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Laser processing of Borofloat®33 glass

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We report our investigation into laser machining of borosilicate float (Borofloat®33) glass using a picosecond pulsed Yb:YAG laser (Trumpf TruMicro 5x50) and a microsecond pulsed CO_2 slab laser (Rofin SCx20). Our laser machining experiments show that the picosecond laser is suitable for milling and drilling the glass substrate, whereas the CO_2 laser is particularly suited to the generation of optically smooth features, such as bumps and craters, on the glass surface. In this paper, we present examples of various applications for the laser machined glass structures, for instance, a scattering (diffusion) surface for OLED devices and a body component for optical fiber sensors.

Keywords: Glass; picosecond laser; CO_2 laser; surface texturing; milling; drilling

1. Introduction

Borofloat®33 is an inexpensive borosilicate float glass manufactured by Schott AG (Germany) [1]. It is characterized by similar optical properties to fused silica, but is less expensive. This colorless and optically flat glass is highly transparent in the visible and near-infrared (NIR) spectral range. It is also highly resistant to thermal shock (CTE = 3.3ppm/K) and to chemicals such as strong acids, alkalis and organic substances. Therefore, Borofloat®33 glass has found use in many industrial and scientific areas, such as micro-electronics, chemistry, biotechnology, optics, lighting and photovoltaics [1, 2].

There are many benefits of using lasers for processing glass. Lasers are flexible tools that enable direct and localized machining of glass with high resolution and accuracy. In contrast to the mechanical tools used for processing glass, lasers allow the workpiece to be machined without wearing a tool, thereby reducing running and maintenance costs. Also the laser-based machining processes are in general 'clean' processes and very often there is no chemical waste.

Various lasers have been used for processing glass substrates. The most common are: CO_2 lasers, excimer laser and ultrashort pulse lasers [3-14]. CO_2 lasers are inexpensive laser sources that provide laser radiation in the IR spectrum range (between 9.2µm and 10.6µm). Since glass is highly opaque in this spectrum range, CO_2 lasers are suited for cutting [3], micro-machining [4-9] and polishing [8-10] of these normally transparent materials. CO_2 laser processing is a purely thermal process in which thermal diffusion, melting, vaporization and re-solidification of glass take place. Since all these processes generate residual stresses in the bulk material, only the glass substrates with a low coefficient of thermal expansion (CTE), e.g. fused silica and Pyrex, can be successfully machined without material cracking [15, 16]. Moreover, the long CO_2 laser wavelength means that the laser spot size is limited to tens of micrometers, and hence the laser-generated surface features are relatively large (typically > 30µm in diameter).

Deep ultraviolet (DUV) excimer lasers are also used for processing glass. They enable machining of glass substrates with a high spatial resolution (< 1µm), giving a roughness of the machined surfaces in the optical grade regime [12]. However, the drawbacks of the excimer laser systems are their high complexity associated with the use of special optics and gases to minimize absorption of the laser beam in DUV, high exploitation costs and also low processing throughput.

Ultrashort (picosecond and femtosecond) pulse lasers offer the capability to machine many types of glass substrates with a high spatial resolution (< 10µm). These lasers, in particular femtosecond lasers, are also used for the three-dimensional (3D) fabrication of various structures (e.g. micro-channels) and optical components (e.g. waveguides) within transparent glass substrates [13]. The drawback of using ultrashort pulse lasers for processing glass is a relatively high roughness of the machined surfaces.

In this paper, we investigate the feasibility of using two different lasers: a 300W CO_2 slab laser and a 50W picosecond pulsed Yb:YAG laser for processing Borofloat®33 glass substrates. The aim of this work was to determine laser processing parameters which are suitable for machining the glass without material cracking. Examples of the laser machined structures for different applications, including the manufacture of scattering surfaces for OLED lighting and optical components for fiber optic sensing applications, are presented.

2. Experimental setups

Fig. 1 shows a CO_2 laser-based micro-machining system used for processing Borofloat®33 glass. The system contains 300W CO_2 slab laser (Rofin SCx20) that provides µs pulses of wavelength 10.6µm. The pulse duration (τ), pulse energy (E_p), peak power (P_p) and the number of laser pulses (N) delivered to the workpiece are accurately controlled by an acousto-optic modulator (AOM). The focused laser spot diameter can be changed from 50µm to 120µm. Laser processing is realized by translating the workpiece using XY stepper motor stages.

Fig. 1. CO_2 laser-based micro-machining system used for processing Borofloat®33 glass.

