Femtosecond laser induced microripple on PDMS surface

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We find the femtosecond laser induced microripple beside the focused femtosecond laser spot and along the movement direction of the laser spot on polydimethylsiloxane (PDMS) surface. The microripple may be due to the melting of PDMS induced by femtosecond laser pulses and the subsequent cool-down solidification of the melting PDMS along with the movement of the femtosecond laser spot. This result will be helpful to understand the interaction between the femtosecond laser and the polymer.

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In the past few years, femtosecond lasers have been widely used in the investigations of semiconductor[1], transparent materials[2−4], and metals[5−7]. Microstructures have been found on the surfaces of materials after the irradiation of femtosecond laser. Wang *et al.* reported femtosecond laser induced periodic surface pattern formation on metals[8]. When a metal surface is irradiated by femtosecond laser beam, periodic energy distribution can be formed along the sample surface because of the interaction between the incident light and surface fields[9]. The formation of the surface ripples is regarded to come from the nonuniform surface energy distribution. Her *et al.* reported microstructuring of silicon with femtosecond laser pulses[10]. The formation of ripples on the surface of Si has been attributed to the interference between incident wave and surface wave, which induces periodic field on the surface of substrate and ultimately leads to periodic surface structure. In this letter, we report that the microripples on polydimethylsiloxane (PDMS) will be formed by using the femtosecond laser pulses. The finding should receive enough attention for femtosecond laser micromaching of PDMS [11,12].

Femtosecond lasers are used to write lines on the surface of PDMS film. Along the lines, microripples are found on the PDMS surface beside the focused laser spot. The shape of the microripples is found to be dependent on the polarization state and power of the femtosecond laser. PDMS is different from metals and Si. The explanations of microripples in metal[8] and silicon[10] are not appropriate to the microripples formed on PDMS. When the laser writes on the PDMS surface, the PDMS under laser irradiation is ablated. The zone near the ablated region is melted and deformed. As the laser spot moves away, the melting zone cools down and the microripples are left on the PDMS surface. A simple explanation of bow wave is used to explain the formation of the microripples.

The experimental setup is shown in Fig. 1. The laser system was a commercial 76-MHz Ti:sapphire laser oscillator (Coherent Inc.), delivering 90-fs, 10-nJ laser pulses at 800 nm. The central wavelength and pulse duration were measured by a home-made Dammann frequency-resolved optical gating (FROG) setup[13]. An isolator was used to block the reflected light back into the laser oscillator. The laser beam was split into two beams by a beam splitter (BS1). One beam was used to monitor the spectrum by using the spectrometer (InSpectrum, ACTON), the other beam passed through the attenuator (ATT) for suitable intensity for micromaching PDMS. The laser pulses were focused by a microscope objective (numerical aperture NA = 0.25) onto the surface of the PDMS film (Sylgard 184, Dow Corning) vertically. The thickness of the PDMS film was 6 μm, which was measured by Taylor Hobson Step Height Standard. The glass substrate was mounted on a motorized translation stage (NAI Company) with a minimum step of 30 nm. In the experiment, the translational speed of the stage with sample was 0.21 mm/s. In the letter, we call "the relative laser moving" for easy illustration. The translation stage and the spectrometer were controlled by a computer.

When the PDMS film is processed by the laser, it will emit yellow light. The yellow light is reflected by the beam splitter BS2 and comes into the power meter. The laser reflected from the PDMS surface is absorbed by the light filter. The power meter is used to monitor the power of yellow light, which indicates whether the sample surface is at the focus of the objective lens. When the laser power is 130 mW, the PDMS will be obviously ablated by the laser. When there is no ablation, the yellow light will not be received by the power meter. Moving the PDMS

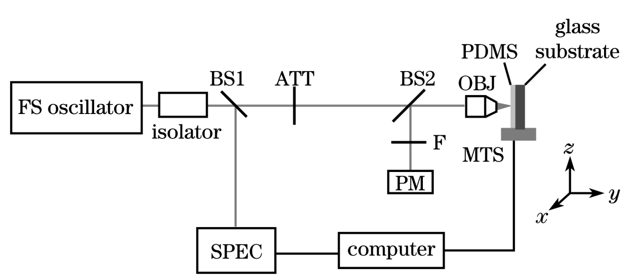
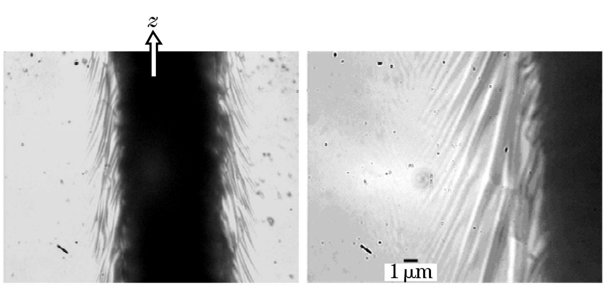


