Nanosecond Laser Processing of Soda-Lime Glass

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Glass is an important engineering material for a number of different applications. Over the last years demand on fast and high-quality processing of glass has increased. Although femtosecond or picosecond laser systems offer excellent processing quality, less complex nanosecond laser systems are more stable and widely used for industrial applications and can offer lower processing costs. In this work, we investigated helical drilling of holes in thick soda-lime glass sheets initiating the process from the backside of a sample. Nanosecond laser pulses with wavelength of 1064 nm or 532 nm, tightly focused in the bulk of transparent material, were absorbed due to avalanche ionization. During the 30 ns laser pulse interaction with glass, micro-cracks were induced and drilling debris was ejected through the etched channel. This approach allowed us to drill the high aspect-ratio taper-less holes in the 4 mm thick soda lime glass with maximum throughput of 1.2 s per hole. Nanosecond Q-switched diode-pumped solid state (DPSS) laser offered low cost and fine quality drilling at high processing speed.

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1. Introduction

Glass is an important engineering material for a number of different applications. Over the last years demand on fast and high-quality processing of glass has increased. Glass is widely used in architectural, medical, automotive and electronics applications. Conventional glass processing techniques such as diamond drilling and dicing, water-jet drilling, sand blasting or ultrasonic processing are still commonly used in mass production, although limitations of these techniques in processing speed and quality requires search for novel technological solutions.

Laser machining of transparent materials, such as flat glass, is fast growing market, driven by new developments in displays [1, 2], optoelectronics [3] and medical device technology [4]. In case of laser drilling applications, three main types of laser sources can be used. Pulsed CO_2 laser drilling offers high processing speed with high $ per Watt ratio, although main glass removal mechanism is direct laser ablation associated with relatively large heat effect zone and micro-crack propagation [3, 5]. On the other hand, a lot of efforts are made for ultra-short pulsed laser glass processing [1, 6-15]. Picosecond and femtosecond lasers offer excellent glass processing quality, although high quality usually is associated with low processing speeds. Low throughput and the cost of ultra-short pulse technology make it complicated to use in the industrial glass processing. Less complex and more stable nanosecond Q-switched diode-pumped solid state (DPSS) lasers are already widely used in the industrial manufacturing. This technology offers reasonable $ per Watt ratio, fine glass drilling quality at high processing speeds. In this paper, we demonstrate the possibilities of the rear-surface-side helical drilling of thick glass sheet using nanosecond laser. This approach allowed us to drill 1 mm size high-aspect-ratio taper-less holes in the 4 mm thick soda lime glass with maximum throughput of 1.2 s per hole.

2. Experimental

Relatively simple set-up was used to carry out the soda-lime-glass drilling investigations. Nanosecond $Nd:YVO_4$ Q-switched diode-pumped solid state (DPSS) laser (Baltic HP, 10-30 ns, 10-100 kHz, from Ekspla) was used in the experiments. The laser processing was investigated with the fundamental (1064 nm, 13.3 W) and the second (532 nm, 2.6 W) harmonics of the nanosecond laser irradiation. The laser beam was positioned in the XY plane by galvanometer scanner (from ScanLab) and focused by the f-theta lens with the focal length of 80 mm. Vertical movement of a sample was arranged by applying additional stepper-motor driven axis. The laser beam was initially focused below the rear surface of a sample. There was a gap between the rear surface and the positioning stage to avoid any accumulation of the drilling debris inside the channel. At the beginning of the drilling process, the vertical stage started moving and the focal position was being translated with constant speed towards the front surface in the volume of glass.

