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Influence of Pulse Duration on the Glass Cutting Process

L. Bauer[a,b,*], U. Keller[a], S. Russ[a], M. Kumkar[c], B. Faißt[c], R. Weber[d], T. Graf[d]

[a]*TRUMPF Laser GmbH, Aichhalder Straße 39, 78713 Schramberg, Germany*
[b]*Graduate School of Excellence advanced Manufacturing Engineering, Universität Stuttgart, Germany*
[c]*TRUMPF Laser- und Systemtechnik GmbH, Johann-Maus-Str. 2, 71254 Ditzingen, Germany*
[d]*Institut für Strahlwerkzeuge, Universität Stuttgart, Germany*

Abstract

Glass has recently found increasing importance in industrial markets, especially in the rapidly growing sector of display or cover glass applications for consumer electronics. However, cutting of brittle materials is a demanding process if high quality standards are required. High quality industrial glass sheets with high bending stability require minimal micro-cracks, particularly on the cut edges. Cutting techniques involving mechanical or chemical processes lead to cracks, high levels of waste and therefore high processing costs. Nevertheless, these traditional processes currently dominate this area of industrial manufacturing. In addition, the market trend is towards thinner and hardened glass, where challenging demands are placed on the processing tools and mechanical methods fail or produce high reject rates. Therefore a new processing technology is needed. Cutting with ultrafast lasers has high potential for processing brittle materials efficiently without time consuming post-processing operations (Siebert, 2012).
In this work the influence of pulse duration on the ablation process is discussed. Following our previous findings that the process parameters, such as scanning speed and average power, have a significant influence on the surface properties, which in turn affect the bending stability of the glass sample (Russ, Siebert, Eppelt, Hartmann, Faisst, & Schulz, 2013), we now investigate the influence of the pulse duration on the process by comparing the applications of pulses with 400 fs, 900 fs and 6 ps duration. The influence of the pulse duration on the ablation threshold of aluminosilicate glass is presented, the occurence of nanostructures and the impact on the quality of the cutting edge is discussed.

Keywords: micro machining, picosecond laser, femtoseconds, processing of transparent materials

* Corresponding author. Tel.: +49- 7422-515-393; fax: +49-7422-515-401.
E-mail address: Lara.Bauer@de.TRUMPF.com.

1. Introduction

Ultrashort-pulsed (USP) lasers are well suited for the processing of various materials. High precision and efficiency can be achieved with sub-picosecond lasers because the energy transfer to the atomic lattice and plasma shielding occur on a timescale longer than the pulse duration *(Perry, Stuart, Banks, Feit, Yankovsky, & Rubenchik, 1999)*. The high peak intensities of USP lasers also enable processing of dielectric materials such as glass and crystals, due to the fact that the probability of multiphoton absorption increases with increasing photon fluxes. Thus electrons are excited to the conduction band and avalanche ionization is initiated. Ablation takes place when the quasi-free electron density in the conduction band reaches a critical density *(Vogel, Noack, Hüttman, & Paltauf, 2005).*

The ablation process based on nonlinear absorption is a well established technique for cutting or engraving transparent materials. There are different processes applicable for cutting transparent materials, but they often lack the flexibility to create small geometries or shaped ablation curves. However to cut through the material multiple passes and parallel lines are necessary which makes the cutting process comparatively slow. Furthermore to achieve perpendicular edges of the cut, beam forming or a tilt of the beam axis relative to the surface of the work piece is essential *(Kumkar, et al., 2014)*. Because of the energy penetration into the volume of the material damage may appear and reduce the bending stability of the glass which is a key criterion for the machining success *(Russ, Siebert, Eppelt, Hartmann, Faisst, & Schulz, 2013)*.

