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Rear Side Processing of Soda-Lime Glass Using DPSS Nanosecond Laser

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Abstract

Common drawbacks of the front-side direct laser ablation are laser-induced thermal effects and interaction between the laser beam and ablation products. These aspects consequently lead to the lower processing efficiency, lower quality and the need for post-processing. When the processing is initiated from the rear side of transparent samples, the ablated material is ejected through the formed channel in the opposite direction. Therefore, the incident radiation is not scattered and the laser fluency inside can be kept constant. Tightly focused nanosecond laser pulses are absorbed in the bulk of glass via avalanche ionization, build up thermal stresses and induce formation of micro-cracks in the substrate. By setting a proper laser pulses arrangement in the volume of glass, it is possible to control the material cracking and form a preferred structure. Using this processing approach, less energy is wasted for the material melting and evaporation as the material is removed in particle form.
In our research, we investigated the free-shape cutting of thick soda-lime glass sheets initiating the process from the back-side of samples. Cuts were formed by using diode-pumped solid-state Nd:YVO_4 nanosecond laser (Baltic HP, 10-30 ns, 100 kHz, from Ekspla). The laser beam was positioned in the XY plane by galvanometric scanners (from ScanLab) and focused by the f-theta lens. In our work, we proposed the wobble mode laser beam scanning technique combined with vertical sample movement. This approach enabled us to achieve taper-less geometry of laser cuts. The wall surface was controlled by adjusting laser fluency and laser pulses overlap. The nanosecond laser rear-side processing was proved to be a fast and highly efficient method for forming complex cuts in the soda-lime glass.

Keywords: soda-lime glass; glass processing; cutting.

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1. Introduction

There are many types of glass used for dozens of different applications in the field of architecture, medicine, optics, packaging of electronic components, solar panels, and so on. The constant demand for a quality increase from manufacturers forces the research of new glass processing methods. Despite the fact that conventional glass processing techniques, including wheel cutters and diamond tools may offer low costs and high processing speed, they are limited due to incapability of performing complex cuts, poor surface quality and the need for post-processing. Laser tools are thought to give the best alternative (Nisar et al., 2013).

Common problems with the front-side direct laser ablation are the interaction between the laser beam and ablation products, complicated ejection of ablated material machining high aspect ratio structures, and debris accumulation, that may significantly reduce processing quality and throughput. These drawbacks can be avoided using novel processing techniques including rear-side processing (Ashkenasi et al., 2012; Wang et al., 2015) or generation of laser-induced in-volume defects combined with the cleaving processes (Gay et al., 2014).

Nanosecond laser pulses, which are absorbed in the transparent material due to avalanche ionization, build up thermal stresses and induce the formation of micro-cracks in the substrate. By setting the proper pulses overlap, it was possible to control laser-induced material cracking and to eject processed material as large particles that were previously reported to have a size varying from few microns to hundreds of microns (see Fig. 1 (a) for the processing approach).

The proper laser pulses arrangement on the scanning plane must be considered to form through cuts in thick samples compared to the laser beam spot. In our work, the wobble mode scanning technique was used to enlarge the kerf width as the additional circular movement was added to the regular movement of scanner mirrors. Wobble-mode scanning technique was defined by the scanning speed in the XY plane, wobble amplitude, wobble frequency and it was supported by the translation of the vertical stage.

The experimental set-up, evaluation of processing quality, maximum throughput are shortly introduced in this paper.