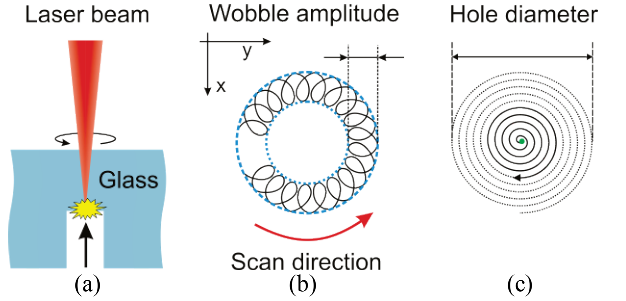


Fig. 1 Illustrations of glass drilling techniques: (a) rear surface side drilling; (b) wobble mode scanning; (c) spiral mode scanning.

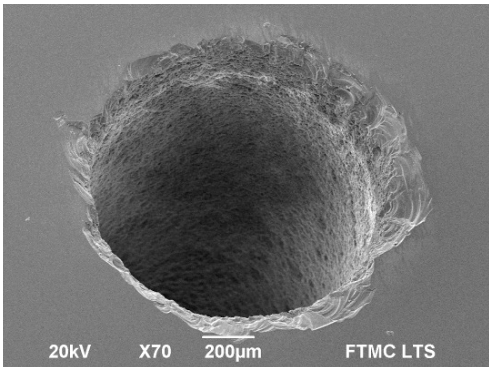
Two laser beam scanning techniques were applied. The first included the smaller diameter wobble movement along the circular path (wobble drilling). This method is also named as orbit-in-orbit laser beam positioning approach by authors in [1]. All experiments using this technique were carried out for 1 mm diameter holes drilling. The second method was realized applying Archimedean spiral scanning (spiral drilling). This method was used only to determine the smallest holes diameters which can be produced by the rear side helical drilling process. Both methods are illustrated in Fig. 1. In all drilling experiments, soda lime glass sheets with the thickness of 4 mm were used.

3. Results

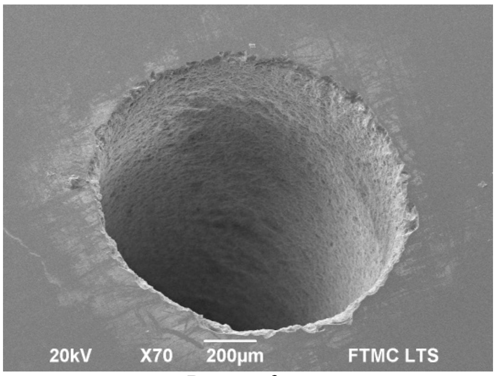
The rear-side helical drilling process is more complicated compared to the conventional front-side ablation, since a lot of system parameters have to be optimized in order for the drilling process to work efficiently. The mean laser power, pulse repetition rate, scanning method and speed in XY plane, vertical sample movement speed have to be taken into account.

3.1 Optimization of laser drilling process

The main material removal mechanism of the rear-side helical drilling is ejection of the particles due to laser induced cracking of glass. Total destruction of laser processed glass volume depends on the distance between the cracks and their size. The laser fluence and pulse overlap in XYZ directions are the main parameters responsible for the efficient removal process. The processed channel width also plays an important role since all the laser processed material has to be removed from the channel. Quality of the drilling process is also very important. Therefore, a balance between the laser fluence and scanning speed has to be maintained.

