Optics and Laser Technology 111 (2019) 307–314

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Investigation of the surface morphology in glass scribing with a UV picosecond laser

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HIGHLIGHTS

- Glass scribing by a UV (355 nm) picosecond laser (Nd:YVO_4) is studied.
- Surface morphology and crack are analyzed in relation to accumulated laser energy per unit beam spot.
- Threshold laser energy accumulation causing surface damage lies between 0.25 and 0.3×10^{-4} J.
- Crack-free groove is successfully produced with the accumulated laser energy of 0.3–0.5×10^{-4} J.

ARTICLE INFO

Keywords:
Picosecond laser
Glass scribing
Ultra violet (UV)
Groove
Surface morphology

ABSTRACT

This study reports the investigation of the morphology of the surface damaged during the laser scribing of glass and the analysis of the corresponding interaction mechanism between the laser and glass. In this study, the soda lime glass of 1.1 mm thick is scribed by an ultraviolet (UV) picosecond laser (Nd:YVO_4) by varying laser power, scan speed and number of scans. From the analysis of experimental results, it is found that the surface morphology can be classified as three groups such as swelled surface, wave pattern (either shallow or deep) and groove depending on the accumulated laser energy per unit beam spot. The accumulation of the large laser energy (12–30×10^{-4} J) into the material induces volume meting and local vaporization below the surface without material removal, which makes bubbles inside glass volume and swelled surface through volume expansion. With the decrease of the energy accumulation (4.2–9×10^{-4} J), the surface morphology is changed into shallow wave pattern by slight material removal. With further decrease of the laser energy accumulation (1.4–3×10^{-4} J), either deep wave or groove morphology is obtained due to the increase of the material removal. Under very low laser energy accumulation region (0.3–1.05×10^{-4} J), the groove shape is only formed. In particular, the groove morphology without cracking is successfully produced within the range of 0.3–0.5×10^{-4} J. The threshold laser energy accumulation for surface damage is found to be around 0.25–0.3×10^{-4} J. Below this energy accumulation, modification in the surface morphology doesn't occur. It is also found that the groove morphology is hard to obtain by even multiple laser scans if it is not well formed by single laser scan. The cracks produced during the scribing process can be characterized with several propagation morphologies. At the region of the relatively low laser energy accumulation, cracks propagating across the scan direction are only generated. However, cracks propagating both across and along the scan direction are found with the increase of the laser energy accumulation. Huge cracks (arc or sinusoidal curve shape) of several millimeters in size are produced under the very large laser energy accumulation.

1. Introduction

Glass has been widely used as an essential material in various fields of the industry. In particular, its outstanding optical, electrical, chemical and mechanical properties enable glass materials to be used for key components of the display and optoelectronic devices. In order to use glass properly in applications above, it should be machined in a precise and economical way. However, glass processing by conventional methods such as a diamond point or wheel cutter [1–3] is still a challenging task due to the brittle characteristic of the glass. These methods use the physical contact of tool bits, which in turn induces propagation of random cracks and a large loss of materials. There are other processing techniques using hot air-jet [4] and water-jet [5,6]. They could provide non-straight cut and relatively good surface finish,

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https://doi.org/10.1016/j.optlastec.2018.10.008
Received 25 July 2018; Received in revised form 11 September 2018; Accepted 6 October 2018

however both techniques needs longer processing time and extra steps for initiation of the cut (hot air-jet) and cleaning of the cut surfaces (water-jet). This manifestly increases the cost of the processing.

Over the last few decades, a laser technology has attracted a great attention in the processing of glass due to various advantages such as non-contact nature, clean and fast process and easy automation of the system [7–14]. In the initial stage of the laser glass processing, a CO_2 laser is the most promising candidate as a tool for processing since the absorption rate of the CO_2 laser beam with a far-infrared (FIR) wavelength (10.6 μm) in glass is very high. Due to the high band gap energy of glass, glass materials are highly transparent to most commercial lasers with a wavelength in visible (VI) and near-infrared (NIR) range. Therefore, the CO_2 laser with a FIR wavelength is initially considered to be an ideal tool for glass processing.

The CO_2 laser cutting of glass through melting and evaporation was investigated by number of researchers [15–17]. In this process, glass is heated by a CO_2 laser far beyond glass transition temperature. As a result, glass materials are removed from melt ejection and evaporation. However, in most cases, the cutting by melting and evaporation processes results in poor surface finish and a large heat affected zone (HAZ), and consequently requires grinding and polishing of the cut-surface after the laser process. The scribing of glass by a CO_2 laser was also reported [18]. In this technique, first the CO_2 laser is used to make a groove in glass, and then the glass is broken mechanically for separation. It was found that scribing by the CO_2 laser produced many damage at the cut edge. Some researchers used a CO_2 laser as a tool for breaking of glass [19–21]. In this technique, a groove and crack are first formed along the cutting path using a mechanical tool bit, and subsequently the CO_2 laser beam fractures glass by extending the crack below glass transition temperature. This method gives relatively good cutting quality through the influence of low process temperature, however optimum scribe force and groove depth should be guaranteed.

