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# Tuning the Energy Deposition of Ultrashort Pulses inside Transparent Materials for Laser Cutting Applications

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**Abstract**

Laser cutting of sheet like brittle materials, in particular glass and sapphire, is attracting attention for an increasing number of applications for the display industry, micro optics, micro electronics and others. Nonlinear absorption in the bulk of transparent materials enables tailored energy deposition for cleaving even along complex contours. The separation can be induced by transient effects, the separation plane defined by permanent modifications.
We demonstrate examples of tuning the energy deposition by controlling the geometry, the density and accumulation of the energy absorbed in the bulk. The influence of pulse duration, pulse groups, repetition rate, feed rate and beam shaping on the absorption, the inscribed modification and the cutting results are presented. This enables developing different processing strategies for cutting applications covering a broad range of materials and requirements.

Keywords: Micro Processing, Micro Cutting; Processing of Transparent Materials

## 1. Introduction

Ultrafast (UF) lasers offer a plurality of different processing strategies for machining of transparent materials based on nonlinear absorption. Machining of display or cover glasses for consumer electronics by UF-Lasers is gaining attention beside other applications. Ablative machining is a well established technology for cutting and drilling of these components. It is well known that the penetration of energy into the bulk of these brittle materials is crucial for the quality of processed parts (*Russ et al, 2013*). As illustrated in Fig. 1

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there are other processing technologies relying on a controlled energy deposition by nonlinear absorption of laser pulses inside the bulk of transparent materials. Index modification can be applied for writing of wave guides or gratings. Welding by localized heat generation at the junction is well known. In this study, we analyze the material separation by volume modifications, either by thermal or mechanical stress generation or by selective laser etching (*Hörstmann-Jungemann, M. et al, 2010*) in particular. For inscription the beam is typically translated with respect to the sample in a multipass procedure. For complex contours and high quality separation, a huge number of well positioned modifications have to be generated, resulting in a low overall processing speed and demanding tools.

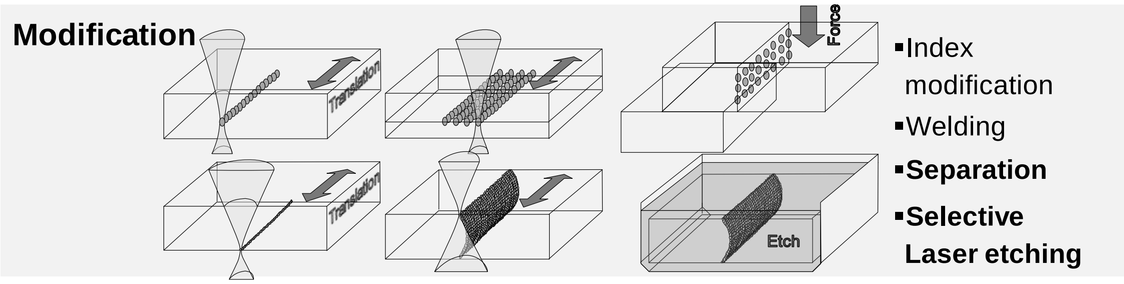



Fig. 1. Processing by modification via energy deposition inside the bulk of transparent materials induced by nonlinear absorption of UF laser pulses.

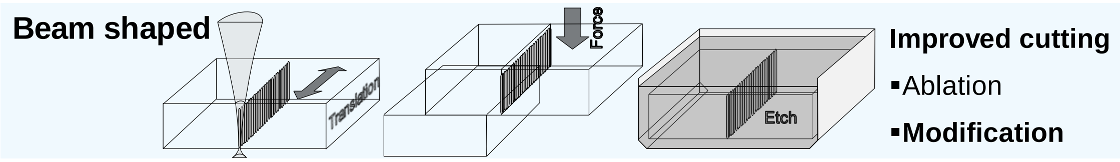



Fig. 2. Beam shaped laser processing, e.g. improved cutting by single pass process with modification over the entire substrate thickness.

Improved processing can be achieved by beam shaping and adaption of processing parameters (Kumkar et al, 2014). Fig. 2 visualizes an example of single pass modification for separation via stress or selective etching, resulting in significant reduction of processing time and overall improved quality.