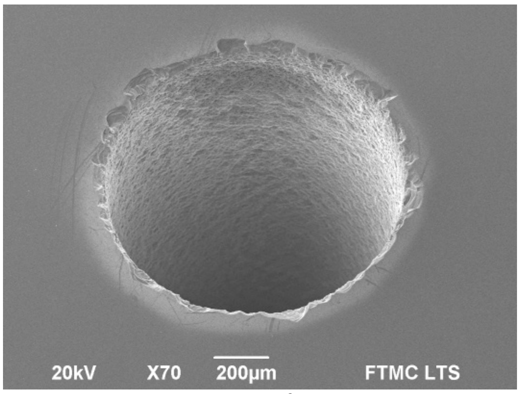


Front surface

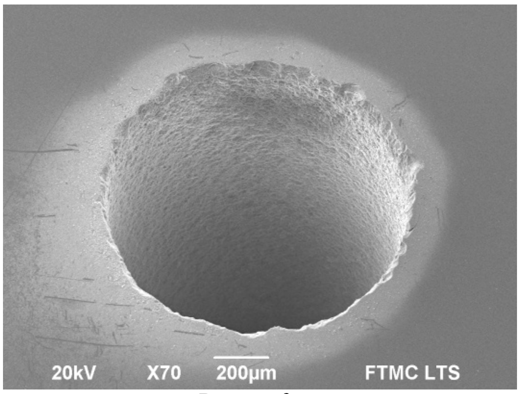


Rear surface

Fig. 2 SEM images of the 1 mm size through hole in a glass sample. Laser wavelength 1064 nm, fluence 68 J/cm^2, 10 kHz repetition rate, vertical drilling speed 0.3 mm/s, wobble-mode helical drilling.



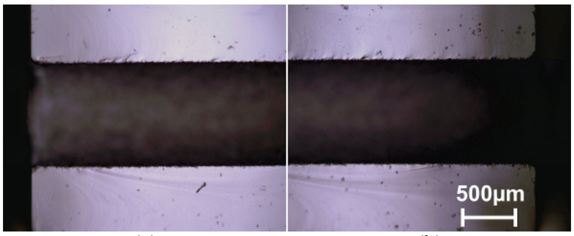
Front surface



Rear surface

Fig. 3 SEM images of the 1 mm size through hole in the 4 mm thickness soda lime glass sample. Laser wavelength 532 nm, fluence 26 J/cm^2, 25 kHz repetition rate, vertical drilling speed 0.15 mm/s, wobble-mode helical drilling.

Optimization of the laser wobble-mode drilling process with 1064 nm and 532 nm wavelengths started by drilling matrixes of 1 mm diameter holes with different system parameters in a glass sheet. Laser power, repetition rate, scanning speed in XY plane, wobble amplitude and vertical sample movement speed were optimized. The fine quality holes were fabricated in the glass sample (see Fig. 2 and Fig. 3). The 532 nm wavelength processing showed better quality of holes compared to the use of fundamental harmonics of the nanosecond laser. Optical microscope image below shows the hole cross-section near the rear and front surfaces (see Fig. 4). The rear-side helical drilling process enabled us to drill cylindrical taper-less holes in the 4 mm thickness soda lime glass sheet. These holes geometries were typical for both wavelength processing.



(a) (b)

Fig. 4 Optical microscope images of the laser processed hole cross-section near the rear (a) and front (b) surfaces. Wavelength 1064 nm, fluence 81 J/cm^2, 35 kHz repetition rate, vertical drilling speed 1.8 mm/s, wobble-mode helical drilling, 4 mm thickness glass sheet.

3.2 Drilling speed and quality

Drilling process throughput and quality are critical for industrial applications. Usually laser processing can offer both, although the high throughput is not always accompanied by the high process quality. In case of the rear-side helical drilling process, the higher laser fluencies induced larger cracks in glass, therefore the lower laser pulse overlap (higher process speed) was needed to be applied for the material removal. The laser-induced crack size determines surface roughness of the processed hole. Therefore, measurements of these laser-affected-area sizes are important for the process quality evaluation.

Drilling quality was evaluated by measuring the cracks sizes at the inner, rear or front surfaces of holes determined as d_1 and d_2 respectively (see Fig. 5). This measurement technique was applied for matrixes of holes processed with different laser fluencies and vertical movement speeds of a sample. Each matrix included groups of holes drilled with the same parameters, so the average sizes could be calculated. Only one drilling process parameter was varied between the holes groups in a matrix.