The development of ultra-short pulse lasers ranging from picoseconds to femtoseconds has made much progress in the area of glass processing [22–26]. In case of the ultra-short pulses, a characteristic time scale of the process is much shorter than that of the thermal diffusion in material [27]. Therefore, energy transfer from irradiation spot to surrounding material is extremely limited, and thermal effect is only confined to very small area of the material since the surrounding material doesn't have enough time to heat up. Owing to this feature of the ultra-short pulse process, the cracks and fractures induced by thermal damage, easily generated by long pulse and CW laser process, can be minimized. In addition, absorption mechanism of the ultra-short pulse with a high peak power follows non-linear characteristics such as multi-photon absorption and avalanche ionization process [28,29], as a result the ultra-short pulse is less restrictive in selection of the wavelength for enough absorption in glass. The ultra-short pulse laser also has a relatively small focused beam spot, so that it could process materials in a more precise way. Thus, the ultra-short pulse laser has a great potential in the processing of glass for diverse purposes. Besides the ultra-short pulse laser, UV laser with a photon of the high energy is considered as an option for glass processing since its absorption mechanism is similar to that of the ultra-short pulse [27,30]. Thus, the UV laser with an ultra-short pulse could be the best tool for the processing of glass.

So far, substantial work has been done on glass processing by laser. However, there are only a few reports for the glass processing by an ultra-short pulse with UV wavelength. This study examines the morphology of the glass surface damaged during the scribing process by a UV picosecond laser and analyzes the corresponding interaction mechanism between the laser and glass. Scribing experiment is carried out for various laser powers, scan speeds and scan numbers. In particular, the morphology of the damaged surface is studied in relation to the accumulated laser energy per unit beam spot, and it is classified as three groups depending on the range of the accumulated laser energy. In this study, the process conditions for damage threshold and crack-free groove formation are also obtained.

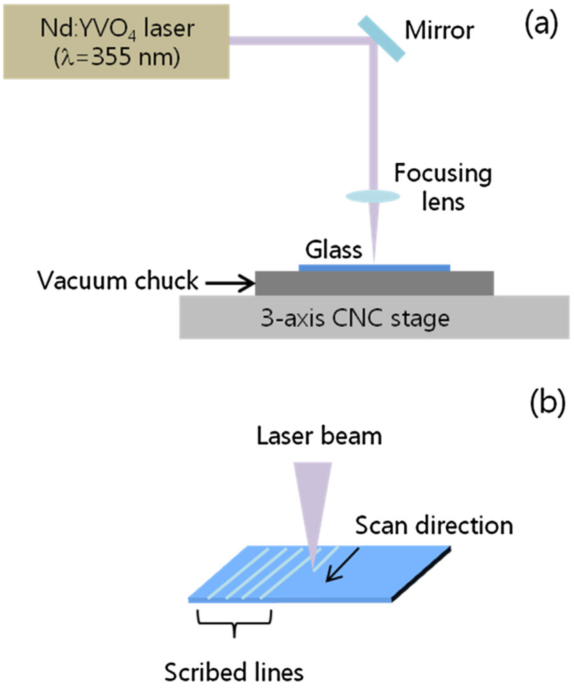

Fig. 1. Schematic diagram of the experimental setup for laser scribing.

2. Experimental details

In this study, the laser unit used for scribing of the glass substrate is a $Nd:YVO_4$ picosecond laser (EOTechnics, ESL-050). This laser is frequency tripled to generate a laser beam of the UV (355 nm) wavelength. The picosecond laser used in this study has a pulse width of ~15 picoseconds and is operated at 400 kHz pulse repletion rate. A picosecond laser beam generated from laser head is finally focused on the surface of the glass substrate via the focusing lens of a 100 mm focal length, and this gives the focused beam spot of ~15 μm diameter. The glass substrate is placed on the vacuum chuck incorporated into a 3-axis CNC machine for precise control of the relative position between the laser beam and glass substrate. The schematic diagram of the experimental setup for picosecond laser processing is shown in Fig. 1.

The glass substrate used for scribing experiment is a soda lime glass of 1.1 mm thick. The length and width of the glass substrates are 20 cm and 10 cm, respectively. The material properties of the soda lime glass are shown in Table 1. Laser scribing is carried out along the width direction of the substrate. Before the experiment, test samples are cleaned using methanol and compressed air to eliminate contaminants. After the experiment, substrates are cut into several pieces to have 3 cm × 1 cm (length × width) using the laser scribe and break method for analysis. An optical microscope (Dino Lite, AM4013MZT) and a field emission scanning electron microscopy (FE-SEM, TESCAN MIRA LMH) are used to analyze the surface morphology of the laser-scribed samples. Before the FE-SEM analysis, cut samples are platinum-coated to

Table 1
Material properties of the soda lime glass.

Property	Value
Density	$2.5 \times 10^3\ kg/m^3$
Thermal conductivity	0.94 W/(m K)
Coefficient of linear expansion	8.3×10^{-6} °C
Specific heat	0.88 kJ/(kg K)
Softening point	715 °C
Refractive index	1.54 (at 355 nm)
Absorption coefficient	$1.58\ cm^{-1}$ (at 355 nm)
Transmittance	0.85 (at 355 nm)