In this paper we present some of our observations and conclusions aiming on identifying levers towards tools and their application for industrial processing of transparent materials.

## 2. Experimental setup

The modifications were inscribed into the sample mounted on translation stages by UF lasers with wavelength 1030 nm by means of fixed optics. For separation the focused beam was directed perpendicular to the sheet (Fig. 3a) and for detailed analysis of the modifications the beam was coupled into the sample through a polished edge (Fig. 3b). Most of the experimental work presented here was carried out by using laser systems based on the TruMicro 5000 series (TRUMPF). For pump probe measurements a PHAROS-SP laser (Light Conversion Ltd) was used in a setup up offering a collimated probe with pulse duration of 200 fs perpendicular to the focused pump and imaging of the interaction region (Fig. 3b). Zero time delay was defined as the occurrence of first changes in the images, therefore was not fixed for all experiments. We inspected the modifications (Fig 3c) additionally by optical microscopy (OM), the cut surface furthermore by laser scanning (LSM) and scanning electron (SEM) microscopes.

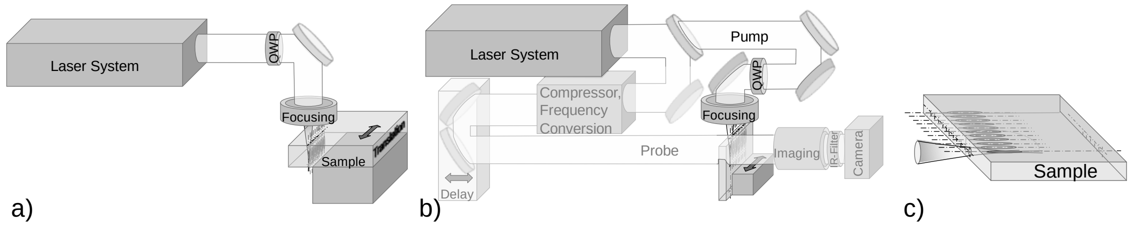



Fig. 3. (a) Setup for UF laser inscription of elongated modifications using fixed optics and sample translation. (b) Experimental setup for inscription of elongated modifications through a polished edge of the sample by a pump beam. The interaction region is illuminated by a collimated probe beam and imaged into a camera. The setup offers the option for compression and frequency conversion of the probe beam. (b) Sample and inscription, illustrating the region of interaction and modification.

## 3. Elongated modifications

We carried out extensive studies on the influence of focusing conditions, pulse duration, repetition rate and pulse groups of different numbers and intervals, without translation and at different translation speeds.

Moderate focusing of a single pulse of 1 ps duration into the sample resulted in just minor visible modifications for the whole range of pulse energies from 40 to 200 µJ (Fig. 4a). A modified refractive index in the focal region was observed beside a “shadow region” extending from the focal region towards the beam entrance. Applying an increasing number of pulses with energy of 200 µJ at a repetition rate of 200 kHz onto the same position resulted in an extended melt zone due to accumulation (Fig. 4b).

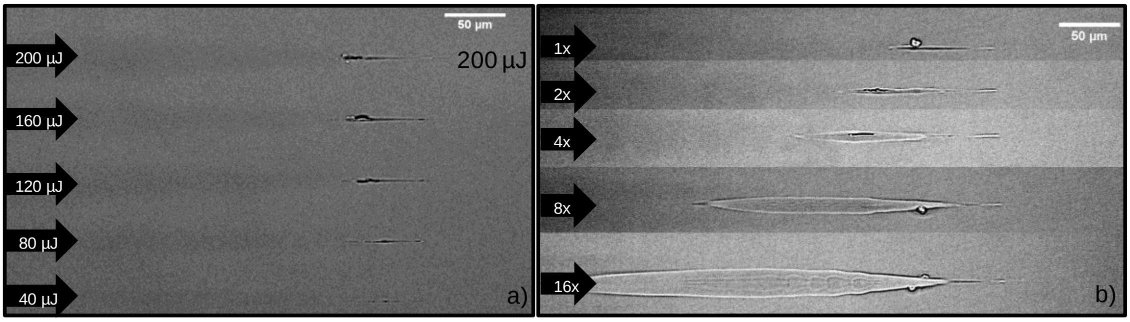



Fig. 4. Microscopic images of modifications inscribed in Corning Gorilla® with 1 ps pulse duration. Collimated beam diameter 4 mm, focusing lens f = 20 mm. (a) Single pulse with different pulse energies, beam direction indicated. (b) Different number of pulses at 200 kHz as indicated, pulse energy 200 µJ.