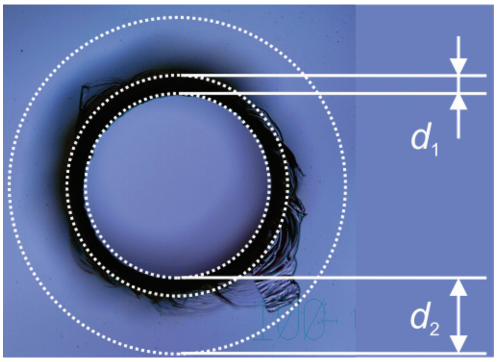


Fig. 5 Illustration of the nanosecond laser induced crack size measurements. d_1 determines inner surface crack size, while d_2 determines the rear or front surface crack sizes.

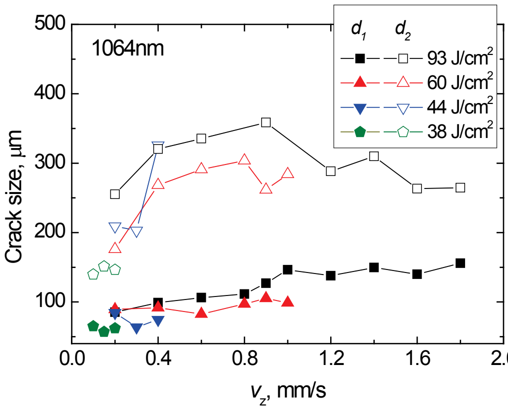


Fig. 6 Relationship between the crack size and vertical drilling speed for different laser fluencies of 1064 nm wavelength nanosecond laser. Solid dots indicate the inner cracking of holes, while open dots indicate the crack sizes on the glass front surface. Laser repetition rate was 30 kHz, 1 mm size holes, wobble-mode helical drilling.

The high laser fluencies up 93 J/cm^2 from the 1064 nm wavelength nanosecond laser enabled stable drilling process in relatively wide range of vertical drilling speeds (see Fig. 6). Laser fluence decrease below 44 J/cm^2 resulted in narrowing of the drilling speed window by the factor of 8, although inner crack sizes were reduced from 85 µm to 63 µm at vertical drilling speed of 0.2 mm/s for 93 J/cm^2 and 44 J/cm^2 respectively. The front-surface crack sizes were also reduced from 255 µm to 145 µm when applying lower laser fluencies at the drilling speed of 0.2 mm/s. When laser fluence was reduced to less than 38 J/cm^2, no stable drilling process was observed. At these fluencies it was enough energy to start the drilling process at the rear surface, but the drilling stopped at the random distance from the top surface and no through holes were fabricated at any vertical drilling speed.

The rear-side helical drilling experiments with the second harmonics of the nanosecond laser were also performed for 4 mm thickness glass sheets. Due to limitations in our system setup, only maximum laser fluence of 26 J/cm^2 could be applied for the drilling investigations with the 532 nm wavelength. Therefore processing results with only 38 J/cm^2 (1064 nm) and 26 J/cm^2 (532 nm) will be discussed below.

Investigations show, that despite relatively low laser fluence at 532 nm wavelength, the broader window in terms of vertical drilling speed can be applied for holes machining (see Fig. 7). The maximum vertical drilling speed with the 532 nm wavelength was approximately 2 times higher compared to 1064 nm drilling and was 0.45 mm/s. Surface cracking was also significantly reduced by applying the green radiation processing. The average front-surface crack sizes were reduced by factor of 2.5 for the 532 nm wavelength drilling at the vertical speed of 0.2 mm/s. Better processing quality was still observed at the rear side of the glass where the drilling process was initiated first, although, at lower vertical drilling speeds, the difference was insignificant between the front- and rear-surface cracking (see Fig. 7).