To optimize the cutting process one needs to take into account the ablation threshold, the ablation rate, and the occurrence of damage. In particular we have investigated the influence of the pulse duration on the ablation properties of aluminosilicate glass. For pulse durations τ> 10 ps the ablation threshold fluence on different glass types was found to scale with $\sqrt{\tau}$ based on thermal conduction during the laser pulse *(Bloembergen, 1974)*. For pulse durations τ< 10 ps the ablation threshold fluences of fused silica have been investigated quite intensely but the values scatter in a huge range ($\Delta\phi_{th} \approx 10\ J/cm^2$) *(Sanner, et al., 2008)*. Here we report on investigations of the influence of the pulse duration on the ablation threshold of aluminosilicate glass for 0.4, 1 and 6 picosecond pulses.

The ablation was investigated for the application of both single and multiple shots. Since the ablation geometry and surface texture have an impact on the propagation of the subsequent pulses the development of nanostructures was also investigated. The occurrence of nanostructures on glass surfaces has been reported by *(Birnbaum, 1965)*. Here we compare the morphology generated by the application of different pulse durations at different stages of the ablation progress.

2. Experiments and Discussion

The experiments were carried out with lasers of the TruMicro 5000 series (TRUMPF) and an experimental laser (TRUMPF) with a wavelength of 1030 nm. The pulse durations of the TruMicro 5000 were measured to be 6 ps and 1 ps respectively and the pulse duration of the non-standard experimental laser were determined to be 0.4 ps by means of an autocorrelator. The beam quality for all lasers was $M^2 < 1.3$.
A 2D Scan System was used to achieve feedrates that guarantee well separated pulses. A quarter-wave plate was used to obtain circularly polarized light on the work piece. A focal length of 160 mm was chosen for the experimental determination of the ablation threshold. The pulse energy was varied from 2 to 250 µJ.
All experiments were performed on aluminosilicate glass (Corning Gorilla, chemically non-strengthened) with a thickness of 0.7 mm.

2.1. Single Pulse Ablation Threshold

The ablation threshold was investigated following the method of *(Liu, 1982)*. The single-pulse ablation threshold is defined as the minimum peak fluence necessary for ablation. For a Gaussian beam, the radial distribution of the fluence is given by

$$\phi(r) = \phi_0 e^{-2\left(\frac{r}{w_0}\right)^2} \tag{1}$$

with the peak fluence ϕ_0 and the e^{-2}–radius w_0. Presuming that the material cannot be ablated by fluences below the threshold fluence ϕ_{thr}, the diameter of the ablation produced by the Gaussian beam is given by

$$D^2 = 2w_0 ln(\phi_0) - 2w_0 ln(\phi_{thr}). \tag{2}$$

With the relation between pulse energy *E* and peak fluence

$$E = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \phi(x,y)\, dx\, dy = \frac{\phi_0}{2}\pi {w_0}^2 \tag{3}$$

Equation (2) can be written as

$$D^2 = 2w_0 ln(2E) - 2w_0 ln(\phi_{thr}\pi {w_0}^2). \tag{4}$$

The diameter *D* of the ablation craters produced by single pulses was measured by means of an optical microscope. Since the accurate knowledge of the radius w_0 is crucial and may be influenced by experimental conditions *(Mannion, Magee, Coyne, & O'Connor, 2003)*, the actual value of w_0 was extracted together with the threshold fluence ϕ_{thr} from the linear fit to the squared diameter plotted over the natural logarithm of the pulse energy shown in Fig. 1.

