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Investigation on material removal efficiency in debris-free ps laser ablation for micromachining of glass

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Abstract
This study investigated the influence of laser beam scanning mode on material removal efficiency in glass cutting with ps NIR laser ablation. The study revealed that crack-free and debris-free ablation could be achieved by optimising the beam overlaps through controlling the beam scanning speed and the pulse repetition rate. The focal position played a significant role in the glass cutting process. Under laser focus at glass bottom surface, laser energy was more efficiently employed to ablate the glass due to negligible energy dispersion caused by the ejected materials. The cutting time was 1.36 times and 24.5 times longer for the beam focus positioned at the centre and top surfaces of the glass respectively. The cut kerf width was found to correlate with the number of scanning lines and to affect the material removal rate. An optimal removal rate was achieved at the kerf width of approximately half of the glass thickness. The pitch distance is another important factor to consider. The optimal shifting pitch was approximately a single scan line width, namely an ablation spot diameter. Compared to beam scanning under raster-mode, the cut-through time was 1.51 times and 13.43 times longer for scanning under merge-mode and group-mode respectively.

Picosecond laser ablation, debris-free and crack-free ablation, glass micromachining, material removal efficiency,

1. Introduction

In the recent years, ps lasers have shown great potential in micromachining of chemically surface strengthened glass developed for portable consumer electronic devices, e.g. smart phones and tablet computers. Chen et al. discussed the nonlinear laser interaction effect in ps laser cutting of glasses [1]. Moorhouse demonstrated the separation of the surface strengthened glass by ps laser internal scribe and break [2]. Haupt et al. showed that ps pulses can achieve significantly high micromachining quality compared to ns pulses [3]. Sun et al. [4] and Russ et al. [5] articulated the ablation mechanism of ps laser on glass. Rekow et al. developed a micro-ablation technique using ps laser pulses [6]. The glass is ablated in the form of microchips until the glass is effectively cut through.

Debris and thermal crack are the general issues involved in laser ablation of glass. Strong thermal effect and debris are produced in surface engraving with ps laser ablation [7], in ps laser ablation of Gorilla glass [5], and in rapid micromachining of high aspect ratio holes with ps laser ablation [8]. This study focused on the investigation of material removal efficiency in terms of processing time in ps laser micromachining of Gorilla glass.

2. Experiments

The commercially available 700 µm thick non-ion exchanged Gorilla glass substrate was ablated by a ps NIR laser (1064nm, $M^2 < 1.3$, 50 kHz to 8.2 MHz, pulse width < 12 ps, spot approximately Ø25 µm at $1/e^2$ after focusing). The laser power measured after focal lens was 3.06 W at 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 a 5 mm length of the glass. 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, beam scanning under a merge, group or raster mode.

3. Results and discussion

3.1. Effect of scanning speed

Figure 1 plots the pulse number against scanning speed. Three speed regions were observed: cracks and debris produced at lower speeds below 75 mm/s, cracks disappeared and mainly debris remained at medium speeds of 75 mm/s to 150 mm/s, and no cracks and debris produced at higher speeds above 150 mm/s. Figure 2 shows the optical images of a cross ablated with a single scan under varied scanning speeds. Clean surface with no cracks and minimal chippings were achieved at high scanning speeds above 200 mm/s.

At low scanning speed, more pulses were deposited and overlapped in one ablation spot. The excessive deposition of multiple pulses resulted in strong thermal shockwaves and therefore produced thermal cracks, and also caused generation of droplets to deposit at the ablation area as so-called debris, as shown in Figure 2. The optimal scanning speed for laser ablation of Gorilla glass without cracks and debris-free was above 200mm/s, i.e. 4 to 8 laser pulses deposited at a single ablation spot.

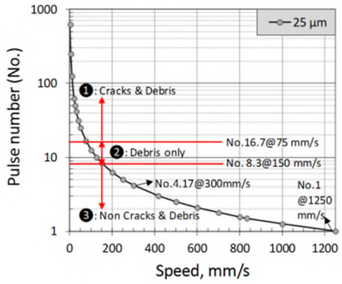

Figure 1. Plot of pulse number versus scanning speed showing no cracks and debris produced under high laser scanning speed.