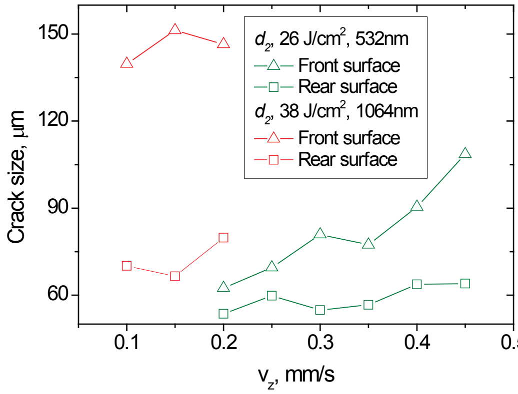


Fig. 7 Relationship between the surface crack size and vertical drilling speed for the 1064 nm and 532 nm wavelength of the nanosecond laser processing. The laser repetition rates were 30 kHz and 25 kHz respectively, 1 mm size holes, wobble-mode helical drilling.

3.3 Maximum process throughput

Drilling process speed is very important for industrial applications. The main material removal mechanism of the rear-side helical drilling is ejection of the particles due to laser induced cracking of glass. Total destruction of laser processed glass volume depends on the distance between the cracks and their size. An average laser power takes into account both laser fluence (laser pulse energy) and pulse repetition rate, therefore the drilling speed is mainly influenced by this parameter. To determine the maximum hole drilling speed, groups of 1 mm diameter holes were fabricated with different settings of the average laser power, pulse repetition rate and vertical drilling speed. Only 1064 nm wavelength was applied in these tests since the average laser output power at the fundamental radiation was much higher compared to the second harmonic generation. The maximum drilling speed dependence on the average laser power and repetition rate is shown in Fig. 8.

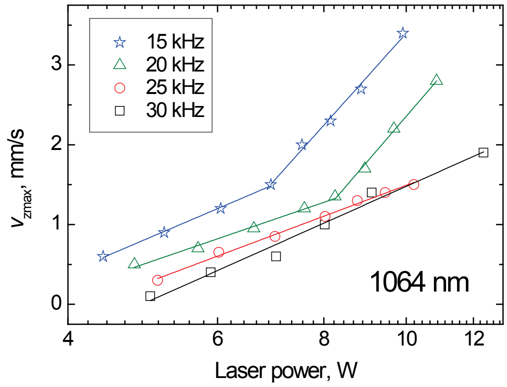


Fig. 8 Relationship between the maximum vertical drilling speed and laser power for different pulse repetitions rates of the 1064 nm wavelength nanosecond laser, 1 mm size holes, wobble-mode helical drilling.

Increase of the average laser power resulted in the higher drilling throughput. The results also show, that the higher laser fluencies at lower pulse repetition rate enables the faster drilling process with the same average laser power level. This could be explained by larger size crack generation in the glass volume, therefore destruction of the laser processed glass volume is more efficient.

The maximum holes vertical drilling speed of 3.35 mm/s was reached with the average laser power of 9.9 W and laser pulse repetition rate of 15 kHz, laser fluence 150 J/cm^2. This enabled us to drill 1 mm holes in 1.2 s per hole with ablation rate of 2.5 mm^3/s.

3.4 Analysis of drilling process debris

Dust and particles after the rear-side helical drilling process were collected and investigated with SEM. Typical SEM view of generated debris after the rear-side helical drilling process is shown in Fig. 9.

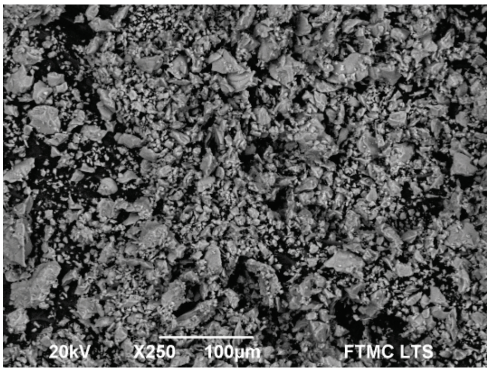


Fig. 9 SEM image of particles generated during the rear-side helical drilling process. Laser wavelength 532 nm, 26 J/cm^2, 25 kHz repetition rate, vertical drilling speed 0.4 mm/s, spiral-mode helical drilling.