The effect of accumulation under translation is shown in Fig 5 for pulses with energy of 80 µJ. Just a minor modification was observed for a single pulse applying standard focusing of the Gaussian beam (Fig. 5a). During translation of 4.5 µm between successive pulses accumulation effects resulted in a remarkable shift of the visible modifications towards the beam entrance, accompanied with a slight elongation (Fig. 5b). By dividing the pulse into eight identical sub pulses of 10 µJ with an interval of 3 ns between successive sub-pulses a more pronounced modification with negligible shadow region was achieved (Fig 5c). Under translation an extended, connected melt zone was generated (Fig. 5d).

Using special focusing optics allowing for beam shaping an extended modification in longitudinal direction became visible even for a single pulse of 80 µJ of 1 ps duration (Fig. 5e). The profile of the refractive index modification was in good agreement with the calculated intensity profile. Translating 5 µm between the pulses the individual profiles of each pulse were still visible, even at a repetition rate of 200 kHz. Splitting the pulse into a pulse group of eight pulses resulted in a long modification region with voids generation located at the regions of highest intensity (Fig. 5g). With a translation of 5 µm between successive pulse groups, these void regions were visible for each pulse even at 200 kHz. Since furthermore there was no visible shift with respect to the modification of the first pulse, accumulation between successive pulse groups was reduced significantly by beam shaping.