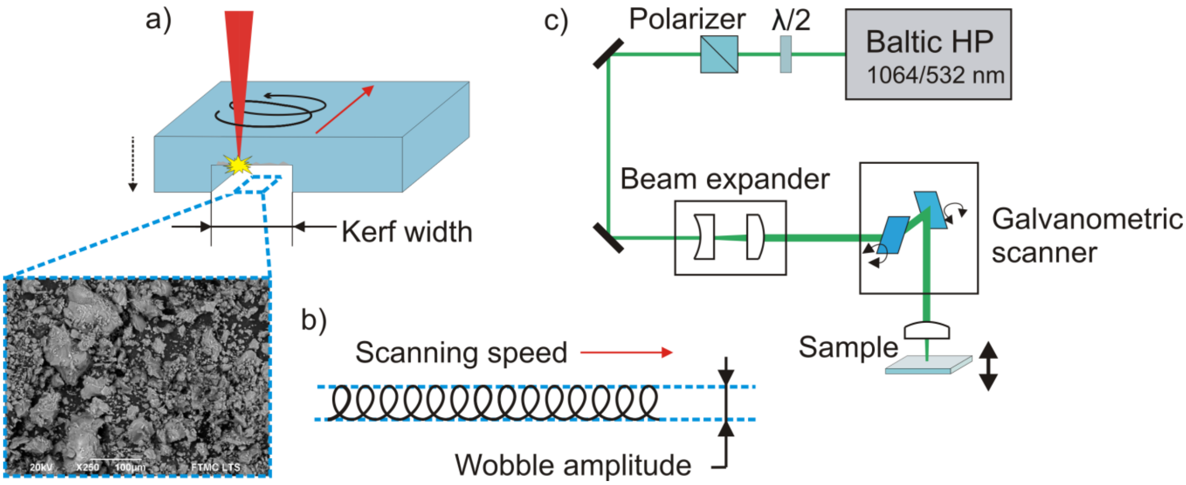

Fig. 1. (a) rear-side processing of glass and debris collected beneath the sample; (b) wobble-mode scanning technique; (c) experimental set-up.

2. Experiments

The fundamental (1064 nm) and the second (532 nm) harmonics of the Q-switched diode-pumped solid-state nanosecond laser Baltic HP (from Ekspla) was used in our relatively simple experimental set-up (Fig. 1 (c)). The typical pulse duration of laser pulses was 10-30 ns, the maximum output power was 9.5 W (1064 nm) and 3 W (532 nm) operating at 10 kHz repetition rate. The laser beam was positioned in the XY plane using galvanometric scanners (from ScanLab) and focused by the telecentric f-theta lenses with the focal length of 80 mm. Samples were placed on a vertical axis using the positioning stage with a stepper motor (from Standa).

In our experiments, glass processing was initiated from the rear-side of samples. The thickness of soda-lime float glass sheets was 1 mm and 4 mm. There was a centimeter gap between the positioning stage and the rear-side of glass to ensure the proper ejection of processing debris. Initially, the laser beam was focused slightly below the rear surface and then the focal position was moved in the volume of material towards the front surface at constant speed. In some experiments, the laser beam was focused straight on the rear-side of glass and 1 mm-thick glass sheets were cut after a sufficient number of scans in the absence of positioning stage translation.

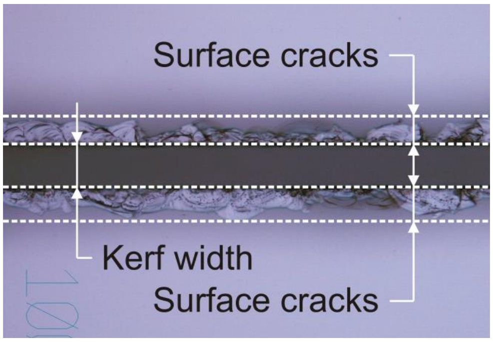

Fig. 2. Evaluation of processing quality.

Glass chipping and surface cracks were observed in all fabricated cuts. However, it was possible to reduce the cracking by adjusting laser pulses overlap, kerf width, laser fluency and vertical speed. Glass sheets with the formed cuts were evaluated by measuring surface cracks in both front- and rear-side of samples, as it is indicated in Fig. 2. The surface roughness of formed sidewalls was evaluated using stylus profilometer.

3. Results

The minimal achieved kerf width was 75 µm for 532 nm wavelength processing of 1 mm-thick glass substrates. However, better quality was achieved when the kerf width was increased to 100 µm. Thus, such width was used for further experiments. The kerf width was enlarged to 200 µm when 4 mm-thick substrates were processed. For the 1064 nm wavelength, a typical kerf width was between 180 µm and 200 µm.

