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Processing microstructure on film by femtosecond laser

DONG-QING YUAN[1, 2], MING ZHOU[2*], LAN CAI[2], JIAN-TING XU[3]

[1]Department of Mathematics and Physics, Huai Hai Institute of Technology, Lianyungang, Jiangsu, 222069, China

[2]Center for Photo Manufacturing Science and Technology, Jiangsu University, Zhenjiang Jiangsu 212013, China

[3]Dong Gang College, Huai Hai Institute of Technology, Lianyungang, Jiangsu, 222069, China

*Corresponding author: mz_laser@126.com

Selective laser patterning of thin films in a multilayer film is an emerging technology for fabrication of MEMS devices. A 775 nm Ti:sapphire laser (130 fs, 1 kHZ) was used to irradiate the thin film stacks with variations in process parameters such as feed rate and numerical aperture of objective lens. Femtosecond laser patterning of Au/Cr films which have the same thickness of about 1000 nm and are coated on glass substrate has been investiged to determine optimal parameters of the patterning process. Through a SEM and an AFM, we investigate the morphology of pattern, including the linewidth, groove depth and the laser-induced periodic surface structures (LIPSSs). The depth of the ablated groove was observed to depend on the scanning speed. And from the energy spectrum we find out which layer has been removed completely. The experimental results show that precise micromachining with desired stability and reproducibility can be achieved by controlling the ablation energy and the feed rate using appropriate numerical aperture (NA).

Keywords: femtosecond laser, Au/Cr film, process, microstructure.

1. Introduction

Due to increasing applications of nanostructures in numerous fields nanostructuring of a variety of materials is gaining widespread importance. Laser-induced surface structuring in silicon has been extensively studied [1–4]. Many studies had demonstrated the advantages of femtosecond laser pulses over longer laser pulses, including a negligible heat affected zone, well-defined ablation threshold, high repeatability and efficiency, highly precise control of ablation geometry, absence of plasma shielding effect and the ability to ablate sub-diffraction limited features [5, 6]. Femtosecond lasers are also capable of processing a wide variety of materials [7–9].

Combining those characteristics, femtosecond lasers as versatile tools have been used to process various micromachining where micrometer and submicrometer feature sizes are required. Some of the potential industrial applications include production of medical devices [10], photonic devices (*e.g.*, gratings, waveguides) [11], micro-mechanical devices [12]. Studies into the process with femtosecond pulses on metal film have been reported by a number of research groups [13]. Micromachining of thin metallic film has wide applications in high-density data storage and semiconductor microelectronics. Metal films, especially gold layers, play a significant role as mirrors and parts of compressor gratings in the path of short pulse laser beams.

In this paper, we study the laser direct ablation of thin Au/Cr film using femtosecond pulsed laser beam and report experimental results and discuss the relationship between the scanning speed and the depth of the ablated groove. Analytical tools used to study the properties were scanning electron microscopy (SEM) and atomic force microscopy (AFM).

2 . Experimental set-up

A schematic diagram of experimental set-up is depicted in Fig. 1. A commercial femtosecond Ti: sapphire laser system was employed in our experiments, which was based on the chirped pulse amplification technique. This system provides laser pulses at a wavelength of 800 nm and repetition rate of 1 kHz, the pulse length of the laser being about 130 fs. The laser beam was introduced into the optical system which was based on a fluorescence microscope. In the experiment, we adjust the pulse energy to 300 nJ. The output beam was in the TEM_{00} mode with Gauss profile. The laser beam was focused by a microscope objective lenses of different numerical apertures on the surface of the Au/Cr films sample which was mounted on a computer controlled

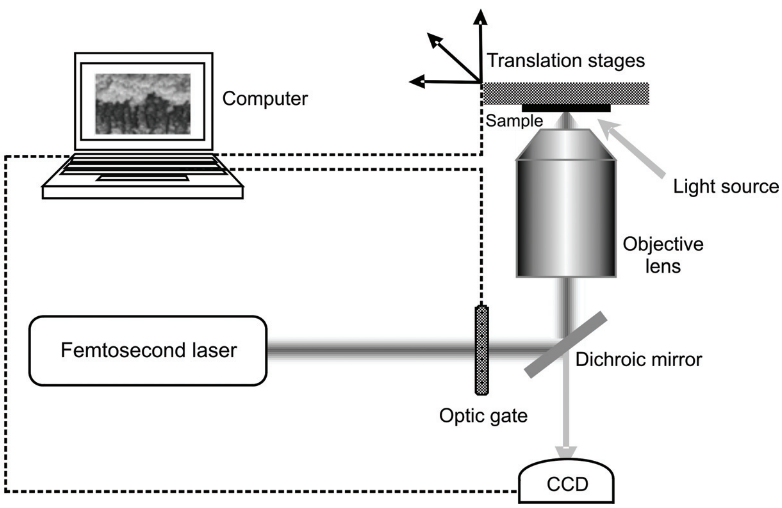

Fig. 1. Experimental set-up for micromachining film by femtosecond laser pulses.

x−*y*−*z* translation stage having a resolution of 100 nm. The sample was moved at scan speed ranging from 100 μm/s to 10000 μm/s.