Broad range of the particle size distribution was observed after the laser processing. Larger particles, which were clearly visible in SEM image, were measured and the results are shown in the Fig. 10. Logarithmic relationship between the size of largest particles and vertical drilling speed was observed. At low vertical drilling speed of 0.05 mm/s, smaller particles were generated in the range of 130 µm. When the vertical drilling speed was increased, particle size started to increase and was in the range of 250 µm at drilling speed of 0.4 mm/s.

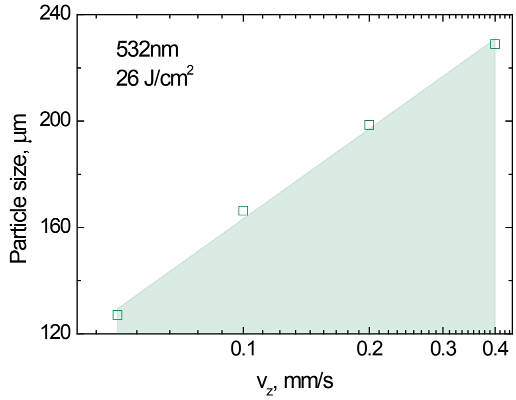


Fig. 10 Relationship between the largest particle size and vertical drilling speed, laser wavelength 532 nm, 26 J/cm^2, 25 kHz repetition rate, spiral mode helical drilling.

3.5 Minimal hole size

The rear-side helical glass drilling process is an efficient method for holes fabrication, because laser processed volume is removed in form of particles. This effect helps to increase the process efficiency since no laser energy is wasted for material melting and evaporation. The particle size plays important role in the drilling process, since it determines the minimal diameter of the processed hole. The laser processed hole cannot be smaller than generated particle sizes, otherwise the debris will block the drilling channel and the process will stop. The smallest size of a hole, drilled with the 532 nm wavelength of the nanosecond laser is shown in the Fig. 11. The minimum diameter was 200 µm. The 532 nm wavelength rear-side helical drilling was applied with laser fluence of 26 J/cm^2, 25 kHz repetition rate, 0.2 mm/s vertical drilling speed, spiral scanning mode. At these processing conditions, the largest particle size of 190 µm was measured after the hole processing (see Fig. 10), therefore, drilling of smaller holes was not possible.

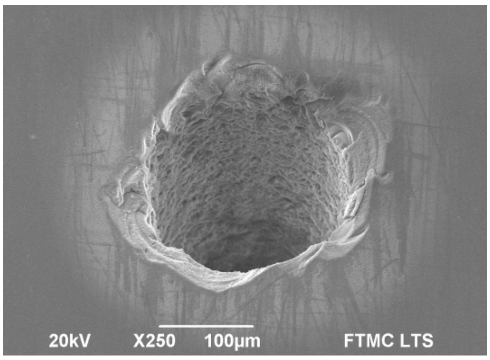


Fig. 11 SEM image of through hole in 4 mm thickness glass sheet. Laser wavelength 532 nm, fluence 26 J/cm^2, 25 kHz repetition rate, vertical drilling speed 0.2 mm/s, spiral-mode helical drilling.

4. Conclusions

The rear-side helical drilling process of soda lime glass was efficient method for holes fabrication in a 4 mm thickness glass sheet with the nanosecond laser. Circular, taperless holes geometries were processed using this technique. The holes quality was controlled by adjusting the laser fluence and vertical drilling speed. Surface cracking near the laser processed hole channel were present in all drilling tests, although at the optimal processing conditions cracks were lowered up to 63 µm. Maximum throughput of 1.2 s per hole with ablation rate of 2.5 mm^3/s was achieved with available system setup. Generated particles limited the channel size during the drilling process, therefore minimal hole size of 200 µm were obtained using this processing technique.

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