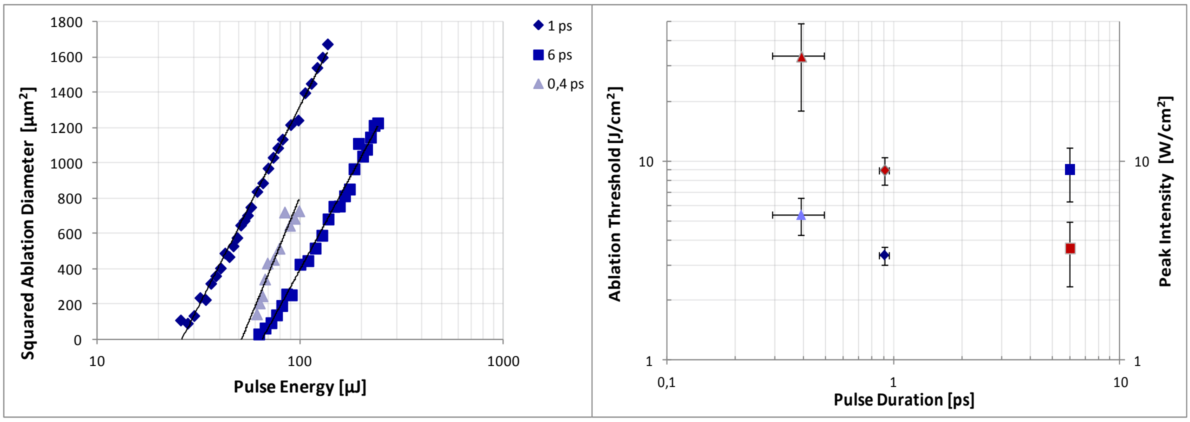

Fig. 1. Determination of single pulse ablation threshold fluence for 0.4 ps, 6 ps and 0.9 ps pulses.

Fig. 2. Dependence of threshold fluence for single-pulse ablation on the pulse duration (blue data points) and corresponding threshold (temporal) peak intensity (red data points).

The single spot ablation thresholds for the different pulse durations are shown in Fig. 2 as blue data points. The results show that the ablation threshold does not scale with $\sqrt{\tau}$ law as would be expected from pure thermal considerations.

For pulse durations of 1 and 0.4 ps the ablation threshold is smaller than for 6 ps. For 0.4 ps pulses we have found an increased ablation threshold as it was already reported by *(Du, Liu, Korn, Squier, & Mourou, 1994)*. The various reports, however, still leave some inconsistencies. Most authors assume monotonically decreasing ablation fluences with decreasing pulse durations *(Sanner, et al., 2008)*. According to *(Sanner, et al., 2008)* we assume that the measurement method is responsible for a scattering of results. It furthermore is essential if the single or multishot threshold is investigated and if only the ablation is investigated or surface modifications are considered for the determination of the threshold fluence.

The (temporal) peak intensities corresponding to the threshold values of the fluence shown by the red data points in Fig. 2 point out that the ablation mechanism is not only dominated by the multiphoton ionization since there the values increase for shorter pulses. It may be expected that the avalanche ionization is still a crucial mechanism at this regime of pulse duration.

2.2. Nanostructures

In order to be able to investigate the evolution of the ablation geometries and the formation of nanostructures, the glass sheets were processed by single and multiple pulses with peak fluences ϕ_0 in the range of $0.9 \leq \phi_0/\phi_{th} \leq 1.8$.
Pauses with a duration of >> 1 ms between the pulses were applied to prevent heat accumulation effects. Selected scanning-electron micrographs of the samples processed with 0.4 ps pulses are shown in Fig. 3. The number of pulses is given on the x-axis and the pulse energy is displayed on the y- axis (left). The y- axis on the right shows the ratio of peak to threshold fluence.