Fig. 2 shows a picosecond laser micromachining system used for processing Borofloat®33 glass substrates. The laser source is a 50W Trumpf TruMicro5x50 laser that provides 6ps laser pulses (FWHM) and has a maximum pulse repetition frequency (PRF) of 400kHz. The laser has three outputs. Laser processing can be performed using any of the following wavelengths: 1030nm, 515nm and 343nm. The laser beam is delivered to the workpiece via a galvo scan head and a 160mm FL F-theta lens. The laser beam delivery is very similar for each wavelength. Diameters of the laser spots focused on the workpiece were calculated to be 22.5μm at λ = 1030nm, 14μm at λ = 515nm, and 10μm at λ = 343nm. Laser processing of Borofloat®33 glass substrates was carried out in air. The mounting arrangement for the glass provided a clear aperture underneath the machining region.

3. Results and discussion

3.1 CO_2 laser processing – texturing

A 1.1mm thick Borofloat®33 glass substrate was machined using the CO_2 laser micro-machining system described in the previous section. Prior to laser processing, the glass substrate was cleaned using Methanol and lens tissues in order to remove any contamination and debris. The focused laser spot used for machining Borofloat®33 glass was fixed to be 60μm, whereas the pulse duration and peak power were varied from 1μs to 150μs and up to 400W, respectively. The glass substrate was machined using single and multiple laser pulses. The PRF was fixed at 250Hz.

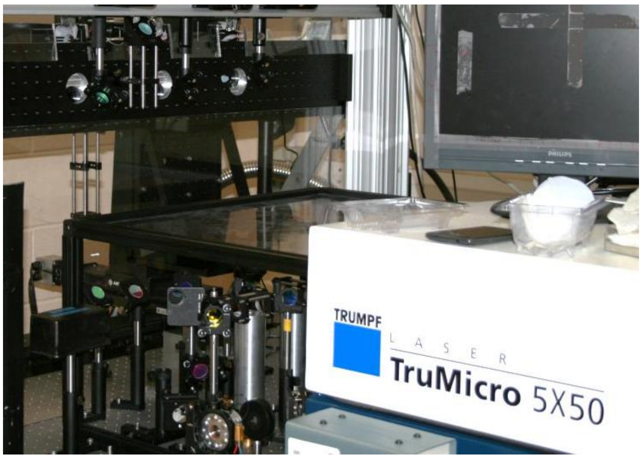

Fig. 2. Picosecond laser system used for processing Borofloat®33 glass.

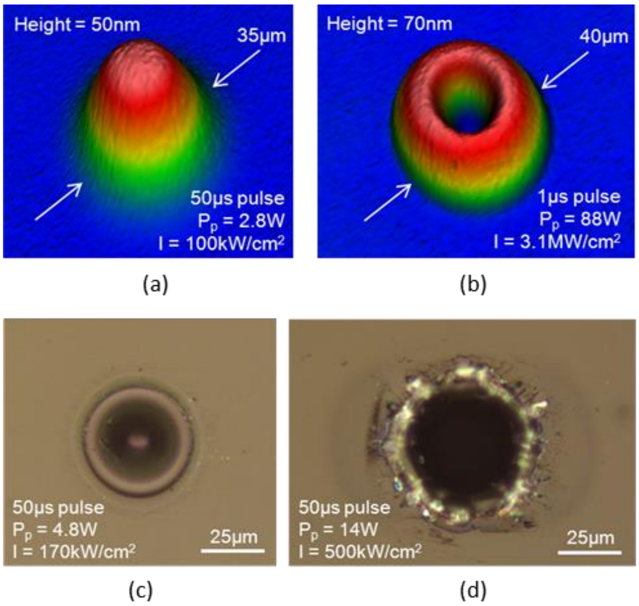

Fig. 3. Laser-induced deformations generated on the surface of a 1.1mm thick Borofloat®33 glass substrate using CO_2 laser radiation. Laser processing parameters (i.e. pulse duration, peak power, and power density) used for the generation of bumps (a, b) and craters (c, d) are listed in figures.

