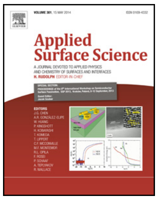
Applied Surface Science 301 (2014) 442–450

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc



Micropatterning on cylindrical surfaces via electrochemical etching using laser masking

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ARTICLE INFO

Article history:
Received 7 November 2013
Received in revised form 13 February 2014
Accepted 17 February 2014
Available online 24 February 2014

Keywords:
Micropatterning
Laser masking
Electrochemical etching
Non-planar surface

ABSTRACT

This paper proposes a method of selective electrochemical dissolution on the cylindrical surfaces of stainless steel shafts. Selective electrochemical dissolution was achieved via electrochemical etching using laser masking. A micropatterned recast layer was formed on the surface via ytterbium-doped pulsed fiber laser irradiation. The micropatterned recast layer could be used as a mask layer during the electrochemical etching process. Laser masking condition to form adequate mask layer on the planar surface for etching cannot be used directly on the non-planar surface. Laser masking condition changes depending on the morphological surface. The laser masking characteristics were investigated in order to form a uniform mask layer on the cylindrical surface. To minimize factors causing non-uniformity in the mask layer on the cylindrical surface, synchronized laser line scanning with a rotary system was applied during the laser masking process. Electrochemical etching characteristics were also investigated to achieve deeper etched depth, without collapsing the recast layer. Consequently, through a series process of laser masking and electrochemical etching, various micropatternings were successfully performed on the cylindrical surfaces.

1. Introduction

Microfabrication technologies for micropatterning have been widely investigated and continuously developed due to their paramount importance in various industries, such as electronics, micro-electromechanical systems (MEMS), micro-total analysis systems (μ-TAS), and miniaturized sensors [1,2]. For instance, the device fabrication of light-emitting diodes on sapphire wafers was developed via laser micromachining with laser micropatterning [3]. The spatial micropatterning of proteins as extracellular matrices for living cells on polyacrylamide hydrogels has been developed by using a polydimethylsioxane (PDMS) stamp and micro-contact printing (μCP), which is a soft lithography technique [4]. One of the most well-established and also most used methods in the micropatterning field is the MEMS fabrication process, which is based on photolithography techniques. Although the photolithographic techniques are suitable for large production, the MEMS fabrication process has limitations in terms of its application to non-planar surfaces, such as limitations regarding the depth of focus of the source lights [5]. As the demands for micropatterning on large areas of non-planar surfaces increases, several methods of micropatterning on curved surfaces were reported. Nanosecond laser machining has been used for surface texturing and micropatterning on non-planar surfaces [6]. However, a heat-affected zone with possible microcracks inside the material and low dimensional accuracy were generated by the nanosecond laser. Micro-electrochemical machining (ECM) using ultrashort pulses was used to fabricate microdimples on cylindrical surface of stainless steel in order to reduce the friction between mechanical components, but the material removal rate was very low in comparison to those of other machining processes [7]. The faster fabrication of micropatterns was carried out via electrochemical etching using a flexible stencil mask [5]. The flexible PDMS stencil was fabricated via a photolithography process and used as a mask on a non-planar surface during electrochemical etching. Despite the fact that micropatterns on a large area can be achieved via electrochemical etching, a flexible PDMS stencil mask was inappropriate for microsize patterns. The hydrophobicity of the PDMS surface makes it difficult for the electrolyte to fill in the micro-sized patterns. Additionally, the process of making the stencil mask requires a high cost due to the expensive experimental equipment involved.

Electrochemical etching that has high selectivity, and a relatively high etch rate was often used to fabricate a large area of micropatterned surface. Electrochemical etching is generally

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http://dx.doi.org/10.1016/j.apsusc.2014.02.095
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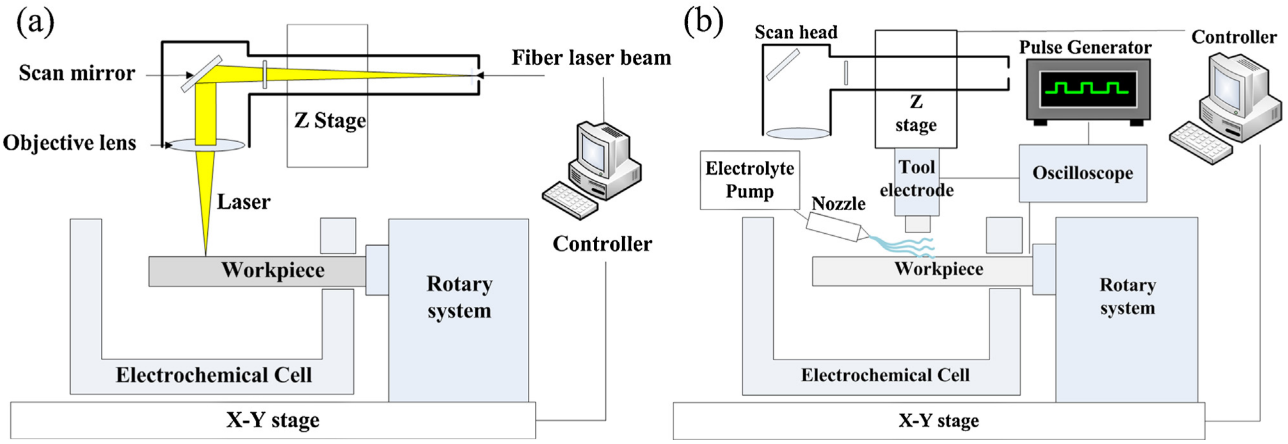

