at the micrometer scale, such as in the use of micro-dimples, microgrooves, micro-pillars, and micr-prisms, has represented an advanced technology in many fields for enhancing functionality and performance, such as improving optical, biological, tribological, and thermal properties [1,2]. Microprism arrays have been widely used in antireflective surfaces, as the functional surfaces for biomedical applications, and in light guide plates [3]. Superhydrophobic surfaces such as lotus leaves have attracted a great deal of interest, both in academia and in industry because of their self-cleaning properties. Inspired from the structured leaves of the lotus, micro-pillar arrays have been employed to obtain superhydrophobic surface properties [4]. Micro-dimple arrays have also attracted research attention because they can reduce friction, improve mechanical seal performance, and extend seal lifetime by acting as lubricant reservoirs or micro-hydrodynamic bearings. Wakuda et al. [5] found that compared with a smooth surface, a surface with micro-dimples was effective for reduction of friction. Surface texturing on a cutting tool could also increase the tool's lifetime and was found to be useful for difficult-to-machine materials, because it decreases the contact length, reduces rake face friction, and alters the chip compression factor and normal forces [6]. It also has been proved that compared to a smooth surface, a surface with micro-dimples can enhance heat transfer [7].

Although most applications of micro-dimples are based on planar surfaces, the technical application of micro-dimples on cylindrical surfaces is also of great importance, such as on piston rings, sliding bearings and heat exchange tubes [8,9]. A number of techniques have been applied for generating micro-dimple patterns on cylindrical surfaces, for example, turning, milling, electrical discharge machining, chemical etching, laser beam machining, abrasive jet machining, and electrochemical machining (ECM).

Micro-dimples on cylindrical surfaces have been successfully generated using computer numerical control (CNC) turning and laser surface texturing (LST). For example, Ko et al. [10] presented a method for generating micro-dimples on cylindrical surfaces using a piezoelectric tool holder actuator with conventional CNC turning. However, because it was limited by the cutting tool, the roundness

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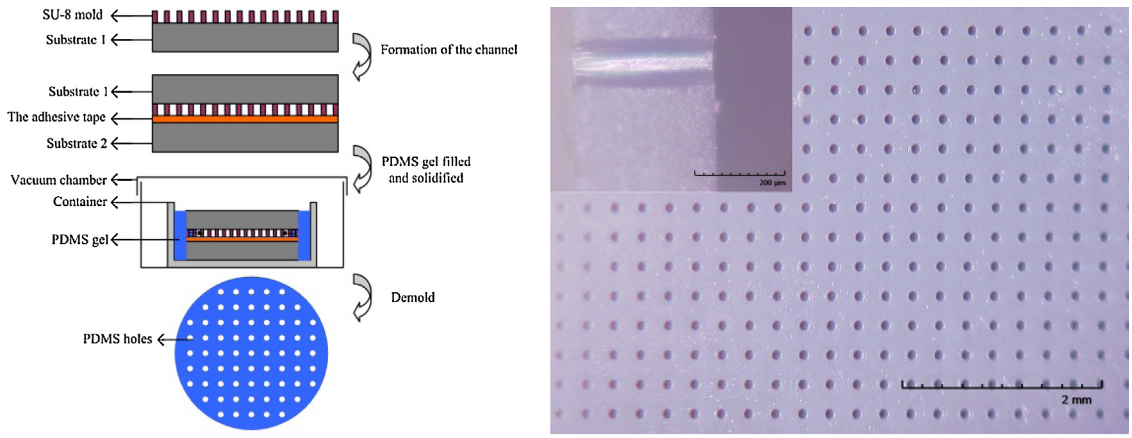

(a) Fabrication procedure. (b) PDMS mask with micro through-holes.

Fig. 1. Fabrication of the PDMS mask with micro through-holes.

of the micro-dimple was difficult to control, and there was a large deviation between its length and width in the cutting direction. Kligerman et al. [8] employed LST to generate micro-dimples on piston rings for reducing the friction between a piston ring and a cylinder liner, but there would be a thermal-affected layer and burrs left on the workpiece. In order to minimize the thermal-affected layer and burrs left on the workpiece, the femtosecond laser non-thermal ablation has been introduced [11]. And the micro-dimples can be well fabricated by femtosecond-laser-enhanced chemical etching process on both planer and cylindrical surfaces [12,13].

