Technical Communication

Using Femtosecond Laser to Fabricate the Interior 3D Structures of Polymeric Microfluidic Biochips

Chia-Yu Lee[1], Ting-Chou Chang[1], Shau-Chun Wang[1*], Chih-Wei Chien[2], Chung-Wei Cheng[2*]

*[*1]Department of Chemistry and Biochemistry, National Chung Cheng University, Chia-Yi, Taiwan, R.O.C.*
E-mail: chescw@ccu.edu.tw (S.C. Wang)
*[*2]ITRI South, Industrial Technology Research Institute, No. 8, Gongyan Rd., Liujia Shiang, Tainan County 734, Taiwan, R.O.C.*
E-mail: CWCheng@itri.org.tw (C.W. Cheng)

We have successfully employed femtosecond laser to craft microstructures on polymeric substrate to imbed micro-mixiers. Since the laser pulse is ultra-short, the heat affected zone is not significant. Therefore the thermal melting damage is not as severe as that using continuous carbon dioxide laser. As a result, using femtosecond laser the fabrications of reproducible and defined micro-structures are able to accomplish. These structures can be used to generate micro-vortices using the mechanisms of induced electro-osmosis, one unique technique developed in our laboratory. The dimensional reproducibility of microstructures was observed with scanning electron microscopy. In addition, using attenuation total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) to inspect the laser fabricated surface of polymeric substrate, we have acquired the spectrum of polymer moieties showing that photothermal effects are also more pronounced than photochemical effects in the fabrication processes to avoid surface reactions. An example of a micro-mixer with three dimensional microstructures about 800 μm x 400 μm x 65 μm on the last slide for transparent glycerol and glycerol with red dyes mixing is presented.

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1. Introduction

In recent years, the femtosecond laser has been reported as a technique for processing of materials with high precision. Compared with long-pulsed (nanosecond or longer) lasers, the laser ablation using femtosecond laser is focused on the materials highly to reduce the thermal and mechanical effect and to improve the quality of components [1-3]. Therefore, undesired defects could be avoided to obtain well-shaped structures.

Femtosecond laser technology has been recently applied to the micromachining of microstructures in dielectrics due to the advantages associated with nonlinear multiphoton absorption while pulse energy is focused within the point of a material. Microfluidic chip of plastic materials has attracted considerable attentions recently in analytical, biological, diagnostics and biomedical research, mainly because of its advantages of low cost, reagent saving, changeable bulk material properties, device portability, and disposability [4, 5]. To fabricate microfluidic devices, polymers play an important role compared with conventional materials such as silicon and glass. The microfabrication methods of polymer can be divided into two main groups, replication methods [6] such as hot embossing and injection molding and direct method such as laser ablation [7, 8]. Some studies reported that femtosecond laser was firstly applied to fabricate poly (methyl methacrylate) (PMMA) [9, 10]. A number of research groups have reported devices fabricated with femtosecond laser in PMMA, such as tubular waveguides [11, 12] and microchannel [13], due to its benefits of highly transparency and rugged material.

In this paper, to characterize the chemical compositions of polymeric surface after femtosecond laser fabrication, we have used attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy. ATR-FTIR is a powerful tool providing a convenient non-destructive method to qualitatively characterize polymer properties. The evanescent wave may penetrate a sample into one depth of a few microns when the ATR incident light approaches; moreover, most of the absorbance information may be considered as being derived from depths about 0.3 - 3 μm. In addition, we have used scanning electron microscopy (SEM) to observe the morphological features of microstructures.

In this paper, we have fabricated 3D microstructures imbedded in microfluidic chip as mixing components by using a femtosecond laser ablation and characterized chemical compositions on the surface and the shape of microstructures by ATR-FTIR and SEM technique.

2. Materials and Method

The experiments for fabricating interior 3D microstructures were performed using a near infrared femtosecond laser, based on a mode-locked Ti:sapphire laser (Spectra Physics, Spitfire Pro) with a regenerative amplifier system, producing pulses of ~120 fs duration at a wavelength of 800 nm, repetition rate 1 kHz. The per pulse radiation in this paper was maintained at 2 μJ, which is the energy to ablate materials of PMMA substrate. The experimental setup used in the experiment is displayed in Fig. 1. Light from the femtosecond laser beam with a Gaussian profile was minimized by λ/2 wave plate and beam splitter. The laser beam is focused onto the planar PMMA workplace through shutter, reflective mirrors system and a 10X objective lens with a numerical aperture (N.A.) of 0.26 (Mitutoyo, M Olan Apo NIR) fixed on a Z stage. The beam diameter was 5 μm. The thermoplastic PMMA slides were industrial available from local store.