The surface morphologies of the grooves and patterns machined in different irradiation conditions were examined using SEM and AFM.

3. Results and discussion

We use objective lens with different numerical aperture (NA = 0.2, 0.25, 0.4, 0.6) to study the morphologies of microstructure on film at the pulse energy of 300 nJ. Figure 2 gives SEM images of groove which were ablated at laser pulse energy of 300 nJ, and the scanning speed of translation stage was 1000 μm/s. For NA = 0.2

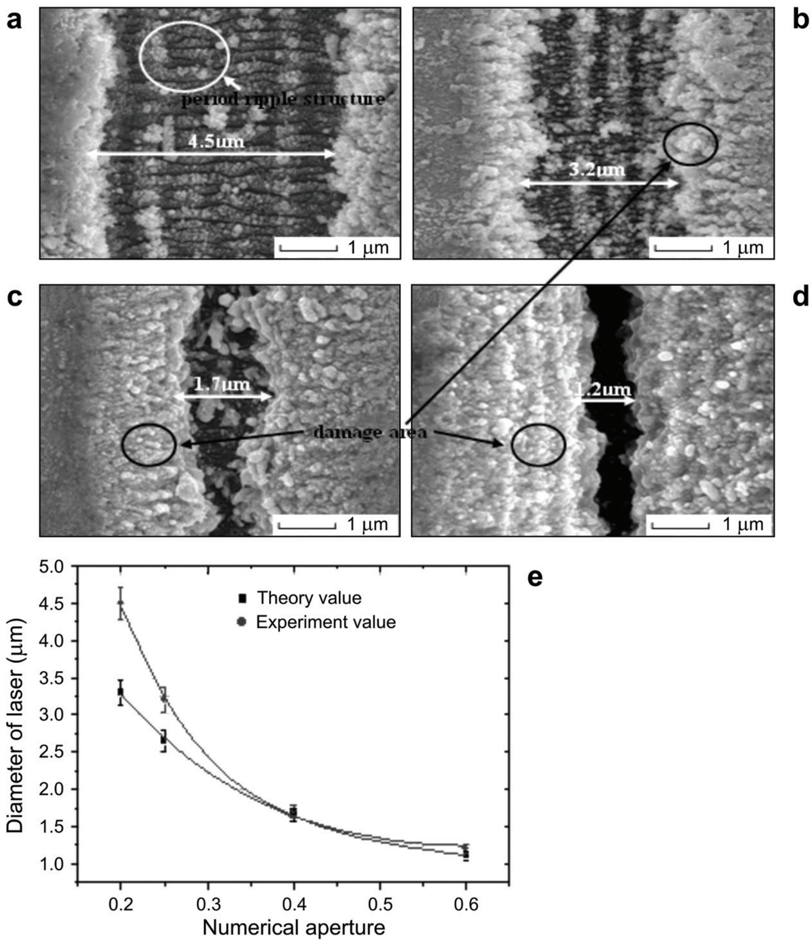

Fig. 2. SEM images of groove which were ablated at laser pulse energy of 300 nJ, and the scanning speed of translation stage was 1000 μm/s at different numerical aperture: NA = 0.2 (**a**), NA = 0.25 (**b**), NA = 0.4 (**c**), NA = = 0.6 (**d**). The curve of relation between NA and beam diameter (**e**).

the image of groove where of the width 4.5 μm is depicted in Fig. 2**a**. We can ascertain that the periodic ripples were formed on the glass by the energy spectrum line. Ripple structures with a spacing significantly smaller than the irradiation wavelength have been observed. A preliminary explanation for the formation of subwavelength ripples is the interaction of the incident wave with surface electro-magnetic waves (SEW) [14]. Figure 2**b** shows the image of groove when NA was 0.25. We can find that the width of the groove was about 3.2 μm, and the ripple structures were still clear. But there exist damage area on the surface of the film. Figure 2**c** displays the image when NA was 0.4. The ripple structure disappeared in this situation, and the width of groove was about 1.7 μm. Figure 2**d** shows the image when NA was 0.6, and the width of groove (d) was about 1.2 μm. Also, the ripple structure does not appear. This is because of the ripples appearing most strongly at intensities close to the ablation threshold. The relationship between the diameter of beam and the numerical aperture is depicted in Fig. 2**e**. When determining the pulse energy and the scanning speed, the width of the groove was reduced when the value of numerical aperture increased. The following equation shows the relation between the diameter of groove and NA [15]:

$$d = \frac{2}{\pi} M^2 \frac{\lambda}{\mathrm{NA}}$$

where the quality of the beam M^2 was found to be 1.3 in this experiment. The wavelength of pulse λ, was found to be 800 nm. The difference between theoretical value and experimental value becomes more evident at lower NA, as shown in Fig. 2**e** for NA = 0.2, 0.25, 0.4 and 0.6. Although, the diameter was decreased for the case of high NA at certain pulse energy and scanning speed, but the damage area was enlarged. In this experiment, the pulse energy was kept unchanged. The fluence was increased when the diameter of spot was diminished. So, the substrate and the films, a breakdown occurs by higher fluence, then the ripple structure disappears.

To study the cutting quality in more detail, the ablated grooves were analyzed by the images captured by AFM. Figure 3 shows the change of the groove depth with the scanning speed increasing when the pulse energy was 300 nJ and NA = 0.25. Figures 3**a** and 3**b** show the 3-D profile and the cross-section profile, the scanning speed being 1000 μm/s, 5000 μm/s and 10000 μm/s. It shows that the groove depth decreases with the scan speed increasing, but the groove width does not change significantly. The shape of the groove matches the Gauss profile, as depicted in Fig. 3**b**. Based on numerous experiments, the effect of scanning speed on the depth of groove is shown in Fig. 3**c**. We can see two trends as regards the curve. At lower scanning speed (100–1000 μm/s), the depth of the groove decreases from 2.1 μm to 1.4 μm. At higher speed (1000–10000 μm/s), the depth varied very little. When the speed increased from 100 to 400 μm/s, the change in the depth was about 100 nm; when the speed increased from 500 to 1000 μm/s, the extent of depth change was about 600 nm. In this experiment, the frequency of the laser was 1000 Hz, that is, the irradiation on the sample surface was 1000 pulses per second, *e.g.*, when the scanning speed was 1000 μm/s, the distance between two pulses was about 1 μm on average, at

