Polarisation-independence of femtosecond laser machining of fused silica

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Abstract

Laser direct processing of glass has been challenging due to the brittle nature and poor heat transfer characteristics of the material. With the advancement of ultrashort pulse lasers, laser direct machining of glass with smooth surface and free of microcracks has become a potential manufacturing technique in microfabrication of optical devices. In this paper, machining of microgrooves on fused silica substrates using a p-polarised femtosecond laser beam was investigated with regards to the groove profile and surface morphology. Microchannels with width and spacing of 20 μm were produced with no microcracks. Repeatable sub-micron gratings within a microchannel along the cutting direction were also observed. These microchannels and gratings may be used for the manufacture of optical and microfluidic devices. The beam polarisation was found to have little effect on the machining results.

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1. Introduction

Micromachining of transparent materials has found increasingly more applications in the optoelectronics and telecommunications industries. Application examples include fabrication of optical gratings and integrated circuits that comprise of waveguides, switches, multiplexers, attenuators, add/drop filters, directional couplers, as well as all solid-state lasers and oscillators. Laser microprocessing has the potential to be used for the manufacture of these devices.

Glass machining with long pulse lasers has been very challenging as the laser-induced thermal stress often leads to microcracks. Redeposit of molten glass on machined surfaces is difficult to remove, which significantly reduces the surface quality. With advancement of ultrashort lasers, surface as well as sub-surface machining has been the focus of many studies recently [1–6]. Ultrashort (femtosecond or Fs) laser pulses offer many advantages over long pulse lasers (nanosecond). Fs-laser has a characteristic time scale that is far shorter than thermal diffusion length, which makes heat transfer to the surrounding layers...
minimal and generates insignificant amount of liquid phase. Absence of liquid phase allows better control of the machining process [7]. Therefore, any energy transfer to the target material is confined to a very small volume. Precise materials removal with minimal heat affected zone is important in electronics [3,5], biomedical [6] and photonics applications [1,2,4]. It is known that the maximum efficiency of long pulse laser cutting is achieved when the cutting direction is parallel to the oscillation plane of the electric field vector [8,9]. However, the beam polarisation effect on Fs-laser machining is not clearly understood. It has been reported that the laser beam polarisation did not influence the cutting speed in linear cutting of silicon wafer [10]. In the same report, it was reported that the beam polarisation did have a major influence on the exit surface quality of the cuts. Best results were achieved when cutting vertically to the polarisation direction (linearly-polarised beam) [10]. In another report, circularly-polarised laser beam was preferred for uniform cutting of silicon wafers [11]. It was also reported that ripple-like structures were formed upon Fs-laser irradiation on various materials. The orientation of the ripples was influenced by the laser beam polarisation. Ripples were oriented to be perpendicular to the beam polarisation for TiN and silicon [12–14], whereas to be parallel to the beam polarisation for polyimide [15,16]. From the literatures, it appears that the beam polarisation effect on Fs-laser machining varied depending on the substrate materials to be processed. To our knowledge, the beam polarisation effect on Fs-laser machining of fused silica has not been reported.

2. Experimental set-up

The substrate used was a UV grade fused silica with thickness of 1 mm. It has thermal coefficient of expansion of $0.55 - 0.57 \times 10^{-6} \, ^\circ\text{C}^{-1}$ that makes it an ideal candidate for high repetition rate laser processing. The Fs-laser emits 775 nm beam with pulse duration of 150 fs. The beam is p-polarised. A typical beam profile measured with a CCD-based laser beam profiler (SPIRICON, LBA-PC Series) is shown in Fig. 1. The focal length of the focusing lens is 50 mm. Machining was carried out by cutting in the direction parallel ($y$-direction) and perpendicular ($x$-direction) to polarisation of the p-polarised beam at a given power density and moving speed. The circularly polarised beam was also used to machine grooves. Surface morphology of the laser-cut grooves was examined using both optical microscope and scanning electron microscope (SEM). The machined profiles were further characterised with a stylus profiler (Taylor Hobson Precision Talyscan 150).

Fig. 1. A typical beam profile of the Fs-laser: (a) 2D, (b) 3D.
3. Results and discussions

The optical micrographs of microchannels machined using the p-beam are shown in Fig. 2(a and b), where Fig. 2(a) shows cutting in the direction parallel to polarisation (y-direction) and Fig. 2(b) shows cutting in the direction perpendicular (x-direction) to polarisation, respectively. The laser power and sample moving speed were set at 36 mW and 50 μm/s. The average power density was calculated to be 7.75 kW/cm² based on the cut width of 20 μm. It was observed that the microgrooves were straight with consistent cut width for both cutting directions. No difference in cut width was observed for cutting in the different directions.

The same microchannels were also analysed with the SEM showing the detailed surface morphologies (Fig. 3a and b) and with the stylus profiler showing depth and 3D profiles (Fig. 4a and b). It is clearly shown that the microchannels are V-shaped with an average depth of about 6 μm. The centre portion of the microchannels is deeper due to the higher power intensity in the centre of the beam (Fig. 1). The laser-machined microchannels in both cutting directions are very similar in terms of depth, profile and surface morphologies. The side surfaces have granular...
Fig. 4. (a) 3D and depth profiles of the microchannels shown in Fig. 2(a), cutting in the direction parallel to beam polarisation. (b) 3D profile of microchannels shown in Fig. 3(a), in the direction perpendicular to beam polarisation.
structures with no indication of microcracks or melting. Some waviness along the cut edges was observed, which was the effect of the stage movement and beam overlaps.

It is very interesting to observe that at higher magnifications (Fig. 5a and b), there exist regular sub-micron gratings on the side surfaces near the bottom of the microchannels. These gratings have width and spacing of about 400 nm and exist in both figures, where the cutting directions are different. The exact reason for the formation of the sub-micron gratings is not known. Judging from the feature size that is roughly half of the laser wavelength, these gratings may be the result of beam interference due to multiple reflections from the tapered side-walls and bottom surface (as fused silica is transparent to the 775 nm beam) during the laser processing.

It was further observed that the electron beams interfered to form interference patterns when scanning over the microchannels (Fig. 6). This indicates that the laser-machined microchannels are potentially useful for grating applications.
4. Conclusions

Crack-free microchannels were realised in fused silica substrates with a p-polarised Fs-laser beam by moving the substrates in the direction parallel and perpendicular to the polarisation orientation, respectively. These microchannels have clearly defined edges, consistent width and cross-sectional profiles.

The regular sub-micron features (400 nm in width) are potentially useful for the manufacture of gratings and microfluidic devices.

The beam polarisation did not show significant effect on the machined quality in terms of cut width, depth, profiles and surface morphologies.

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References