It was noticed that the kerf formation strongly depends on the laser fluency in situations when the vertical speed exceeds the maximum speed, which is determined by the available throughput for given processing parameters. For high fluency regimes, if the vertical speed exceeds the maximum speed, severe cracks started to propagate along cutting line and, in some cases, it led to destructive fracturing of the whole substrate. The high-fluency regime was determined to be above 150 J/cm^2 and 60 J/cm^2 for 1064 nm and 532 nm wavelengths, respectively. Operating at a low laser fluency, if the vertical speed was a bit higher than the maximum processing speed, the inhomogeneous cutting line was observed with randomly damaged areas. If the vertical speed was significantly higher than the maximum speed, the cutting process stopped at some point in the glass volume. There was no sign of material damage or fracturing in layers above.

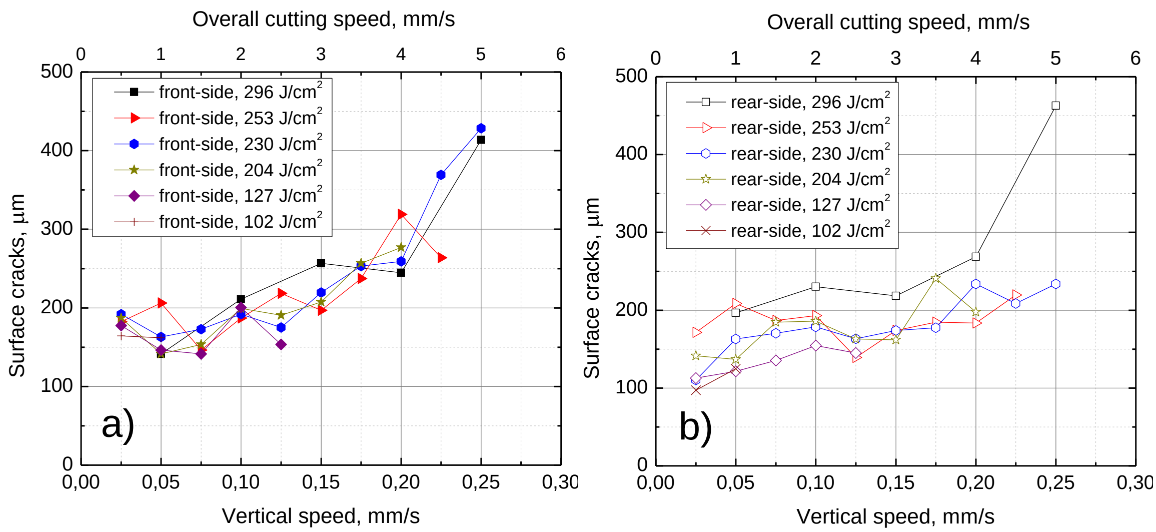

Fig. 3. The front- (a) and the rear-side (b) crack size dependence on vertical speed when different laser fluency was applied. 1064 nm, 20 kHz, scanning speed 100 mm/s, the overall length of a contour was 20 mm.

