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Investigation on material removal efficiency in debris-free laser ablation of brittle substrates

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ABSTRACT

For decades, it is a big challenge to machine glasses even using non-contact machining technology such as laser machining. The study investigated the influence of laser beam scanning mode on material removal efficiency in laser ablation of Gorilla glass using ps NIR laser pulses. The study revealed that crack-free and debris-free ablation could be achieved by optimizing beam overlaps. Optimal scanning speed was above 200 mm/s with a few pulses overlapped in one ablation spot during scanning. When laser was focused at glass bottom surface, laser energy was more efficiently employed for glass ablation due to negligible energy dispersion caused by ejected materials. The cutting time was 1.36 times and 24.5 times longer for focus at glass center and top surface, respectively. The cut kerf width was found to correlate with scanning line numbers. Optimal kerf for high material removal rate was approximately half of the glass thickness. Optimal shifting pitch between two lines was approximately a single scan line width, namely an ablation spot diameter. The cutting time was 1.51 times and 13.43 times longer for merge-mode and group-mode, respectively, when compared to scanning with raster-mode. Fixed parameter mode reduced 86% of cutting time compared to non-fixed parameter mode. Similar protocol of scanning mode for high material removal efficiency was applicable to ps NIR laser ablation of aluminosilicate glass and ns UV laser ablation of silicon substrate. Mathematical model for calculation of beam overlaps, scanning speed and line number was provided.

1. Introduction

Due to its brittle nature, glass cracks easily and edge chippings are often produced during mechanical machining. For decades, laser micromachining of glasses has attracted much attention. Overview on glass cutting by scribing and breaking, hot airjet cutting, waterjet cutting, CO_2 induced controlled fracture and laser melting and evaporation can be found in the recent review by Nisar et al. (2013).

In principle, when laser is employed to machine glasses, the optical absorption of the glass to laser beam determines laser machining competency. Yang et al. (2010) reported that as glasses absorb laser energy in a way which is highly dependent on the incident wavelength, photon absorption mechanism plays a key role in laser machining of glass materials. When the wavelength of a laser beam is above 5 μm, laser energy is highly absorbed by glasses, such as borosilicate, fused silica and soda lime. In earlier studies, Buerhop et al. (1990), Allcock et al. (1995) and Kitamura et al. (2006) have revealed that CO_2 laser radiation at wavelength of 10.6 μm is strongly absorbed through Si—O vibration mode. The strong absorption makes CO_2 laser suitable to machine glass materials. However, cracks are often generated due to CO_2 laser induced thermal stress, for example, in microchannel fabrication reported by Issa et al. (2008) and laser cleaving of glass reported by Kuo and Lin (2008).

When wavelength deceases and is in visible and NIR regions, photons are absorbed little by glasses. The poor absorption makes it difficult to machine glass using nanosecond (ns) visible and NIR lasers, such as Nd:YAG laser (1064 nm) and its second harmonics (533 nm). When wavelength continuously decreases to UV region, the shorter wavelength may provide high photon energy and thus enhance the glass absorption to lasers, such as ns excimer lasers (ArF193 nm, KrF 248 nm) reported by Tseng et al. (2007), the third harmonics of Nd:YAG laser (355 nm) reported by Nikumb et al. (2005) and the fourth harmonics of Nd:YAG laser (266 nm) reported by Chen and Darling (2008). The increased absorption makes it possible to machine glass using such lasers. The point which needs to take care is that chippings possibly with microcracks are produced in ns UV laser ablation.

On the other hand, it is well known that laser pulse width plays a significant role to influence the glass absorption to laser beam. In earlier studies, Davis et al. (1996) reported that when laser pulse

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width decreases to ultrashort level, such as femtosecond (fs), the interaction between laser pulse and glass material at the focal point becomes highly nonlinear, in a way of multiple photon absorption instead of a single photon absorption, which leads to a local photo-modification in glass. This absorption mechanism makes it possible to machine glass with fs transparent wavelengths such as visible, NIR and IR laser ablation of glasses. Varel et al. (1997) reported that the non-linear optical effects could precisely drill glasses and crystals. The unique characteristics of ultrafast lasers, such as picosecond (ps) and fs lasers, for advanced glass processing have been well-addressed very recently by Sugioka and Cheng (2014).

In the recent years, chemically surface strengthened glass developed for portable consumer electronic devices, e.g. smart phones and tablet computers, requires advanced micromachining technologies due to its high surface strength. Noted that the power stability, low pulse frequency, low pulse energy and the high cost of fs laser, micromachining of the surface strengthened glass with ps laser pulses has shown its great potential compared to fs laser. Chen and Wu (2013) discussed the nonlinear laser interaction effect in ps laser cutting of glasses. Moorhouse (2013) demonstrated the separation of the surface strengthen glass by ps laser internal scribe and break. Haupt et al. (2013) showed that shorter pulse widths such as ps reduce thermal effect and can achieve significantly high micromachining quality compared to ns width. Sun et al. (2012) and Russ et al. (2013) revealed the ablation mechanism of ps laser on glass. Rekow et al. (2014) developed a micro-ablation technique using ps laser pulses. The glass is ablated in the form of microchips until the glass is effectively cut through.

