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The formation of convex microstructures by laser irradiation of dual-layer polymethylmethacrylate (PMMA)

Jiang Li, Wenjun Wang *, Xuesong Mei, Xuefeng Sun, Aifei Pan

State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710054, China
Shaanxi Key Laboratory of Intelligent Robots, Xi'an 710049, China

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ABSTRACT

This work presents the fabrication of convex structures by laser irradiation on dual-layer polymethylmethacrylate (PMMA). The surface PMMA layer can prevent gaseous product from escaping and the high absorption of underlying black PMMA layer can ensure enough gas products produced. It is shown that convex structures can only be formed in a particular focus range. The focus position range for appearance of convex structures is determined in our experiments to be 180–400 μm. And then the dependences of height and diameter of convex structures on pulse energy, pulse number and film thickness of surface layer have been investigated. The result demonstrates that the size (both diameter and height) of convex structures could be tuned by pulse energy; compared with the diameter, the height of convex structures is more sensitive to pulse number and film thickness of surface transparent layer. The formation of convex structures is attributed to the sensitively balanced combination effect between the softening of surface material and expansion of underlying material. Finally, large-area-arrays of convex structures with high consistency and variable tunable sizes were generated. The diameter and height of convex structures were measured to be 149 μm and 43 μm, respectively.

1. Introduction

Microlens arrays have been widely used in many optical devices, organic light emitting diodes, biochemical systems, and artificial compound eyes [1–5]. During the past decades, various methods have been proposed to fabricate microlens, which can be classified into laser-based methods and non-laser-based methods. Non-laser-based methods generally includes lithography [6], thermal reflow [7,8], and imprinting [4,9]. However, these techniques are not only complex, but also commonly vulnerable to size uncontrollable and untenable [7,9].

Laser-based methods offers some advantages compared with non-laser-based method, such as direct writing and contactless etching [10]. For this method, structures could be fabricated either by the laser ablation effect [11–18] or by the swelling effect of laser-material interaction [10,19–23]. However, irregular surface accompanied by poor finish is usually created by the ablation method [12,18,24]. While for the swelling method, on one hand, a regular convex structures with highly smooth surface could be fabricated due to the fact that the reaction region resides inside the material, leaving the surface unperturbed [25]; on the other hand, this method is capable of fabricating structures on non-planar surface [23].

At present, there are two methods to fabricate convex structures by laser swelling, namely rear-side modification [23] and front-side modification [24–26]. Until now, few studies have been reported for fabrication of convex structures by rear-side modification. The reasons could be a relatively large energy transmittance loss or requirement of transparent substrate. Currently, fabrication of convex structures is mainly by means of front-side modification and it is considered to be an appropriate method to create convex structures. But it still suffers from size limitation and poor uniformity of large area preparation [10]. The reasons are as follows: Firstly, if the laser beam focus on the sample surface, convex structures only appears when laser intensity well below the ablation threshold of the material [19,20,27], which not only result in poor controllability of laser energy, but also largely limit the size of convex structure; otherwise, ablation process starts [20,26,28], leading to failure for formation of convex structures. Secondly, for mono-layer transparent material, if laser beam focus inside the material, unneglectable amount of energy would be expended because of diffusion or transmission [25]; while for non-transparent material, the high absorption would prevent energy from penetrating inside the material. Consequently, in order to improve the controllability

* Corresponding author at: State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710054, China.
E-mail address: wenjunwang@mail.xjtu.edu.cn (W. Wang).

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and tunability of convex structures, a method to both focus the laser beam inside the material and improve the absorptivity of material is necessary.

In this work, we fabricated convex structures with controllable sizes, high consistency and wide tunable range by laser front-side irradiation on the dual-layer PMMA. The surface non-doped PMMA could protect gaseous product from escaping; the underlying doped PMMA could ensure production of enough gaseous product. Convex structures were firstly obtained by optimizing focus position. And then the influences of pulse energy, pulse number and film thickness of surface layer on morphology of convex structures are investigated. Finally, with the help of replica technology, microlens were formed. The imaging performance of microlens was tested.