Fig. 1. Experimental setup for micromachining PDMS. FS oscillator: femtosecond laser oscillator; BS1 and BS2: beam splitters; ATT: attenuator; OBJ: objective lens; F: light filter; PM: power meter; MTS: motorized translation stage; SPEC: spectrometer.

through the motorized translation stage for the maximum value of the power meter, the PDMS surface should be located in the focus of the microscope objective. In order to detect the diameters of spots on the PDMS surface, a charge-coupled device (CCD) was placed at the same place of the PDMS. When the CCD surface was located in the focus of the microscope objective, the spot radius was 9 μm.

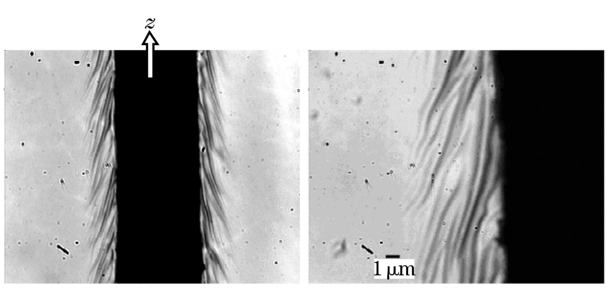
When the power of the femtosecond laser is 125 mW, the PDMS will be just damaged by the femtosecond laser. This was chosen to be the initial point of the micromachining on the PDMS surface. Then the laser power was reduced to 60 mW, and the sample was moved along the z direction (Fig. 1) from the initial point for ablation. The reason for the laser with lower power can ablate the sample is that the absorption efficiency of the laser energy of the ablated part is much higher than that of the unablated part. Moving the sample along the z direction and decreasing the power continually, we can observe different microripple formation. When the power is higher than 60 mW, there are few microripples along the ablated line due to the cracks formed on the PDMS surface. The microripple is thinner and the distribution is not uniform. When the power is decreased to 40 mW, the regular microripples are formed and two lines are processed on the sample by linearly polarized light and circularly polarized light, as shown in Figs. 2 and 3, respectively. If the power is smaller than 20 mW, no microripple will be formed. The microripples formed on the surfaces of materials are normally obtained with a relatively low laser power, which happens similarly in other materials[8,10].

The widths of the ablated lines are roughly 30 and 27 μm in Figs. 2 and 3, respectively, and the maximum height of the microripples is about 1 μm, which are measured by the Taylor Hobson Step Height Standard. It is obvious that the edge of the ablated line in Fig. 3 is more clear and regular than the one in Fig. 2, which is similar to the cleaner edge obtained with the circularly polarized femtosecond laser than the linearly polarized in micromachining of other materials[14]. The femtosecond laser scanned from the bottom to the top of the samples. There are microripples at both sides of the ablated lines. The width of the ridge of the microripple is about 0.5–1 μm. There is an acute angle between the roughly oriented directions of the microripples and the laser writing direction. The microripples in Fig. 2(b) are straighter than that in Fig. 3(b). It means that the formation of the microripples is related to the polarization of the laser, which is similar to the experimental result in glass[15].



(a) (b)

Fig. 2. Optical microscope images of microripples on PDMS surface formed by linearly polarized femtosecond laser. (a) 40× magnified image, z denotes the relative laser moving direction; (b) 100× magnified image.



(a) (b)

Fig. 3. Optical microscope images of microripples on PDMS surface formed by circularly polarized femtosecond laser. (a) 40× magnified image, z denotes the relative laser moving direction; (b) 100× magnified image.

The experimental phenomenon appears very similar to bow waves from a ship running in the water. The melting temperature of PDMS is low. When the femtosecond laser irradiates on the PDMS surface, the material around the laser spot is fused. When the laser spot moves on the PDMS surface, the material is deformed and the bow waves are produced with the relative laser movement. After the laser spot moves away, the fused material is cooled down and microripples remain on the surface of PDMS. The concrete forming process of the microripples is complex and further research should be done in the future work.

In conclusion, microripples are found in the processing of the PDMS by moving the femtosecond laser. There is an acute angle between the microripples and the ablated line. The movement of the laser spot on the surface of the PDMS and the melting of the material induced by femtosecond laser are able to produce microripples. The shape of the microripples is related to the power and polarization of the laser. A bow wave explanation is put forward to elucidate the experimental phenomenon. The physical mechanics of the microripples on PDMS surface is different from the microripples formed on metals and Si. Consequently, the finding of the microripples should be interesting for us to understand the interaction between femtosecond laser and polymer.

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