Fig. 3 shows examples of the CO_2 laser-induced surface deformations generated on Borofloat®33 glass. Optically smooth bumps, such as those shown in Fig. 3 (a) and (b), can be produced on the glass surface when the pulse energy is relatively low (between 50μJ and 175μJ). In general, it was found that the energy threshold for appearance of the bumps depends on the pulse duration and the number of laser pulses. When the pulse energy was increased above 175μJ, it was possible to produce optically smooth craters, such as that shown in Fig. 3 (c). For higher pulse energies, the craters became deeper but also were surrounded by resolidified glass (splashes), as can be seen in Fig. 3 (d). The same effect on the glass substrates was also observed for multiple laser pulse treatments ($N > 1$). When $E_p > 0.4$mJ, the substrate very often underwent fractures due to excessive thermal stresses that were generated inside glass by the laser beam. It was found that there is a higher risk of material cracking when longer laser pulses are used. In general, the heat affected zone (HAZ), which can be seen in Fig. 3 (d), increased for increasing pulse energies, pulse durations and numbers of laser pulses.

Excellent control over the laser processing parameters, such as pulse energy and pulse duration, enabled the fabrication of various textures on the Borofloat®33 glass surface. Fig. 4 shows an example of the laser-generated texture that potentially can be used as a scattering (diffusion) structure in OLED devices for enhancing their outcoupling efficiency and light extraction [17]. Currently, similar structures are produced on polymeric substrates by embossing. By producing the scattering structures directly on the glass substrate, it would be possible to reduce the number of layers in OLED devices and hence the fabrication cost.

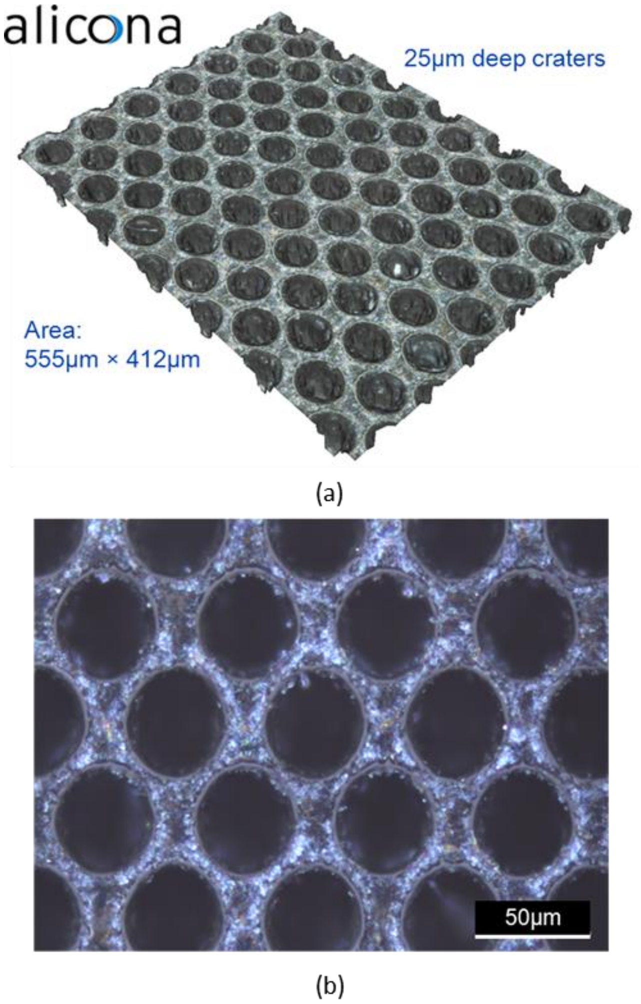

Fig. 4. An example of CO_2 laser-generated texture on the Borofloat®33 glass surface.

3.2 Picosecond laser processing – milling and drilling

We also investigated picosecond laser machinability of Borofloat®33 glass substrates. We studied the impact of laser wavelength on the machining performance of Borofloat®33 glass as well as the impact of the pulse overlap and the number of laser passes on the ablation depth.

Fig. 5 shows 1.1mm thick Borofloat®33 glass substrates that were machined using picosecond laser pulses of wavelengths 1030nm, 515nm and 343nm. Different pulse energies (laser fluences) and pulse overlaps were used in order to find laser processing parameters suitable for machining the glass substrate. Laser processing of Borofloat®33 glass with the 1030nm wavelength was unsuccessful because at this wavelength both sides of the workpiece were partially machined, as can be seen in Fig. 5 (a). Using shorter wavelengths, however, we obtained more consistent results, i.e., only the front side of the glass substrate was machined, as can be seen in Fig. 5 (b) and (c). It was found that Borofloat®33 glass substrate can be successfully machined using picosecond laser pulses of the wavelengths 515nm and 343nm when the laser fluence is above 2J/cm^2 and the pulse overlap is approximately 90% (see Fig. 6). The pulse overlap (o) was defined as follows:

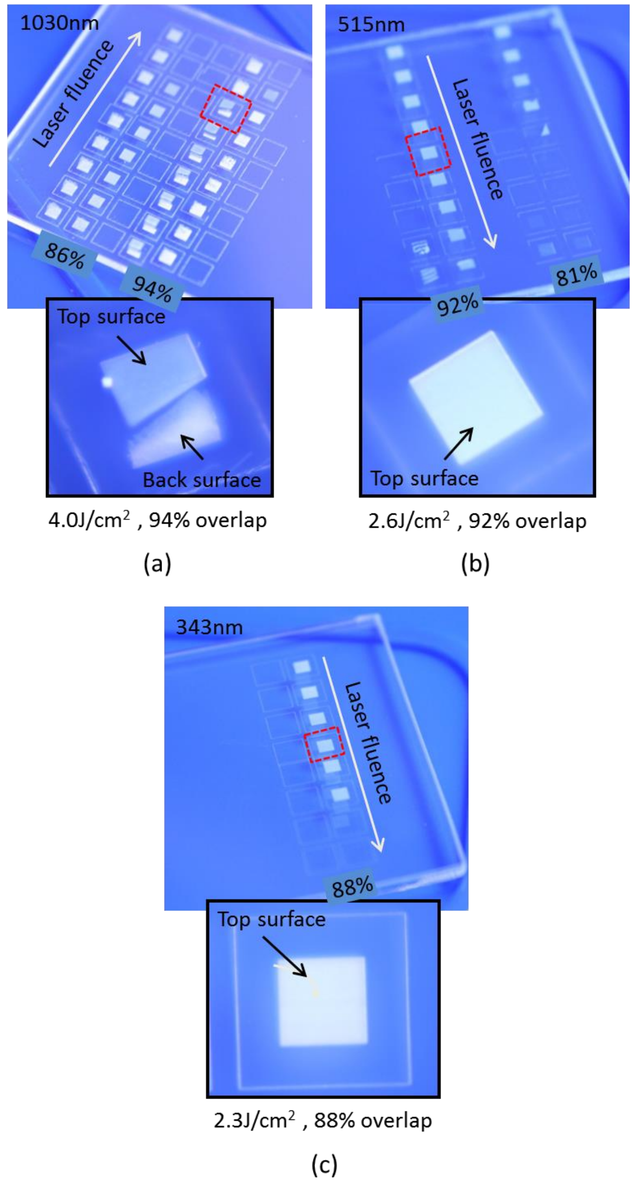

Fig. 5. 1.1mm thick Borofloat®33 glass substrates machined by picosecond laser pulses of wavelengths (a) 1030nm, (b) 515nm, and (c) 343nm wavelength.

$$o = \left(1 - \frac{v}{d \cdot PRF}\right) \cdot 100\% \qquad (1)$$

where v is the scanning speed, d is the laser beam diameter and *PRF* is the pulse repetition frequency.

Fig. 6 shows an average ablation depth obtained with different values of laser fluence for wavelengths of 343nm and 515nm. This shows that the ablation depth increases linearly with increasing laser fluence (when above 2J/cm^2). Pulse overlaps were similar for both wavelengths (i.e. 88% for λ = 343nm and 92% for λ = 515nm). The results also show that more efficient laser machining is obtained with the 515nm wavelength.

We also studied the impact of laser passes on the ablation depth. It was found that the ablation depth is also linearly dependent on the number of laser passes. For almost identical pulse overlaps and laser fluences, it was found that the ablation depth obtained with the 515nm wave-

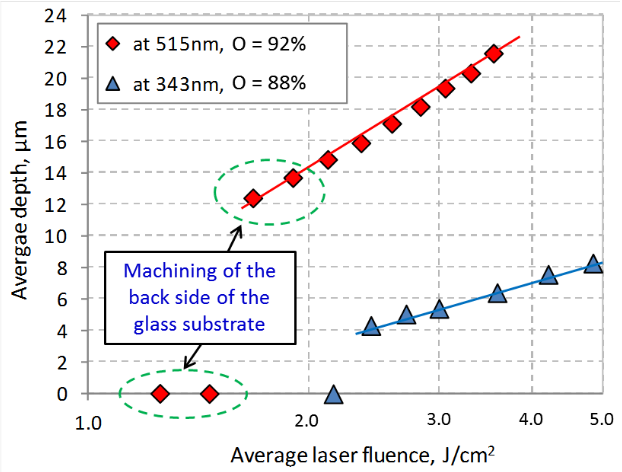

Fig. 6. Average ablation depth obtained with different laser fluence and similar pulse overlap. Results presented for 343nm and 515nm laser wavelengths.