2. Method and experimental section

2.1. Sample preparation

The film was generally prepared by using PMMA crystal and chlorobenze as starting materials. The process was as follows: The commercial available PMMA (20 g) crystal was dissolved in chlorobenze (80 g), mixed and stirred at a speed of 1200 rpm for 24 h using magnetic stirring apparatus. The 20% concentration of solution was obtained. Subsequently, PMMA solution (50 μL) was carefully squeezed out of a 200 μL micro-syringe, was deposited uniformly on a commercial available black acrylic plate (20 mm × 20 mm). The transparent PMMA film was measured to be 56 μm. Finally, the sample was covered tightly with a petri dish to create a confined space and dried at room temperature overnight.

2.2. Experimental section

The laser used for irradiation was a Ti: sapphire amplifier operating at 800 nm with pulse width duration of 120 fs and a repletion rate of 1 kHz. The energy distribution profile of beam was Gaussian with a quality factor of $M^2 = 1.3$. The laser beam was incident normal to the sample surface and focused using a 0.60 NA objective lens in our experiment. Samples were placed on a motorized translation stage (DaHeng photoelectric technology co., Ltd) with high accuracy to allow sample to move in three perpendicular axes. Spot sizes can be calculated from the formula: $d = 1.22\lambda/NA$, where d is the diameter of focused spot, λ is the wavelength, and NA is the numerical aperture of microscopic objective lens. The diameter was estimated to be 1.6 μm.

The experimental setup diagram is shown in Fig. 1. The whole system consisted of two parts: optical system and motion controlled stage. The optical systems consisted of laser head, diaphragm, half-wave plate, and polarization splitting prism. A diaphragm was used to shape the laser beam. A half-wave plate and polarization splitting prism was used to adjust laser power, which was measured by a power meter. An electromechanical shutter was used to adjust the pulse number delivering to the sample. The laser beam was propagated through the optical system, focused by an objective lens and normally irradiated onto the sample that fixed on the motorized xyz stage.

2.3. Sample characterization

The field emission scanning electron microscopy (Hitachi) was used to observe the surface morphology of resulting microstructures after laser irradiation. The Laser scanning confocal microscopy (Olympus OLS4000, Japan) was used to characterize the film thickness, morphology and profile of convex structures. The SMZ 1500 stereomicroscope (Nikon, Corporation, Tokyo, Japan) was used to characterize the cross section of prepared sample.

3. Results and discussion

3.1. Formation of convex structures

3.1.1. Experimental results

Focus position, the distance of focal point from the surface of the material, is of great importance for the final morphology on the surface of PMMA because that the focus position directly determines the energy distribution inside the material. In order to obtain convex structures, we firstly studied the evolution of focus-position-dependent morphology under laser irradiation and determined the focus position range that can produce convex structures.

Experiment was carried out on the set-up described above. Convex structures was fabricated by laser irradiation on dual-layer PMMA. The material of upper layer of the prepared sample was transparent PMMA, and the underlying material was doped PMMA. We obtained microstructures with pulse energy of 30.4 nJ, pulse number of 1000, film thickness of surface transparent layer of 56 μm, focus position ranging from −20 to 400 μm.

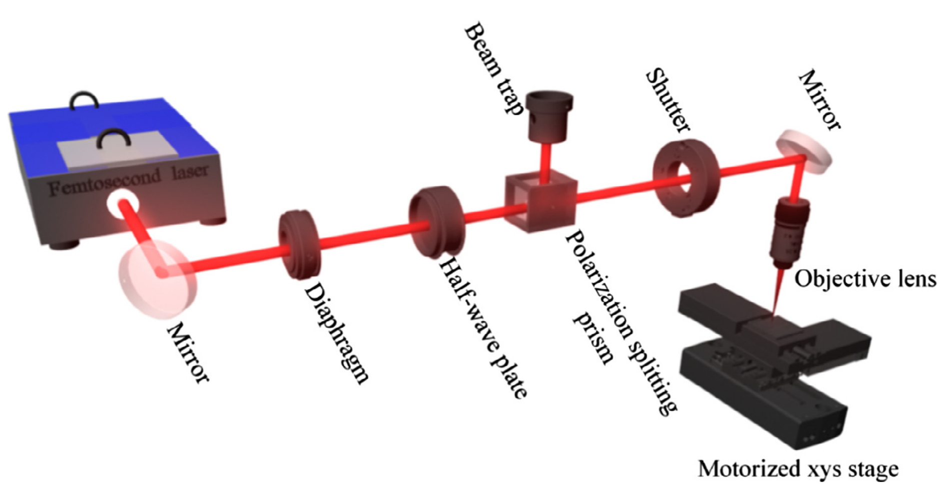

Fig. 1. Schematic diagram of experimental setup.