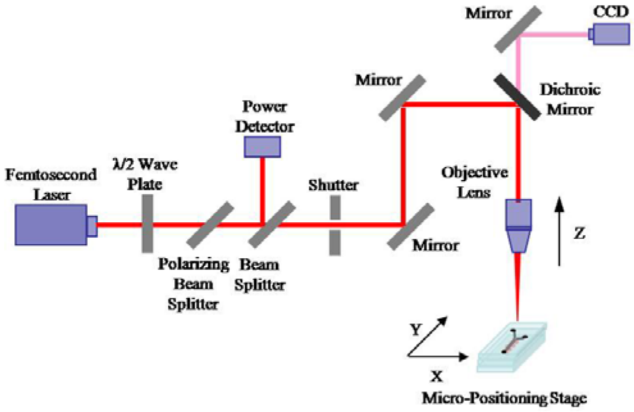

Fig. 1 Schematic illustration of the experimental setup for fabrication of microstructures.

The schematic diagram of micromixer is shown in Fig. 2. The dimensions were 45 mm x 20 mm x 2 mm. We decomposed the sketch into three parts. Among them, we drilled three holes on the top one and carved flow channel of Y-shape by CO_2 laser marker (Universal, V460) on the middle one. Microstructures (800 μm x 400 μm x 65 μm) were fabricated on the last slide with femtosecond laser. The three slides were bound together as a component of micromixer and placed with a clamping apparatus. The clamping apparatus with micromixer were set on the X-Y translation stage, space resolution of 1 μm to be scanned, and microstructures were fabricated by moving X-Y stage controlled by computer. CCD camera was located behind the objective lens to observe the process of laser ablation. The fabricated structures can be used to generate micro-vortices using the mechanisms of induced electro-osmosis, one unique technique developed in our laboratory [14].

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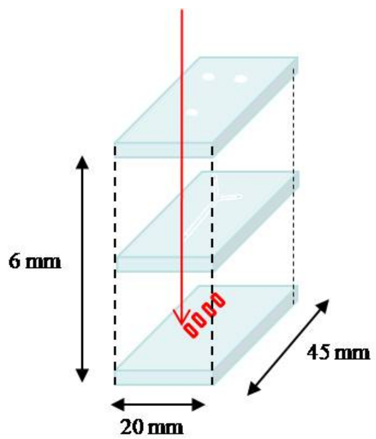

Fig. 2 Schematic illustration of micromixer. We decomposed the sketch into three parts. The red arrow indicates the laser beam.

3. Results and Discussion

3-1. Microstructures ablation experiment

In this experiment, femtosecond laser was used to manufacture the microstructures on the surface of thermoplastic PMMA substrates which is imbedded in microfluidic chip. At the beginning of this experiment, femtosecond laser was focused on the surface of PMMA slide to fabricate microstructures. Microstructure was created with 2 μJ laser energy at repetition rate 1 kHz. While stage moving rate was controlled over 0.5 mm/s, the laser beam wrote across the chip for two times. The overlapping between two laser strokes was 50%. According to Fig. 3, the edge of microstructure was not smooth and covers with many debris pieces after ablation.

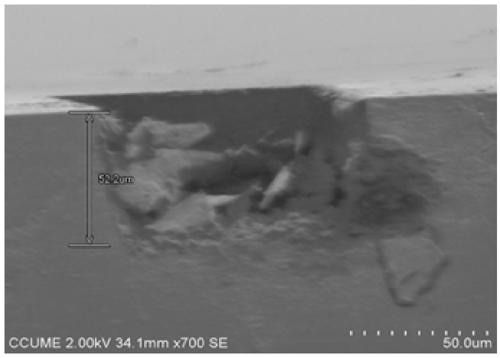

Fig. 3 SEM image of coarse microstructure fabricated with two consecutive strokes laser focused on the surface of PMMA slide.

In the second writing procedure, the stage Z-axis was raised for 5 μm to defocus the laser radiation and stage moving velocity was increased as 2 mm/s to sweep the debris. This method is also known as “a low laser fluence finishing” which could decrease laser energy and avoid the shape out of expected as much as possible. The SEM image was shown in Fig. 4 to demonstrate one well-shape structure.

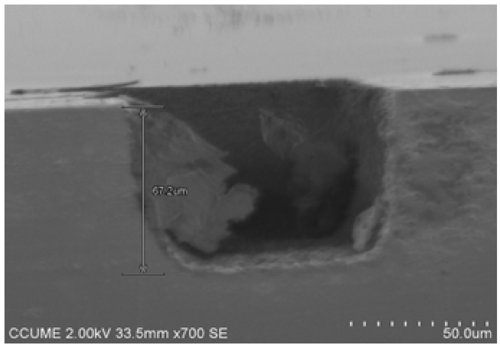

Fig. 4 SEM image of polished microstructure using the procedure described in the content.

In order to totally remove the debris, we further increased stage Z-axis to 10 μm to write the structure with defocused beam one more time and to observe the dimension of microstructure, which was nearly close to what we expect (Fig. 5). The microfluidic chip was finally immersed in an ultrasonic bath at room temperature for 1hr to eliminate the remnant debris.

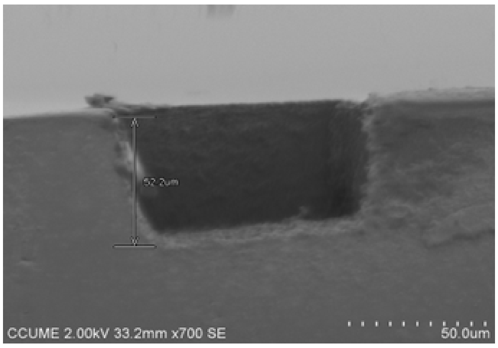

Fig. 5 SEM image of final finished microstructure.