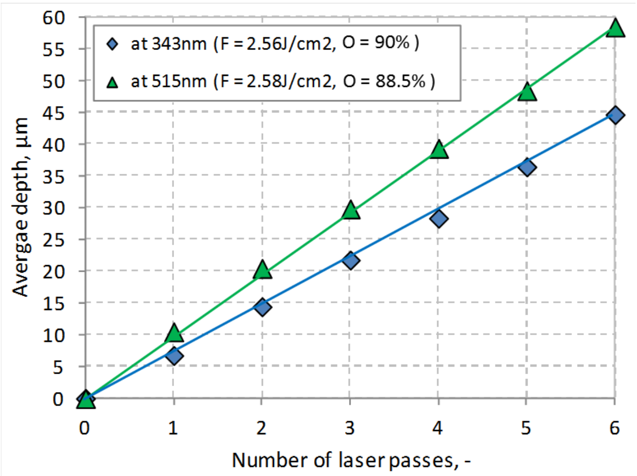

Fig. 7. Average ablation depth vs. the number of laser passes. Results obtained with the 343 and 515nm wavelengths, using almost identical laser processing parameters (i.e. pulse overlap and laser fluence).

length is approximately 20% higher than that obtained with the 343nm wavelength, as can be seen in Fig. 7.

Fig. 8 shows a miniature fiber optic sensor body component that was machined using picosecond laser pulses of wavelength 515nm. This is a 3.5mm diameter disc that contains two concentric grooves, 30µm deep cavity of diameter 1mm and a through hole of an inlet diameter 400µm. The disc was cut out from a 1.1mm thick Borofloat®33 glass substrate, whereas the hole was produced by trepan drilling. Multiple laser passes were used to cut out the disc and to drill the hole through the glass substrate. An assembled miniature sensor with an attached optical fiber is shown in Fig. 8 (d).

4. Conclusions

In this paper, it was demonstrated that CO_2 and picosecond lasers can be successfully used for processing Borofloat®33 glass. CO_2 lasers are particularly useful for the generation of smooth structures on the glass surface. Such structures can potentially be used as scattering (diffusion) surfaces in OLED devices for enhancing their outcoupling efficiency and light extraction. Picosecond lasers, on the other hand, have a capability to ablate a large volume of glass without material cracking. Picosecond laser pulses of wavelengths 343nm and 515nm are suitable for cutting, drilling, milling and micro-machining Boroloat®33 glass substrates.

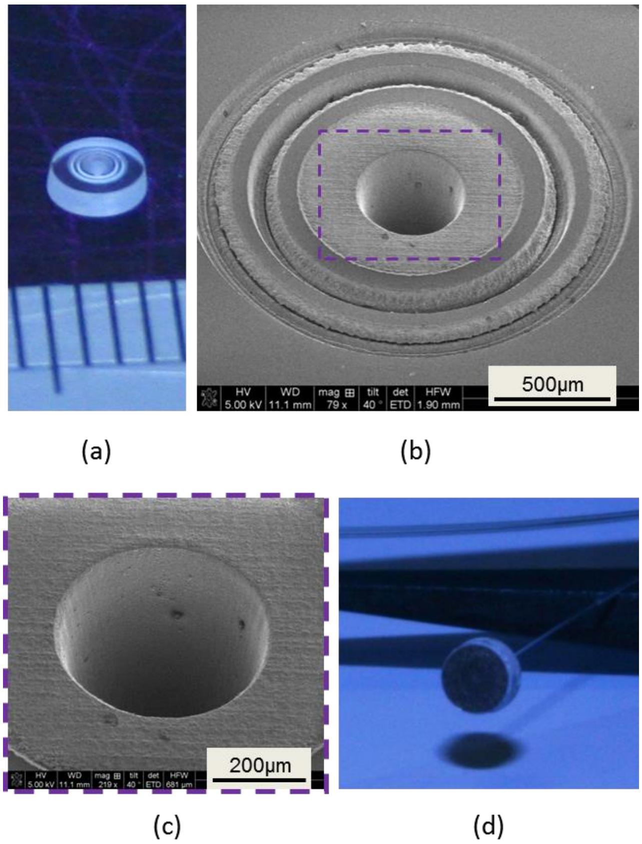

Fig. 8. (a) Photograph and (b) SEM image of a miniature fiber optic sensor body component fabricated using the picosecond laser, (c) close-up of the selected area in (b), and (d) assembled fiber optic sensor.

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