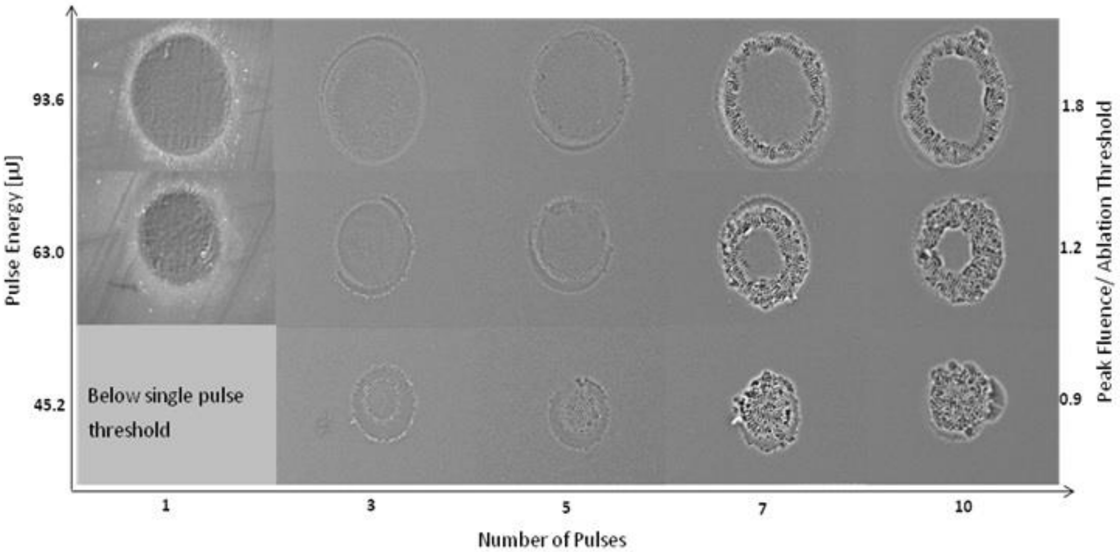

Fig. 3. SEM pictures of surface processed with single shot and multi shot pulses with a pulse width of 0.4 ps. From left to right: number of pulses increases. Bottom to top: Pulse energy is increased.

Even with pulses which each provide a peak fluence below the single-pulse ablation threshold ($\phi_0 = 0.9\ \phi_{th}$), a series of three pulses is nevertheless able to generate material removal. Two areas with different features are formed. The areas can be distinguished between an inner area which shows a wavy structure and an outer area which is rather smooth. With five pulses the inner area shows a deeper corrugated structure and the surface of the outer area is still apparently smooth. With the application of additional pulses the inner, corrugated area spreads out and after ten pulses it covers the whole irradiated area and some chipping at the border to the unmachined surface can be seen. As expected, at pulse fluences $\phi_0 = 1.2\ \phi_{th}$ beyond the ablation threshold, surface modifications are generated already by one single pulse. After the application of three pulses again two areas are formed but in contrast to the case with pulses below the threshold the deep corrugation now starts in the outer region and spreads inwards with increasing number of pulses. After ten pulses the outer area is deeply corrugated while the inner area is still smooth. With pulses with peak fluences of $\phi_0 = 1.8\ \phi_{th}$ the same behavior occurs but with a smaller deeply corrugated area. Apparently the deeply corrugated area is always formed at fluences close to the threshold of a single pulse.

The features shown in Fig. 3 were generated by pulses with a duration of 0.4 ps. A comparison of the results obtained by applying pulse with the three different durations of 0.4 ps, 1 ps, and 6 ps and a peak fluences of $\phi_0 = 1.8\ \phi_{th}$ are shown in Fig. 4. The pictures on top show the result of single pulse ablation. The single pulse ablation with 0.4 ps exhibits small splashes at the side (cf. Fig. 4 (a)) and the modified area is wavy with shallow bulges. In contrast, the ablation crater generated by the pulses with a duration of 6 ps shows a ripple-like structure and small holes in the surrounding area (cf. Fig. 4 (c)). As shown by the lower row of pictures, the features observed after the application of ten pulses are quite different to the ones generated by one single pulse. With pulses of 6 ps the corrugated area covers the whole spot, with chipping at the side, whereas for pulses of 0.4 ps the corrugation only occurs at the edge of the ablated area, is less