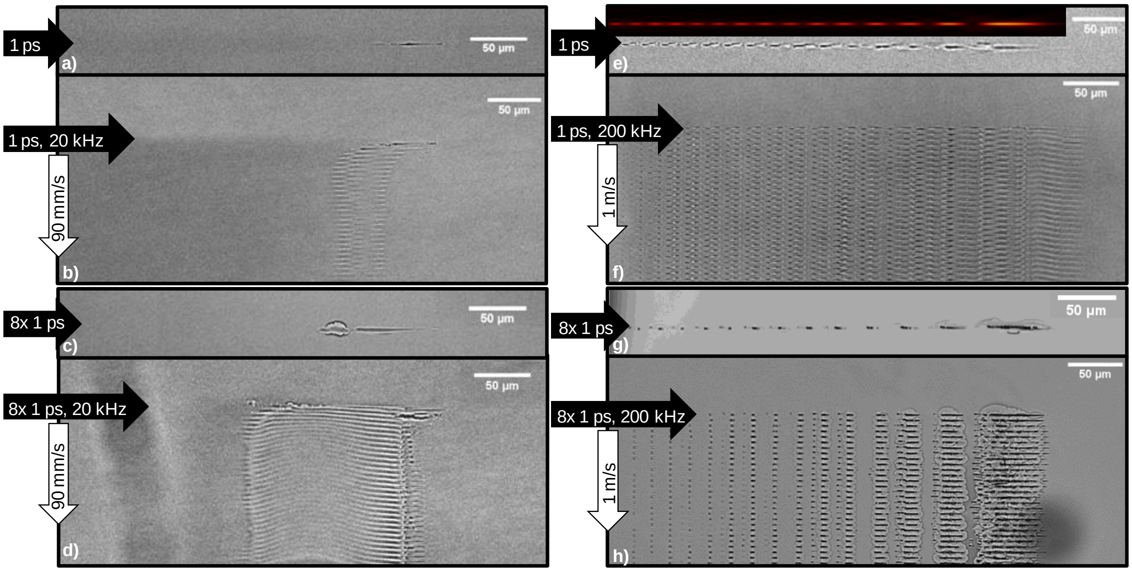



Fig. 5. Microscopic images of modifications inscribed by 80 µj pulses of 1 ps duration. (a - d) Gaussian beam. (e - f) beam shaped. (a) Single pulse, direction of beam propagation indicated. (b) Modifaction by pulses at 20 kHz repetition rate at translation speed of 90 mm/s; directions of beam propagation of first pulse and translation indicated. (c) Group of 8 pulses with interval of 3 ns and overall energy of 80 µJ. (d) Modifications by pulse groups as in (c) at 20 kHz repetition rate and translation with 90 mm/s. (e) Single pulse beam shaped, calculated intensity profile is inserted in the upper left corner. (f) Modification by beam shaped pulses at repetition rate of 200 kHz an translation of 1 m/s. (g) Group of 8 beam shaped pulses with interval 3 ns and overall energy 80 µJ. (h) Modifications by pulse groups as in (g) at repetition rate of 200 kHz at translation with 1 m/s.

We compared standard and beam shaped focusing in pump probe experiments (see Fig. 3b).

In Fig. 6a the calculated on axis intensity for standard focusing of a Gaussian beam is shown, a 2D cross section of the intensity profile is given below. Corresponding pump probe images are given in Fig. 6b for different delays between the 6 ps pump and 200 fs probe beams. The nonlinear absorption was initiated at the position of the geometrical focus. During the rising edge of the pulse the absorption was expanding towards the beam entrance, resulting in an overall growing of interaction volume in direction opposite to the beam propagation. Shielding effects prevented the buildup of absorption behind the focus. The maximum lateral extend was reached in front of the focus, the interaction time and absorbed energy density was dependant on the longitudinal position within the interaction volume.

The calculated on axis intensity and cross section of a rotational symmetric “longitudinal flat top” profile is shown in Fig. 6c. For such beam shapes the buildup of absorption was nearly simultaneous and the lateral extend did not change significantly over the whole length of the profile (Fig. 6d). By designing a “longitudinal modulated flat top” (Fig. 6e), we were able to generate an elongated, modulated absorption profile (Fig. 6e). The individual absorption regions were growing slightly in length during the pulse, nearly filling the gaps.