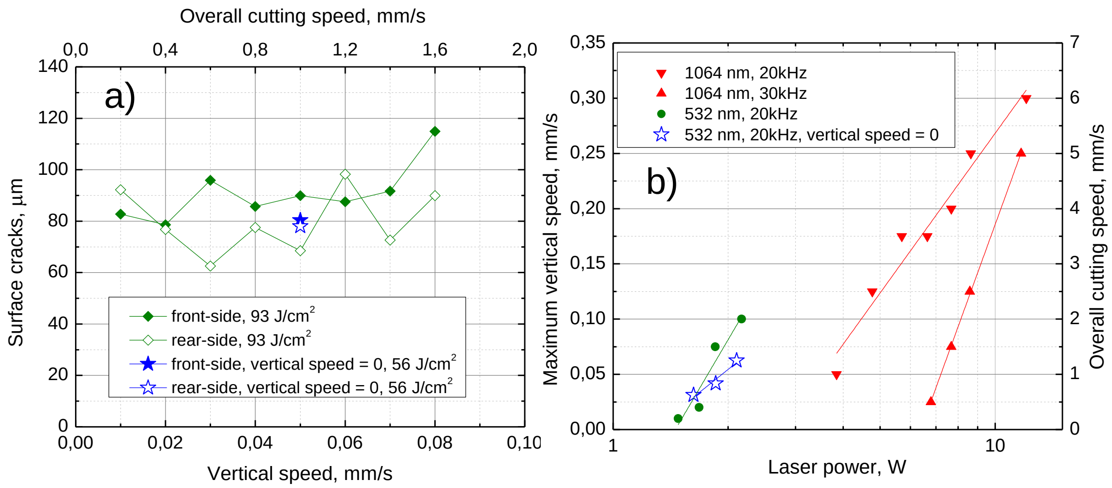

Fig. 4. (a) surface crack size dependence on vertical speed (533 nm, 20 kHz, scanning speed 50 mm/s); (b) maximum processing speed; the overall length of a contour was 20 mm.

The crack size dependence on vertical speed for different 1064 nm wavelength laser fluency in 1 mm-thick glass substrates is given in Fig. 3. The size of cracks was significantly reduced to approximately 200 µm when lower vertical speed and laser fluency was applied. The front and the rear-side surface cracking was similar while operating at high fluency regimes. However, the rear-side surface cracks were reduced more at lower laser fluency. The size of surface cracks was lowered to 100 µm and less by using the 532 nm wavelength radiation (Fig. 4 (a)).

The maximum throughput of cutting 1 mm-thick glass substrates was evaluated for both wavelengths (see Fig. 4 (b)). The effective overall cutting speed is given on the right side. The calculated material removal efficiency reached 1.1 mm^3/s for 1064 nm wavelength and 0.2 mm^3/s for 532 nm wavelength. The energetic efficiency was 0.1 mm^3/J. By using the 532 nm wavelength and loose focusing conditions, it was possible to cut through 1 mm-thick glass sheets by sufficient number of passes in the absence of vertical movement. In this case, the laser beam was focused on the rear surface, and the minimal number of scans ranged from 60 to 80 depending on laser power. However, the processing speed was lower compared to situation when the vertical translation was applied. Finally, it should be noted that operation with a high vertical speed, which was close to the maximum available speed, led to the lower surface quality and unstable process as it was already discussed in this paper.

The rear-side processing approach was applied for cutting variously shaped structures in 4 mm-thick soda-lime glass sheets (Fig. 5 and Fig. 6). Scanning electron microscope images revealed a taper-less shape of formed channels and provided closer insight into surface cracking and overall processing quality. The measured average surface roughness of processed sidewalls was less than 4 µm for 1064 nm wavelength and depended on applied laser fluency. By using the 532 nm wavelength, surface average roughness was lowered to 1.7 µm.

