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Precision glass machining, drilling and profile cutting by short pulse lasers

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Abstract

Demands for producing micro-crack free, high quality and high-aspect ratio microholes and microfeatures in glass substrates have been increasing for a number of applications such as in MEMS device packaging, optical fibre alignment, mini-vision systems and microelectronic packaging. However, due to the poor thermal properties of most glasses the fabrication of finely machined features e.g. grooves, microholes etc. has been a challenging task. In this study, short pulse solid-state lasers with pulse duration in the ns to fs range were used to process different types of glass materials. The effect of the pulse duration and other process parameters on the machined features was analyzed to reveal the underlying thermal effects and nonlinear processes. Edge quality, circularity, aspect ratio, formation of the redeposit material and machining rate were also studied with respect to the process variables such as focusing optics, laser power, wavelength and repetition rate. Arrays of drilled micro-hole patterns and fabricated microfeatures are demonstrated with discussions on their potential applications.

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1. Introduction

Small components free of micro-cracks, good edge and surface quality as well as with a high aspect ratio, made of hard materials such as ceramics and glass, are difficult to fabricate and often require complex, multi-step processing. On the other hand, demands for microholes and microfeatures in these materials have been increasing for a number of miniature product applications such as in MEMS device packaging, optical fiber alignment, mini-vision systems and microelectronic packaging. Direct write laser processing, in which the material removal occurs at high power densities during the laser ablation process, has been demonstrated as a powerful technique. Compared to other conventional techniques of machining glass, laser machining offers a number of advantages such as single-step processing, high flexibility, direct writing of features by integrating CAD/CAM software, high speeds, no contamination and sterility. Precise focusing of the laser beam allows material removal with high accuracy, high repeatability and localized material removal with micron size tolerances [1]. However, due to the presence of thermal effects, the spatial resolution available from conventional, wider pulse lasers operating at visible and infrared wavelengths of the spectrum is limited. At present, there are mainly two ways to overcome this limitation. One way is to use UV laser wavelengths that can be focused down to smaller spot size and thereby reduces the extent of thermal damage around the machined edges [2,3]. During processing, materials having a higher absorption coefficient in the UV region, tend to concentrate the absorbed energy in relatively smaller volume resulting in controllable material removal. The other approach is to use ultra-fast lasers with much shorter pulse durations, e.g., in the picosecond (ps) or femtosecond (fs) regimes [4-6]. It is clear from the literature that the energy coupling into the materials at ultra-fast time scale significantly reduces the thermal effects during processing [7,8]. Additionally, the ultrafast laser pulses can induce multiphoton absorption and other non-linear optical effects, which can be of significant advantage to fabricate precise

microfeatures in a controlled fashion [9,10].

Glass is one of the most important materials in optoelectronic devices and other industrial applications with a high transmission from the UV to IR wavelength region, excellent thermal and electrical properties, and high chemical resistivity [11,12]. Furthermore, the glass properties are controllable by adjusting the composition during development and fabrication. However, these very properties make the glass a challenging material to machine [1,13]. Due to poor thermal properties, fabrication of finely machined features using laser-based processes e.g. grooves, channels, microholes, stand-alone levers etc. in glass materials has been quite a difficult task. Although a significant amount of efforts were expended in using the simulation methods, analytical techniques and the experimental observation of morphologies of micro-structures/features [14-23], comparative discussions are lacking primarily due to the fact that the individual results have been obtained under different laser conditions and specific experimental arrangements. In this study, short pulse solid-state lasers with pulse duration from ns to fs regime and laser-induced plasma machining technique have been used to process different types of glass materials under comparable experimental conditions. The effect of the pulse duration and other process parameters on the feature qualities and its formation is analyzed to reveal underlying thermal effects and nonlinear processes. Edge quality, circularity, aspect ratio, burrs formation, re-deposition of materials and machining rate were also studied with respect to the process variables such as focusing optics, laser power, wavelength and repetition rate. Examples of arrays of drilled micro-hole patterns and fabricated microfeatures are included with discussions on their potential applications.

2. Experimental details

Figure 1 illustrates a schematic diagram of the workstation used in this study for the laser micro-machining of glass samples. The laser beam was focused onto the sample surface through a beam expander and a fused silica lens or a microscope objective, mounted on the Z-axis translation stage. The lasers used in this work, include a Q-switched Nd:YVO₄ laser operating at 532 nm wavelength with pulse width 3 ns and a repetition rate of 1 kHz. A frequency-tripled Nd:YAG laser, operating at 355 nm wavelength with pulse duration ranging from 10-30 ns, and an ultrafast Ti:sapphire laser (Clark MXR 2000) at operating at its fundamental 775 nm wavelength having a fixed pulse duration of 150 fs and a repetition rate of 1000 Hz was also used. Depending on the experimental arrangement, different optical configuration was chosen and the optical beam path was modified to meet the process requirements. For femtosecond laser machining experiments, a $\frac{1}{4}$ wave plate was introduced into the beam path to convert the original *p*-polarized beam in to a circularly polarized beam and the beam was focused on to the glass surface using a 50 mm focal length lens.