We use the optimized procedures to create two separate microstructures of low variations imbedded in microfluidic chip. Fig. 6 shows the SEM images of microstructures in the same PMMA slide.

(a) (b)

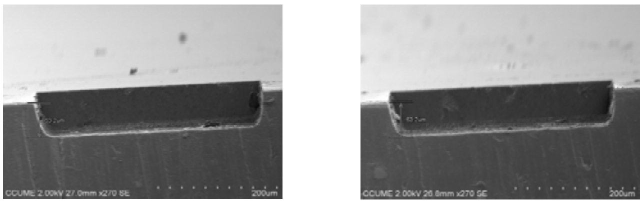

Fig. 6 SEM images of microstructures fabricated with femtosecond laser ablation. Images of microstructures in (a) and (b) are two separate microstructures on the same PMMA slide.

As indicated in the images, there are no depth differences while width and length difference are less 0.8 % between these two separate microstructures. The table 1 is shown the comparison between the structures. The roughness on the bottom of the microfabricated structures was measured and the average roughness Ra values ranges between 120 and 250 nm. We have concluded one successful fabrication technique to create three dimensional structures of high precision.

Table 1 Dimensional deviations of microstructures measured with SEM.

No. of structure	Length (μm)	Width (μm)	Depth (μm)
1	790	385	63.2
2	792	382	63.2
Error %	0.25%	0.78%	0%

3-2 Chemical composition characterization of polymeric surface treated with femtosecond laser

The chemical functional groups on plastic surface were inspected using ATR-FTIR when the substrate was ablated with femtosecond laser. We used laser energy 6 mW, 9 mW and 27 mW to work on PMMA within the area of 3mm x 3mm. We have observed the changes of spectra treated with different laser energies which are showed at Fig 7.

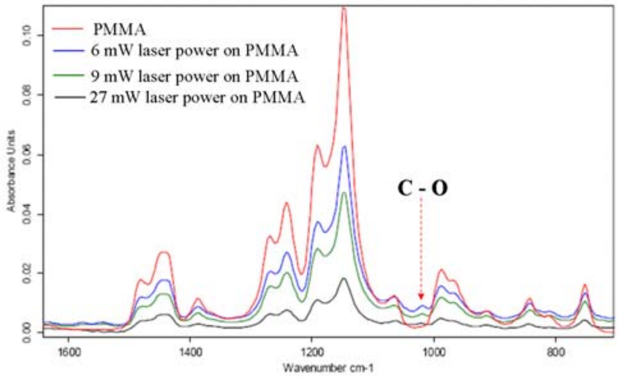

Fig. 7 Spectra of PMMA polymeric surface treated with different laser energies.

We found intensity ratio of C-O production peak (1018 cm^{-1}) to reference peak (1150 cm^{-1}) was risen up while laser energy became stronger (Table 2). The change of C-O functional group is mainly due to photo-decomposition. So laser fabrication is dominated by an optical-thermal process since the decomposition was minor. Optical-thermal effect expected to be more significant than optical-chemical effect in this region, so that the chemical bond is less decomposed.

Table 2 The change of CO functional group intensity under different laser energy treatment.

	Intensity (1018 cm^{-1})	Intensity (1150 cm^{-1})	Intensity ratio
PMMA	0	0.099	0
6mW	0.001	0.052	0.019
9mW	0.001	0.039	0.026
27mW	0.001	0.015	0.067

Figure 8(a) and (b) show a schematic illustration of the mixing results. We used two separate fluids which is transparent glycerol solution and the other is glycerol solution with red dye. It is conducted to the Y-shape microchannel with syringe pump and observed the results in a high frequency AC electro field. The designed microstructures have the ability to increase the uniformity and efficiency in the short time. We compared the consequences with AC field started and closed with microscope. It can be observed that micro-mixer has obvious electro-osmotic and mixing result finished within 30 seconds when AC field started. Fig. 8(b) shows it can not have the uniform mixing result when transport by diffusion with no induced electro-osmotic vortex.

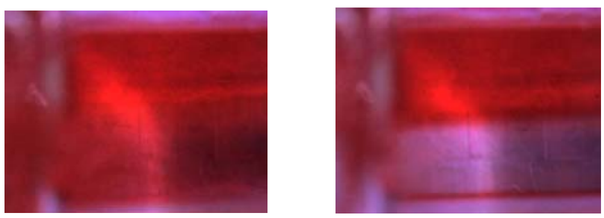

Fig. 8 (a) Result in AC field on (b) Result in AC field off at 30sec

4. Conclusions

We have demonstrated one femtosecond laser micromachining method to fabricate microstructures on PMMA imbedded in a flow channel, which is potentially used as a micromixer. The high precision of microstructure dimensions is accomplished. Besides, we found the alternations of spectrum after femtosecond laser treatment via ATR-FTIR.

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