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Electrochemical micromachining of micro-dimple arrays on cylindrical inner surfaces using a dry-film photoresist

Qu Ningsong [a,b,*], **Chen Xiaolei** [a], **Li Hansong** [a], **Zeng Yongbin** [b]

[a] *College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*
[b] *Jiangsu Key Laboratory of Precision and Micro-Manufacturing Technology, Nanjing 210016, China*

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Texture

Abstract The application of surface textures has been employed to improve the tribological performance of various mechanical components. Various techniques have been used for the application of surface textures such as micro-dimple arrays, but the fabrication of such arrays on cylindrical inner surfaces remains a challenge. In this study, a dry-film photoresist is used as a mask during through-mask electrochemical micromachining to successfully prepare micro-dimple arrays with dimples 94 μm in diameter and 22.7 μm deep on cylindrical inner surfaces, with a machining time of 9 s and an applied voltage of 8 V. The versatility of this method is demonstrated, as are its potential low cost and high efficiency. It is also shown that for a fixed dimple depth, a smaller dimple diameter can be obtained using a combination of lower current density and longer machining time in a passivating sodium nitrate electrolyte.

1. Introduction

The application of surface textures has been employed to improve the tribological performance of various mechanical components. For example, Kligerman et al. found that partial surface texturing improved the tribological performance of piston rings.[1] Typical surface textures are micro-dimple arrays, prism arrays, pyramid arrays, and micro-grooves, among which micro-dimple arrays have received most attention because the excellent results achieved. Nakano et al. reported that the friction coefficient increases or decreases depending on the geometry of the micro-texture pattern and that lower friction coefficient can be obtained with micro-dimple arrays than with groove- or mesh-patterned textures.[2] Bruzzone et al. found that reductions in friction of 30% or more were feasible with a dimpled surface.[3]A more detailed study by Greco et al., investigating the influence of dimpled surfaces, revealed that the dimensions and layout of the features must be precisely controlled to optimize performance.[4]

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[*] Corresponding author at: College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China. Tel.: +86 25 84893870.
E-mail address: nsqu@nuaa.edu.cn (N. Qu).

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To generate micro-dimple arrays, several micro-texturing techniques, such as mechanical machining, ion-beam texturing, laser texturing, chemical etching, and electrochemical machining (ECM), can be employed. Compared with other methods, ECM is a promising machining technique, with 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.[5–7] The fabrication of micro-dimple arrays by ECM can involve maskless or through-mask material removal. Natsu et al. prepared micro-dimple arrays 300 μm in diameter by electrolyte jet machining without a mask.[8] Nouraeiz and Roy presented a method of maskless electrochemical microfabrication, in which the anode is placed in an electrochemical reactor close to the cathode carrying the micropattern.[9] Costa and Hutchings fabricated micro-dimple arrays with a feature diameter of 120 μm using a maskless electrochemical texturing method.[10] Byun et al. prepared dimples 300 μm in diameter and 5 μm in depth on a workpiece using the micro-ECM technique, with a tool electrode diameter of 275 μm.[11] This method of machining is simple in comparison with photolithographic processes, but is time-consuming because the dimples are fabricated point by point.

Through-mask electrochemical micromachining (TMEMM) is a commonly used ECM method for the generation of micro-dimple arrays. TMEMM employs photolithography to produce micro-patterns on photoresist-coated substrates, with the process involving a soft bake to dry off the solvent after spin coating, exposure to ultraviolet (UV) light, a post-exposure bake, and photoresist developing. The metal is then selectively dissolved from the unprotected areas.[12] However, the preparation of micro-dimple arrays on non-planar surfaces remains a problem, because it is difficult to use photolithography with such surfaces. Wang and co-workers presented a new method for the fabrication of large-scale micro-dimple arrays on cylindrical objects using proximity rolling-exposure lithography and electrochemical micromachining, in which a cylindrical rod covered with photoresist was sub-area-exposed to a collimated UV source through a mask by rotating the rod through a specific angle to expose each area.[13] Micro-dimple arrays with a feature diameter of 40 μm were prepared on the outer surface of the cylinder. Zhu et al. developed a low-cost modified TMEMM method for the preparation of micro-dimple arrays on non-planar surfaces.[14] However, their approach cannot be used to fabricate micro-dimple arrays on the scale of tens of micrometers, because the minimum hole size of the mask is 100 μm. Landolt et al. reported that with the use of oxide film laser lithography instead of a conventional photoresist technique, it might be possible to fabricate micro-dimple arrays on a non-planar surface by electrochemical micromachining.[15]

Micro-dimple arrays need to be produced not only on the outer surface of a hollow cylinder, but also on its inner surface. However, all of the reports mentioned above were concerned with the fabrication of micro-dimple arrays on outer surfaces, and, to our knowledge, little has been published about the fabrication of micro-dimple arrays on inner surfaces. In this paper, we focus on the preparation of micro-dimple arrays on cylindrical inner surfaces by TMEMM.

Dry-film photoresists (acrylate-based photopolymers) have been used as masks for powder blasting, to define microfluidic channels, and as electroplating molds for the LIGA process.[16,17] These films have excellent flexibility, and the study reported here exploits this property by using a patterned dry-film photoresist to cover the inner surface of a cylinder and act as a mask during fabrication of a micro-dimple array on the surface by electrochemical micromachining.

2. Fabrication of a dry film with micro-sized through-holes

The following procedure (illustrated in Fig. 1) was used to prepare the dry film with micro-sized through-holes: ① O_2 plasma treatment for 3 min was first used to clean the substrate; ② the dry film was then laminated onto the substrate; ③ a UV oven was employed to expose the dry film through a photomask; ④ the dry film was then developed for 1 min in an aqueous solution of sodium potassium carbonate at a concentration of 1% by weight at 30 °C; ⑤ finally, the patterned dry film was peeled from the substrate and then applied to the workpiece surface. It is worth noting that no baking step is required in this procedure, which results in a reduction in processing time.

It has been demonstrated that the diameter of the holes formed in a photoresist is determined by the light energy reaching the latter, and hence by the exposure dose. An inappropriate choice of exposure dose and exposure time can result in the occurrence of blind holes in the dry film, as shown in Fig. 2.

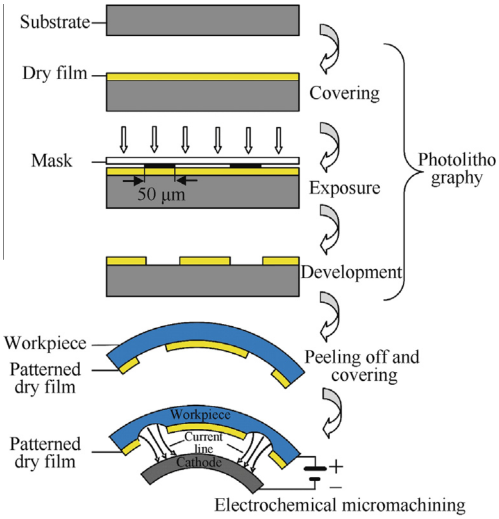

Fig. 1 Through-mask electrochemical micromachining process with a patterned dry film.

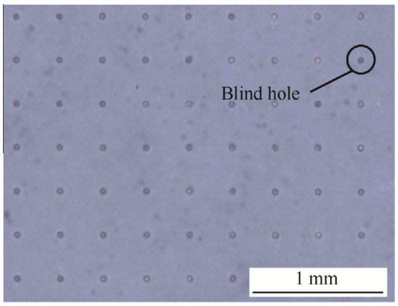

Fig. 2 An example of a blind hole in dry film.