The samples were held on to a mount fitted to the computer-controlled X-Y translational stage. The resolution of the translation stages was $\pm 1 \mu\text{m}$. Corning microscope slide, commercial Vitrocom S-105, doped silica and fused silica capillary fibers were used as sample glass materials. The morphology of the sample specimens was observed using optical microscopes, scanning electron microscope, and the WYKO interferometric profiler (NT-2000).

3. Results and discussion

3.1. Laser micro-machining of grooves in glass using nanosecond lasers

The frequency-tripled Nd:YAG laser beam at 355 nm wavelength was focused on to a sample surface in ambient with an 8X beam expander and a plano-convex lens having a focal length

of 50 mm. The minimum spot diameter available was approximately 7 μm at beam waist. The sample was machined at a scan rate of 2.5 mm/s during the machining process. Figure 2 illustrates the laser micro-machined grooves on the glass surface under a number of focused and defocused conditions. The central grooves in Fig. 2(a) and (b) (marked by arrows) represent the optimum machining with the best focusing conditions. The grooves from left to right represent conditions when the focusing lens moved away from the sample surface consistently in steps of 25 μm in the upward z-direction for each neighboring groove. Machined surface grooves with noticeable cracks can be found in Fig. 2(a). The large cracks in the glass were produced when the high intensity laser beam was directly focused on to the surface. Using careful selection of experimental parameters such as wavelength, intensity, repetition rate, sample surface conditions, scanning rate, etc. to control the thermal process interactions, high quality, crack-free laser machined micro-features can be produced in the glass material. These results are evident in Fig. 2(b) in which no cracks were observed in the fabricated grooves under both focused as well as slightly defocused conditions. However some amount of debris accumulation was noted at the edges. This debris can be removed using a secondary cleaning process after laser machining procedures. Figure 3 shows magnified images of the laser-processed glass surface for different pulse energies ranging from 50, 100, 150, and 241 mJ/pulse from (a) to (d) respectively, under optimal focusing conditions and corresponding to the laser fluence of 0.65×10^6 , 1.30×10^6 , 1.95×10^6 and $3.14 \times 10^6 \text{ W/cm}^2$ respectively. It is apparent that the groove width control can be realized by judicious adjustment of the laser power density and the beam spot overlap.

3.2. Laser cutting and hole drilling of glass using nanosecond lasers

Upon the development of optimal process parameters, the applications of high quality, crack-free laser micro-processing method, was used to machine complex features on a number of

glass materials. In Fig. 4(a), a complex feature in the shape of letter “S” was laser cut in Vitrocom S-105 glass material. The total feature size was 1.7×1.4 mm and the thickness of the glass material was 630 μm . The width of the feature was about 250 μm . In order to obtain burr-free machining, a solvent-based masking material MAC-STOP 9554 from MACERMID Inc., in the form of thin film, was applied initially to the material surface. The film, approximately 125 μm thick, was stripped off manually after the cutting operation. Application of the maskant film reduced the material deposits at the edges significantly and resulted in smooth, clean cuts even at sharp turning points and curvatures. In Fig. 4(b), a section of the cut edge surface is shown. Clean quality cuts as well as good surface finish on the kerf are evident along the entire sample thickness.

For the hole drilling experiments, fused silica glass fiber was used as sample material. The hollow optical fiber had an over all outer diameter of 260 μm with the inside capillary diameter of 50 μm and a 20 μm polyimide clad thickness as outer jacket. Fig. 5(a) illustrates, micro-fine holes machined through the optical glass fiber walls in a transverse direction and opened up inside the capillary. The holes were drilled with the entrance and exit diameters of 12 μm and 3 μm , respectively within the glass wall thickness of ~ 85 μm . Fig. 5(b) shows the view from the laser entrance side on the fiber glass surface. The techniques to fabricate such complex and delicate features have potential applications in microfluidic systems, biomedical devices, nonlinear optical devices and photonic bandgap devices in optoelectronics.

3.3. Femtosecond laser drilling of micro-hole arrays

In comparison to the nanosecond lasers, the femtosecond laser offers distinct advantages during the processing of glass material, which includes significant reduction in heat dissipation, thermal damages and possible utilization of multiphoton processes for machining

transparent materials. A case in point, for drilling micro-hole arrays for optical fiber alignment application, the objective was to produce arrays of micro-holes in thin glass plates that are suitable to guide fiber optics for precise alignment purposes. In this experiment, the glass substrate was specially doped with less than 10% Ag ions (Nippon Sheet Glass Co.) and had a thickness of 100 μm . Ag ions in glasses were reported to be effective in minimizing cracking and chipping during laser machining [24].

In these experiments, much finer debris particles were observed as compared to those produced by longer pulse lasers (nanosecond duration). Normally, the fine particles can be wiped out with alcohol or with assist gas streams. However, some particles around the drilled holes on both the entrance and the exit sides were adhered to the glass and were not easily removable. The use of an assist gas stream such as compressed air and pre-coated layers of acrylic glue was found to be effective in reducing such debris.