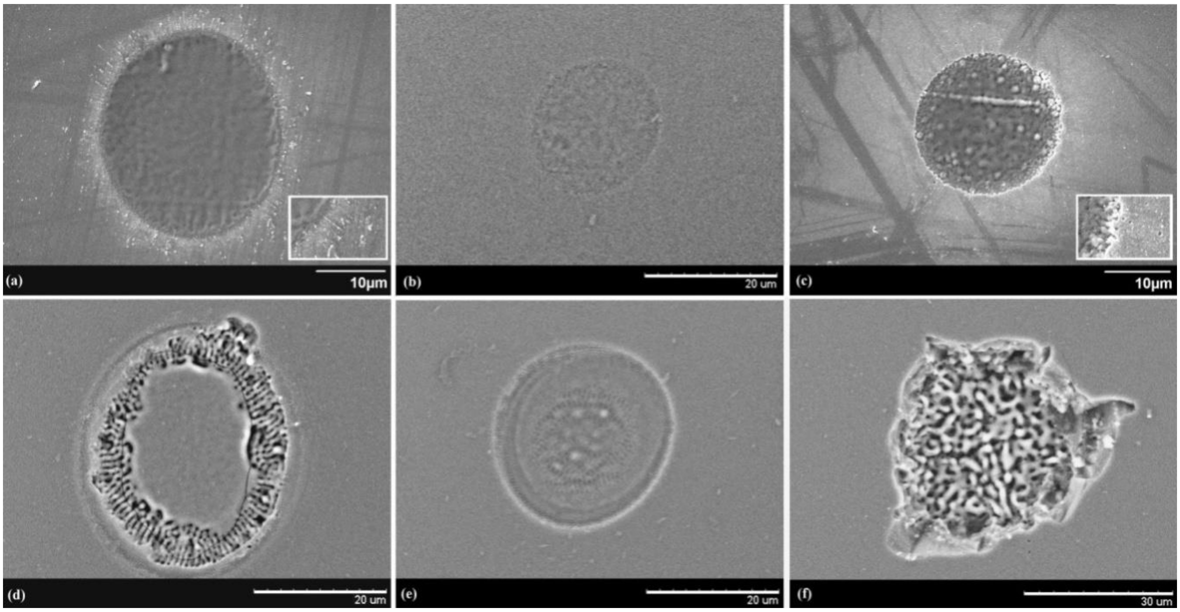

Fig. 4. (a)-(c) Ablation crater caused by a single pulse with a pulse duration of 0.4, 1 and 6 ps and fluences $\phi_0 = 1.8\ \phi_{thr}$. (d)- (f) Ablation crater caused by 10 pulses with a pulse duration of 0.4, 1 and 6 ps and fluences $\phi_0 = 1.8\ \phi_{thr}$.

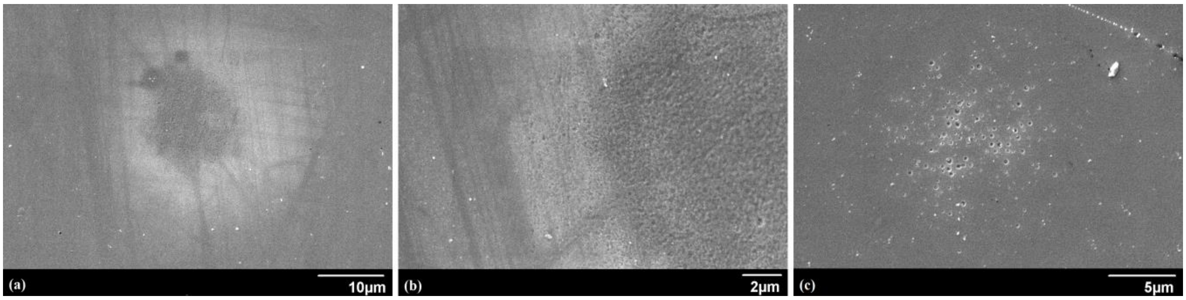

Fig. 5. (a) Surface modification induced by a 0.4 ps single pulse with a fluence below the single spot ablation threshold (b) magnification of the structure (c) impact of a 6 ps single pulse with a fluence below the single spot ablation threshold.

coarse, and looks more periodic. Surprisingly for a pulse duration of 1 ps, there is no deep corrugation visible.

That the ablation threshold is reduced for a higher number of pulses was already described by *(Jee, Becker, & Walser, 1988)*. Our experiments confirm this finding but still raise the question on the reason for the decreased threshold for multishot ablation. The surface of a sample after the incidence of one single pulse with a fluence below the experimentally found threshold fluence was therefore investigated in more detail. The scanning-electron microscope pictures shown in Fig. 5 indeed show noticeable material modification induced already by these low-energy pulses.