Fig. 1. Schematics of system configuration: (a) experimental setup for laser masking system and (b) experimental setup for electrochemical etching system.

conducted in conjunction with a photoresist mask, which creates complex processing steps, high costs, and difficulty in coating a uniform patterned mask on the non-planar surface. These limitations can be compensated for via the laser masking process. The protective layer that is formed through laser masking could be used as a mask during electrochemical etching [2,8]. Furthermore, the laser masking process brings the advantages of quickness and low cost in various patternings because the masking process is carried out in the air and does not require photolithography at all. Thus the fabrication of micropatterning on non-planar surfaces could be conducted under normal experimental conditions without any expensive equipment, such as clean room and vacuum chamber. The purpose of this research is the development of a process for micropatterning on non-planar surfaces without a specific mask that complicates the process and increases costs due to expensive experimental equipment. To achieve the purpose, a serial process involving laser masking and electrochemical etching was investigated and presented.

However, the laser masking characteristics change along the geometrical surface because the workpiece's surface is non-planar. Therefore, an investigation of the factors causing the non-uniform formation of the mask layer was performed. The characteristics of electrochemical etching were also investigated to improve the etching depth after the formation of a uniform mask layer.

2. Experimental setup and details

The experimental setup for the process consists of a rotary system, a pulsed fiber laser system for laser masking, an electrochemical etching system, and an ultrasonic vibration cleaning system. Platinum was used as the tool electrode, and a stainless steel (AISI 304) rotary shaft 3 mm in diameter was used as the workpiece. The surface of the workpiece was observed via a scanning electron microscope (SEM) and the surface profile of the workpiece was measured via a 3D surface profiler (Nano View-E1000, Nanosystem Corp).

The workpiece was clamped to the constructed rotary system, and the rotational speed of the workpiece was controlled during the laser masking and electrochemical etching processes, as shown in Fig. 1. The rotational speed of the workpiece should be synchronized with the laser scanning speed during the laser masking step to form an appropriate recast layer that can be used as a mask layer during the electrochemical etching step. Also, the rotational speed of the workpiece should be controlled during the electrochemical etching step to achieve micropatterning that has a uniform etching depth along the entire area of the cylindrical surface of the workpiece.

Table 1
Experimental conditions for laser masking [2].

Parameters	Value (unit)
Peak power density	0.34 MW/mm^2
Marking speed	19.6 mm/s
Line spacing	10 μm
Spot size	43 μm

During the laser masking step, the stainless steel workpiece that was clamped to the rotary system was irradiated by an ytterbium pulsed fiber laser in the air. A micropatterned recast layer was created on the surface via the laser beam irradiation, which was controlled via a galvanometer. An ytterbium (Yb)-doped pulsed fiber laser (IPG Photonics Corp.) that had a 1064 nm wavelength and a 100 ns pulse length was attached to a *Z*-axis moving stage for the focusing of the laser beam, as shown in Fig. 1(a). A galvanometer scanning system (SCANLAB AG SCANcube® 10) allowed the laser beam to be transmitted flexibly at a high scanning speed. All the experiment conditions for the laser masking are shown in Table 1.

After the laser masking, electrochemical etching was the next step. The surface of the workpiece was electrochemically etched with a continuous supply of electrolyte via a circulation pump. Fig. 1(b) shows a schematic of the system configuration of the electrochemical etching. The electrochemical etching system consists of a tool electrode, which is attached to a *Z*-axis moving stage; an electrochemical cell, the rotary system, an electrolyte circulation pump, a pulse generator and an oscilloscope. The tool electrode was scanned above the workpiece, which was rotated by the rotary system. The electrolyte was circulated and flushed onto the workpiece surface by the circulation pump to eliminate sludge, such as $Fe(OH)_2$ or $Fe(OH)$, during the electrochemical etching. The experimental conditions for the electrochemical etching were described in Table 2: the anodic dissolution of the stainless steel was conducted in 2 M sodium nitrite ($NaNO_3$) electrolyte, and pulse voltages were applied via a pulse generator.

Table 2
Experimental conditions for electrochemical etching.

Parameters	Value (unit)
Pulse on-time	50 μs
Pulse period	500 μs
Electrolyte	2 M $NaNO_3$