During the percussion drilling process, the resulting holes were elongated and resembled the original beam intensity profile. Beam aperture methods e.g., placing an annular metal disk before the focusing lens did not improve the circularity requirements. To further improve the circularity and to obtain holes within desired tolerances, the trepanning technique was investigated using the XY translational stages. The glass substrate was rotated in a defined circular movement while the beam was maintained stationary. A number of passes were required for the complete cutting of the glass material and acceptable quality of micro-hole array pattern was obtained as seen in Fig. 6. The micro-hole with average diameter of 127 ± 2 μm with center-to-center spacing of 250 μm was achieved. It can be seen that the hole size is consistent, regular in shape and is in line with the deterministic nature of the femtosecond laser material processing. The measured circularity was within $\pm 1.8\%$ of the desired value. A

high magnification SEM picture of the drilled hole in the glass material showing the side walls of the hole is illustrated in Fig. 7. It can be seen that the machined hole-walls have good surface finish and no visible micro-cracks are present around the edges.

3.4. Laser-induced plasma micro-machining on glasses

Another method of machining, particularly suitable for obtaining shallow features with high optical surface quality in glass materials, was also developed. In this technique, a focused laser beam when targeted on to a metal surface produces charged particles, which were used for the production of precise micro-features in glass substrate that was placed in close proximity of the target material. The charged particles, from the corona region of the plasma resulted from the metal target, effectively machines the glass substrate. A number of metal foils were used as the target material to produce the charged particles to control feature dimensions. During the experiment, the intensity of the laser beam from a Q-switched Nd:YVO₄ laser was adjusted using a neutral density filter and the working voltage of the pumping diodes. The beam was collimated using an 8X beam expander and focused using a 10X microscope objective. More detailed description on the experimental set up and results can be found elsewhere. [25]

An example of the laser-induced plasma machining is illustrated in Fig. 8(a), which shows a spherical crater with 15 μm in diameter and central depth of 4.5 μm on the glass substrate machined by electrons and ions using brass plasma at a laser fluence of 4.2 J/cm² and 2000 laser shots. A highly defined, clear, sharp-edged and mirror-like smooth surface finish is evident. Fig. 8(b) is the cross-sectional profile of an individual 15 μm diameter crater machined using 60 laser shots at a fluence of 3.8 J/cm², as measured by the WYKO surface profiler. It can be seen that the surface roughness is less than 20 nm and of high quality.

A more complex pattern, having sharp corners and curvatures was machined on a glass surface using the above method. A machined glass micro-slide is shown in Fig. 9(a). In this case, high quality micro channels were machined with a channel width of $\sim 8 \mu\text{m}$. Figure 9(b) reveals the smooth surface profile of the channel with the surface roughness of about 50 nm. The diode pumped solid state laser with 3 ns pulse duration, pulse repetition rate of 1 kHz and scanning speed of $400 \mu\text{m/s}$ were used in this experiment. Superior quality edges, cracks-free machining and smooth surface finish at the bottom are evident.

3. Conclusions

Laser machining technologies based on nanosecond, femtosecond and laser-induced plasma processing were investigated in order to obtain high quality laser micro-fabricated features on glass materials. Direct write laser machining using short pulses from ns and fs lasers influences the quality of processed glass significantly and produces crack-free, clean machining with careful control of the associated thermal processes. Laser-induced plasma machining technique allows fabrication of small-size, shallow features along with superfine surface finishes within the channels. These technologies have potential benefits in the fabrication of complex features for biomedical, microfluidic, MEMS and optoelectronic devices.

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Figure captions:

Figure 1. Schematic diagram of the laser micro-machining system.

Figure 2. The laser-processed glass sample surface under the best focused and defocused conditions (Z-axis step movement of 25 μm for each neighboring lines): (a) micro-machining with cracks, and (b) with no cracks.

Figure 3. The laser-processed sample surface images at different laser intensities under optimal processing condition: (a) $0.65 \times 10^6 \text{ W/cm}^2$, (b) $1.30 \times 10^6 \text{ W/cm}^2$, (c) $1.95 \times 10^6 \text{ W/cm}^2$, and (d) $3.14 \times 10^6 \text{ W/cm}^2$.

Figure 4. Laser machined complex features on glass sample (Vitrocom S-105): (a) feature image, and (b) section of the cut edge surface.

Figure 5. Laser machined capillary hole drilling on optical glass fibers: (a) transverse view, and (b) top view.

Figure 6. Arrays of holes drilled by the femtosecond laser at 500 mW with trepanning speed of 50 $\mu\text{m/s}$.

Figure 7. Enlarged view of the femtosecond laser-drilled hole in doped glass.

Figure 8. A spherical cavity with a diameter of 15 μm and central depth of 4.5 μm on micro-slide glass plate machined using laser induced brass plasma: (a) Crater fabricated at a laser

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Figure 9. Laser induced plasma machining was used to fabricate micro-channels on glass surface with a width of $8 \text{ }\mu\text{m}$ using CAD/CAM programming. Laser pulse repetition rate was 1 kHz and scanning speed was $400 \text{ }\mu\text{m/s}$: (a) machined channels, and (b) WYKO profile of the channel surface.

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