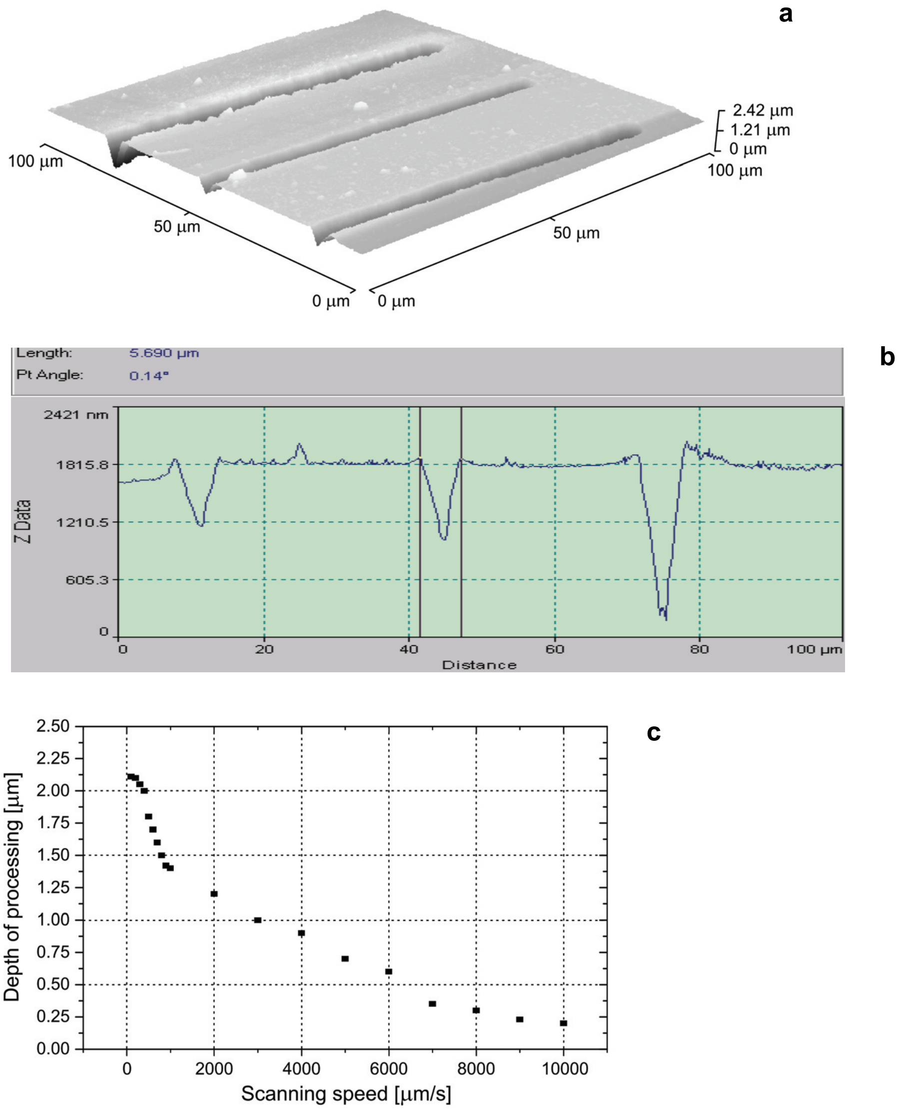

Fig. 3. AFM image of ablated groove with pulse energy of 300 nJ, NA = 0.25 at different scanning speed: 3-D profile of groove by AFM (**a**); cross-profile of depth (**b**); the curve fitted by scanning speed and the depth of ablated groove (**c**).

the same time, the diameter of focus beam was about 3.2 µm and the superposition rate of sequence pulses reached 80%. So, when the speed ranged from 100 µm/s to 400 µm/s, the fluence of a laser was higher than in the case of glass. Then, the film was ablated completely, the depth change corresponding to that of the glass. With the speed increasing from 500 to 1000 µm/s, the fluence of the laser diminished and was lower than the threshold of the ablation of glass. Then the change of depth corresponded to the ablation rate of the film. For the high speed region, *e.g.*, when

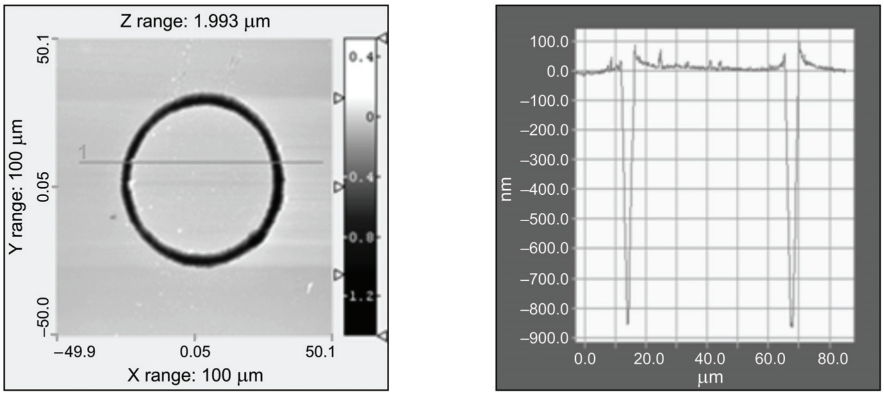

Fig. 4. The AFM image of the pattern of a circle which was processed by the femtosecond laser with pulse energy of 300 nJ, NA = 0.25, and scanning speed 3000 μm/s.

the scanning speed was 7000 μm/s, the distance between two pulses was about 7 μm on average, and the diameter of focus beam was about 3.2 μm, so the film ablation was due to the discontinuum pulse. Upon boosting the speed, the fluence of was kept unchanged. So the rate of the depth changing was very small.

The experimental results show that precise micromachining with desired stability and reproducibility can be achieved by controlling the pulse energy and the scanning speed as well as the numerical aperture. Figure 4 shows the pattern of a cirlce which was processed by the femtosecond laser with pulse energy of 300 nJ, NA = 0.25 and the scanning speed of 3000 μm/s. We can see that the boundary of cutting was very smooth, the depth was very consistent about 850 nm. So, by controlling the parameters of the experiment the process can be obtained.

4. Conclusions

Femtosecond laser patterning of Au/Cr films which have the same thickness of about 1000 nm and are coated on glass substrate has been investiged to determine the optimal parameters for patterning process. Using SEM and AFM we investigate the morphology of pattern including the linewidth, groove depth and the laser-induced periodic surface structures (LIPSSs). The ablation depth was observed to be dependent on scanning speed when keeping the pulse energy and the NA unchanged. The experimental results show that precise micromachining with desired stability and reproducibility can be achieved by controlling the ablation energy and the feed rate using appropriate numerical aperture (NA).

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