When laser ablation is used to remove materials for glass micromachining, material removal efficiency is a significant issue in view of laser micromachining throughput. Miller and Haglund (1997) and Batani (2008) disclosed that laser ablation is a process of material removal starting from the material surface through laser beam irradiation. Material removal induced by high intensity laser pulse is generally called pulsed laser ablation. The parameters which determine the laser ablation include laser parameters such as beam wavelength, beam focus, pulse energy, pulse width, pulse frequency etc. and material properties such as optical and thermal properties etc. Knappe et al. (2010) found that bursts of ps pulses with high pulse repetition frequency for micromachining can improve ablation rates. Karimelahi et al. (2014) demonstrated that rapid micromachining of high aspect ratio holes is achieved by applying flexible delivery of high repetition rate and burst trains of ps laser pulses.

When materials are cut or drilled through laser ablation, materials are ejected from the laser ablation spot. The ejected materials with the plasma generated from the former laser pulses at the cutting kerf or drilling area influence the energy deposition of the subsequent laser pulses. On the other hand, the redeposition of the ejected materials causes the so-called debris around the ablation region. Furthermore, energy accumulation from ablation with multiple pulses causes thermal effect at the micromachining zone. Debris, thermal effect, smoothness of the hole or kerf inner wall, taper and circularity of holes are the general issues involved in laser ablation. For example, the strong thermal effect and debris are produced in surface engraving with ps laser ablation demonstrated by Lopez et al. (2012), in ps laser ablation of surface strengthened and non-strengthened Gorilla glass showed by Russ et al. (2013), and in rapid micromachining of high aspect ratio holes with high frequency ps laser pulses reported by Karimelahi et al. (2014).

This study focuses on the investigation of material removal efficiency in terms of processing time during micromachining of Gorilla glass with ps laser ablation. The special effort was placed on the influence of laser beam scanning mode on the material removal efficiency in ps laser debris-free ablation of the glass.

2. Experiments

The commercially available 700 μm thick non-ion exchanged Gorilla glass substrate (Corning, USA) was ablated by a picosecond near infrared (ps NIR) laser (Time-Bandwidth DUETTO, Switzerland). This laser has a wavelength of 1064 nm, beam quality M^2 of <1.3, pulse frequency of 50 kHz to 8.2 MHz, pulse duration of <12 ps, output power of 10 W to 15 W. The laser beam was focused by a conventional lens of 100 mm in focal length which produced a spot diameter of approximately 25 μm at $1/e^2$ of the maximum beam intensity. In ablation experiments, the laser power measured after the focus lens was 3.06 W at the lowest repetition rate of 50 kHz, which produced a maximum laser fluence of 9.0 J/cm^2. The ablation was carried out through scanning of the laser beam with a galvanometer scanner. Effect of laser beam scanning mode on the material removal efficiency was investigated through evaluation of the processing time for cutting through a 5 mm length in the glass substrate. The parameters investigated on the beam scanning mode includes the scanning speed i.e. the overlapped pulse number in one ablation spot during single line scanning, focus position, overlapped line number and the shifting pitch between two lines in one ablation layer in the kerf, beam scanning under a merge, group or raster mode, and scanning with fixed or non-fixed laser parameters.

In order to study the universality of the influence of laser beam scanning mode on the material removal efficiency in laser ablation, the application of varied scanning mode was studied through ps NIR laser cutting of 100 μm thick aluminosilicate glass and Coherent ns UV laser cutting of silicon. In cutting of silicon, a 3 mm diameter hole was ablated out from a 725 μm thick silicon wafer. The UV laser system was operated at a wavelength of 355 nm, pulse width of <30 ns and pulse frequency of 40 kHz. The laser beam was focused with a lens of 108.3 mm in focal length and scanned using a galvanometer at laser fluence of 35.57 J/cm^2.

3. Results and discussion

3.1. Effect of scanning speed

As the laser beam of 1064 nm is a NIR transparent beam to Gorilla glass, it makes it possible to place the focus of the laser beam at the top surface of the glass, center of the glass thickness or bottom surface of the glass during laser ablation.

Fig. 1 is a plot of pulse number against scanning speed for a single scan of the laser beam when the focus was placed at the glass top surface. It shows that there are three regions: cracks

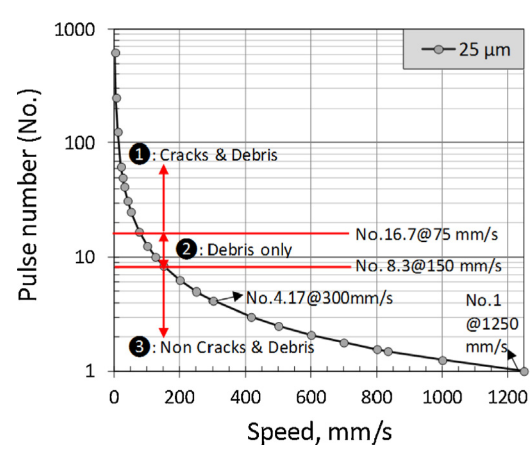

Fig. 1. Plot of pulse number versus scanning speed showing no cracks and debris produced under high laser scanning speed.