ECM has also been used for generating micro-dimples on cylindrical surfaces. This has the advantages of: a high machining efficiency; lack of a heat-affected layer, residual stresses, cracks, tool wear, and burrs; independence of material hardness and toughness; and low production cost. Natsu et al. [14] demonstrated electrolyte jet machining to generate micro-dimples on planar and non-planar surfaces by moving the workpiece or the nozzle. Through-mask electrochemical micromachining (TMEMM) is a common method used to generate micro-dimples, in which the workpiece is covered with a patterned photoresist as a mask. As an advantage, the sizes of the micro-dimples can be controlled by the patterned photoresist, and the micro-dimple arrays can all be generated at the same time. This method has been widely used for generating micro-dimple arrays on planar surfaces. Hao et al. [15] developed a rolling-exposure lithography technique to create micro-dimples on cylindrical objects, in which the exposure angles could be accurately controlled to reduce errors in the sizes of the micro-dimples. This process was complicated because every workpiece must be treated with a coating of the photoresist and must undergo prebaking, rolling exposure, development, and post baking. Qu et al. [16] proposed a method for generating micro-dimple arrays on a cylindrical inner surface using a flexible dry film as a mask, which simplified the processes of coating with photoresist, prebaking, rolling exposure, and post baking. The mask was a single-use mask, no matter whether it consisted of photoresist or a dry film, and so mass production would be expensive because the photolithography process is time consuming and costly. Therefore, it is necessary to explore a low-cost and high-efficiency method for generating micro-dimple arrays on cylindrical surfaces.

With the advantages of chemical resistance, low cost, good flexibility, and high molding capability, PDMS has been widely used in microelectromechanical systems for microchannels, micro-molds, etc. In this paper, a PDMS micro through-hole film is employed as a mask for generating micro-dimple arrays on a cylindrical surface. Because of its flexibility, the mask can be attached to the cylinder. In addition, because of its chemical resistance, there is no damage to the PDMS mask during ECM, and it can be reused.

It has been proved that a pulsed current is useful for improving machining accuracy and enhancing product removal, because each current pulse is followed by a relaxation time of zero current, which allows for removal of reaction products as well as replacement of the electrolyte [17]. Although a pulsed current has been employed in ECM for achievement of higher precisions and better surface qualities [18], it has not been previously introduced in TMEMM for creating micro-dimple arrays. In this paper, a pulsed current is used to generate micro-dimple arrays in TMEMM, and the influences of pulse frequency and duty cycle on the micro-dimple arrays are experimentally investigated.

2. Experimental procedures

The procedure of fabricating patterned PDMS masks for generating microstructures has been described in detail in our previous paper [19]. The fabrication procedure is shown in Fig. 1(a): (1) the micro-pillar arrays employed as the mold were fabricated with SU-8 resist on substrate 1; (2) substrates 1 and 2 were stuck together using adhesive tape to form a micro-pillar array channel; (3) the 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).

In this paper, the material of the cylindrical workpiece was stainless steel 304, and both the diameter and length of the cylinder was 10 mm. Fig. 2 shows a schematic diagram of the experimental setup for generating the micro-dimple arrays on the cylindrical outer surface. As the PDMS mask was flexible, it could be easily attached to the cylindrical workpiece. To enhance the bond between the PDMS and the workpiece surface, the electrolyte was flowed forward onto the PDMS mask. In addition, a circular insulating fixed block with a quarter opening was used to fix the mask. Hence, a quarter of the region on the cylinder can be generated with micro-dimple arrays at one time, and other region was protected by the circular insulating fixed block from being dissolved. Then the cylinder was rotated by 90°, the generated micro-dimple arrays can be protected by the circular insulating fixed block, and another quarter of the region was machined, as shown in Fig. 2. With this method, there would be no misplacement between the micro-dimples generated by different processes, because only the machining region was exposed. With repetition of three times, the micro-dimple arrays can cover the whole cylinder.