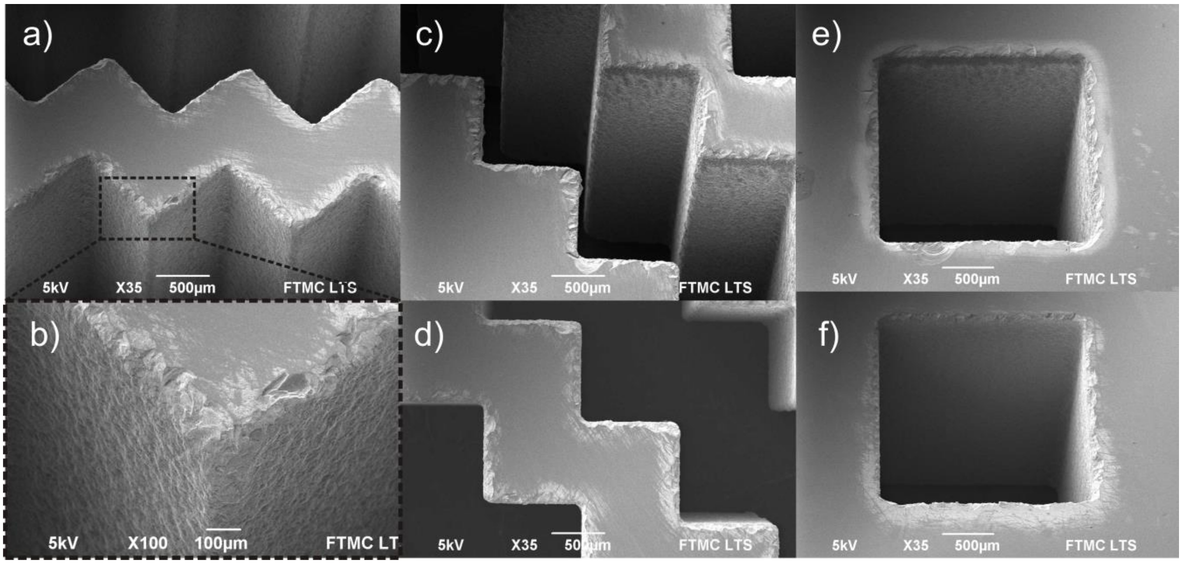

Fig. 5. Structures cut in 4 mm-thick glass sheets using 1064 nm wavelength (20 kHz, scanning speed 100 mm/s). A 22 mm-long complex structure: (a) the rear surface; (b) edge quality; (c) the front surface; (d) the rear surface, no tilting applied. A square-shaped 2x2 mm hole: e) the front surface; (f) the rear surface.

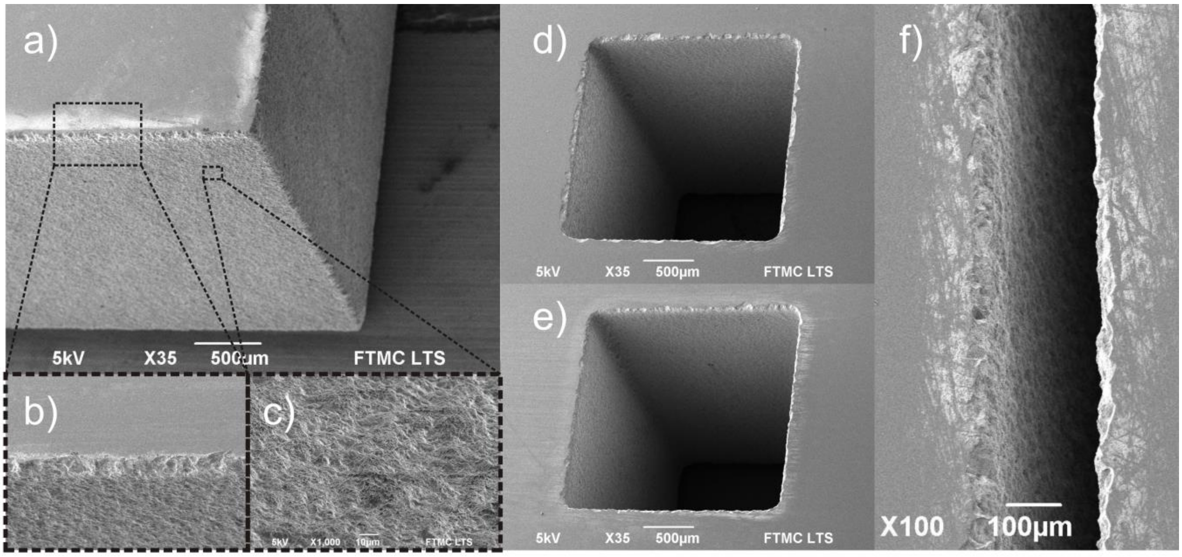

Fig. 6. Structures cut in 4 mm-thick glass sheets using 532 wavelength (20 kHz, scanning speed 50 mm/s): (a) a 25x25 mm^2 square; (b) edge quality; (c) surface roughness; (d) the front surface of a square-shaped 2x2 mm^2 hole; (e) the rear surface of a square-shaped 2x2 mm^2 hole; (f) the rear-side of a formed channel.

4. Conclusions

DPSS nanosecond laser with 1064 nm and 532 nm wavelength of radiation was successfully applied for processing of 1 mm and 4 mm-thick soda-lime glass substrates as the process was initiated from the rear surface and was supported by moving down the positioning stage at a constant speed. By using the 1064 nm wavelength, the material removal efficiency was as high as 1.1 mm^3/s, and that enabled us to achieve 6 mm/s overall cutting speed of 1 mm-thick glass sheets. However, better quality was achieved using second harmonics radiation, and the surface cracks were lower than 100 µm. It was proved that surface cracking can be reduced by applying lower vertical speed and laser fluency.

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