For pulse durations of 0.4 ps a modified area is visible surrounded by an area covered with nanoparticles. In the detail picture Fig. 5 (b) a fine structure is visible. For pulse durations of 6 ps holes with diameter in the sub micrometer range were found instead. It was stated by *(Perry, Stuart, Banks, Feit, Yankovsky, & Rubenchik, 1999)* that when the carrier density produced by multiphoton ionization approaches a critical value, the material will have metal like behavior and morphology. For short pulses (eg. 0.4 ps) with a fast temporal rise of the intensity a fast generation of carrier electrons occurs and the stage of metal like behavior is reached on a shorter timescale. Therefore we observe metal like surface texture (cf. the similarities of corrugations of metals in *(Perry, Stuart, Banks, Feit, Yankovsky, & Rubenchik, 1999)*) for the short pulse durations. A slower temporal rise of the intensity of the longer pulses (6 ps) could be the reason why the electromagnetic wave penetrates further into the material before the electron density reaches the critical value and material modification occurs with a deeper structure.

A similar modification of the surface emerges at the cutting edges during the ablation process where the laser is scanned over the material several times to ablate a groove as shown in Fig. 6. Due to the tilted walls of the groove the absorbed fluence on the angled walls is reduced and eventually is in the range of the threshold fluence for ablation. *(Russ, Siebert, Eppelt, Hartmann, Faisst, & Schulz, 2013)* described this effect for the ablation process of glass and explained the occurence of a maximum taper angle. Considering our findings from above it is now plausible that the nanostructures also occur at the cutting edges, where the fluence is near the ablation threshold.

Fig. 6 (b) and (c) show a comparison of the structures generated by multishot ablation with 6 ps pulses and fluences close to the ablation threshold to structures observed at the walls of a cutting groove.

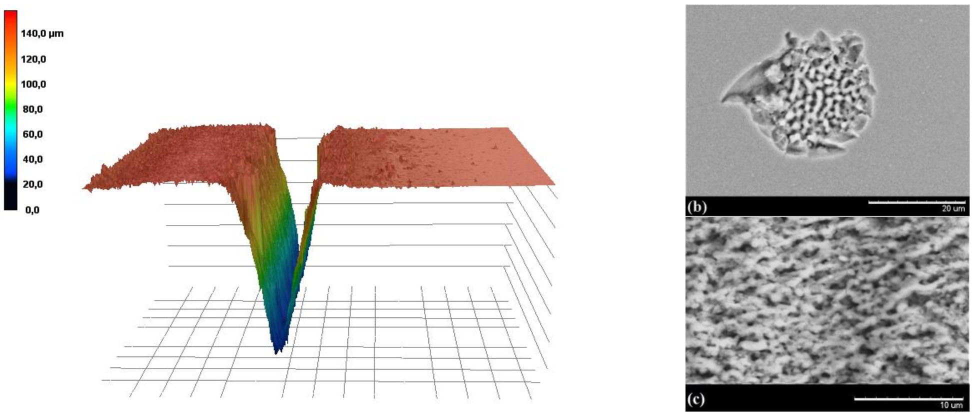

Fig. 6. (a) Image of the ablation geometry measured with a laser scanning microscope. (b) Structure generated by 10 pulses with 6 ps pulse duration and fluences close to the ablation threshold. (c) Surface condition of the cutting front.

3. Conclusion

In summary we reported on our investigations on the single-pulse ablation threshold fluences on aluminosilicate glass for pulses with durations of 0.4, 1, and 6 ps. For pulse durations of 1 and 0.4 ps the ablation threshold fluences were lower than for 6 ps. For 0.4 ps pulses we found an increased ablation threshold than for the ablation threshold fluence of 1 ps.

The analysis of multishot ablation indicates that material modification occur already at fluences below the single pulse ablation threshold. Systematic investigations of the nanostructures generated by single- and multi-shot ablation have shown that the modification is generated at fluences close to the ablation threshold.

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