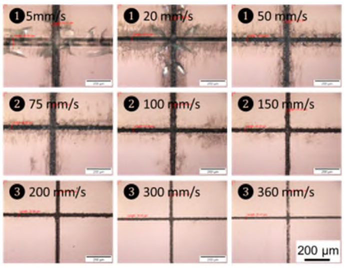

Figure 2. Optical images of a cross ablated with focus at glass top surface using a single scan under varied scanning speeds.

3.2. Effect of focus position

Results showed that the minimal processing time was achieved when the focus was at the glass bottom. The total processing time for cutting a 5 mm length was 34 sec. Ablation starting from bottom of glass avoids laser energy dispersion caused by the ejected materials and allow the ejected materials to escape efficiently from the ablated kerf. In comparison, when the focus was at the middle and top of the glass, the cutting time increased by 1.36 times and 24.5 times, respectively. The ablation surface appeared free of cracks, as shown in Figure 3.

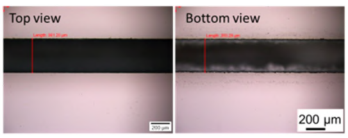

Figure 3. Optical images of the cutting kerf showing the clean surface without cracks and chippings.

3.3. Effect of number of scanning lines

The optimal number of scanning lines is determined by the optimal kerf width required for high ablation efficiency in terms of minimal cut-through time. A narrower kerf hindered ejection of the ablated materials out of the cut kerf, whereas a wider kerf led to more material removal. In practice, narrow kerf is desirable for better material usage and higher machining accuracy. The study showed that an optimal material removal rate was achieved when the kerf width was at approximately half of the glass thickness.

3.4. Effect of shifting pitch

Shifting pitch of the laser beam defines the distance between two lines during multi-line scanning in one ablation layer. The optimal shifting pitch is approximately a line width of a single scan. When the pitch was larger than an ablated line width, certain material between the two scanning lines could not be ablated due to the non-overlapping space between the two scanning lines. The pitch smaller than the ablation line width could lead to excessive overlapping of the beam, and therefore increased the scanning line numbers and caused longer machining time.

3.4. Effect of scanning mode

Figure 4 shows the schematic illustration for each scanning mode. Obviously, scanning layer by layer would create a reasonable spatial space which allowed the ablated materials to escape easily out of the kerf. Thus, group mode required a longer machining time compared to merge or raster mode. As the beam could be scanned continuously in one ablation layer in raster mode, the minimal cut-through time was achieved compared to the group or merge mode. The cut-through time increased from 31.42 sec to 47.57 sec. when switching from the raster mode to the merge mode. The cut-through time increased from 31.42 sec to 422.10 sec., when switching from the raster mode to the group mode.

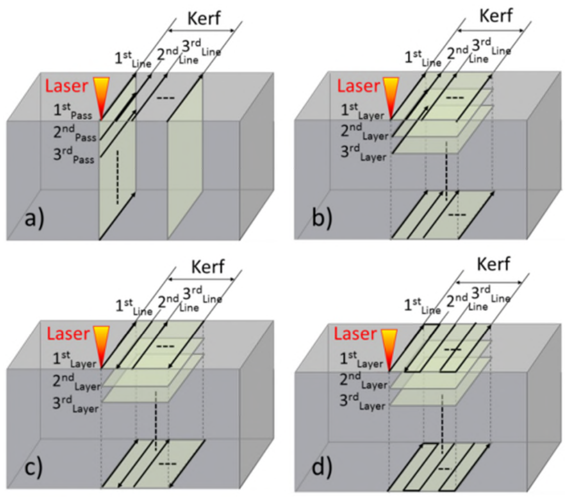

Figure 4. Schematic illustration for each scanning mode. *a) Group mode:* Scanning of first line with multi-passes, then scanning next line with the same multi-passes in the same direction. *b) Merge mode:* Scanning of multi-lines with one pass, then scanning multi-lines again with next pass layer by layer in the same direction. *c) and d) Raster mode:* Similar multi-lines scanning to merge mode but able to scan in two direction or continuous scanning.

4. Conclusions

High material removal efficiency with debris-free, crack-free in ps NIR laser ablation of Gorilla glass can be achieved with the following conditions: ablation starting from the glass bottom, in raster mode, at high beam scanning speed with only a few pulses overlapped in one ablation spot, and with kerf width of half thickness of the glass through controlling of the scanning line number and shift pitch.

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