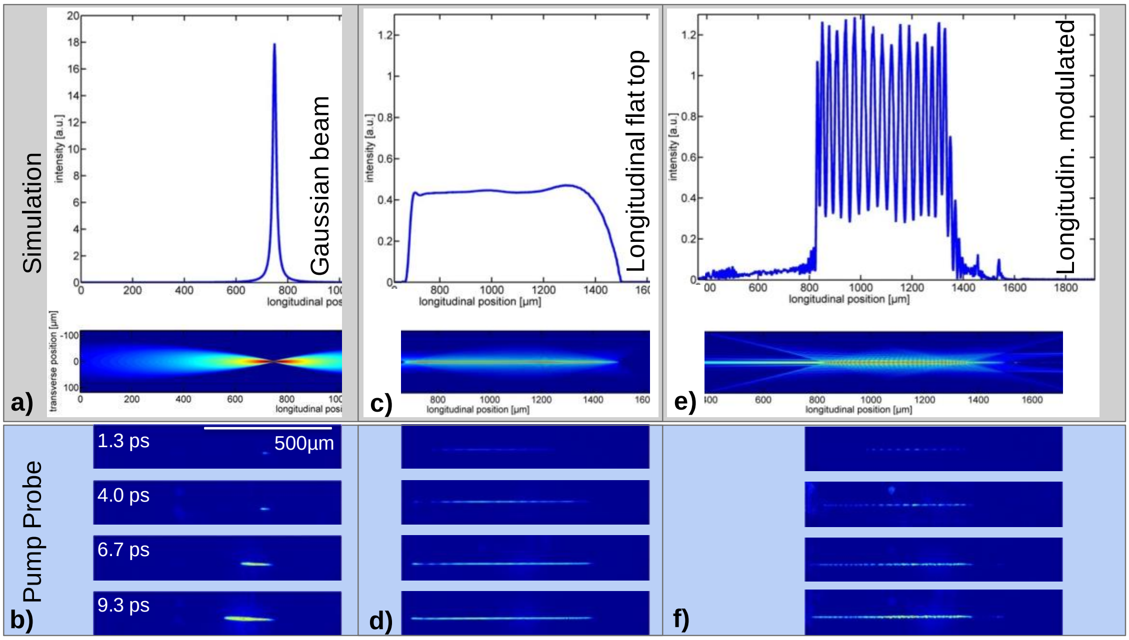


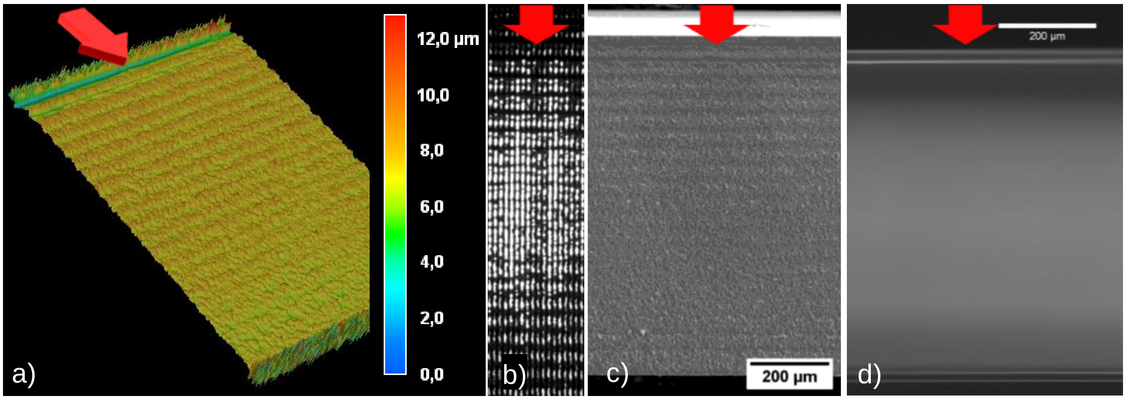

Fig. 6. Calculated intensity profiles (a , c, e) and corresponding pump probe images (b, d, f) for 6 ps pump and 200 fs probe and 70 µJ of pulse energy. (a) Calculated on axis intensity of focused Gaussian beam and logarithmic scale cross section intensity profile below. (b) Pump probe images at Gaussian beam focusing for increasing delay of probe. (c) Calculated on axis intensity and cross sectional intensity of circular symmetric “longitudinal flat top” profile. (d) Pump probe images of longitudinal flat top profile for increasing delay of probe. (e) Calculated on axis intensity and intensity cross section of circular symmetric “longitudinal modulated flat top” profile. (f) Pump probe images of longitudinal modulated flat top profile for increasing delay of probe.

## 4. Separation based on elongated modifications

As shown by the examples presented above, in contrast to standard focusing, beam shaping combined with temporal tailoring of pulses offers high flexibility for tuning the energy deposition inside of transparent materials based on nonlinear absorption. The potential resulting from essentially independent control of interaction volume by beam shaping and type and strength of modification by energy, duration and the interval of the pulses is exemplified for separating Corning Gorilla® glass with 700 µm thickness (Fig. 7).

For non strengthened glass permanent modification were inscribed using pulses of 6 ps duration by applying a modulated beam shape (Fig. 7b, compare Fig 3c). Following the inscription (compare Fig. 3a) cleaving was achieved by a moderate force in a subsequent step (compare Fig. 2), resulting in edges shown in Fig 7a and Fig. 7c with corresponding processing parameters on left side Fig. 7d.

For strengthened glass a mirror-like edge surface was achieved by standard focusing of 1 ps pulses (Fig. 7d, parameters right column Fig. 7d). Separation took place directly after inscription, induced by the temperature profile generated. Typically the cleaved surface we achieved by such a transient process was not straight but was curved in direction of beam propagation. We assume that cleaving developed along regions of maximum tensile stress, located not in the center but in the outer region of the interaction volume. For strengthened glass we were able to generate such a mirror-like surface by single pass processing reliably even for slightly curved contours. However, for non-strengthened glass it was hard to control separation for such processes based on accumulation between successive pulses, it is complicated to cleave along complex contours and to adapt the process for different processing speeds. In contrast, inscription of permanent modifications by shaped beams is more robust, can be used for cleaving of non-strengthened glass for different distance of individual modification and translation speeds without the need of adapting pulse energy, and furthermore is suitable for complex contours (Fig. 9).




e)

| Material | Corning Gorilla® | Not strengthened (a, b, c) | Chemically strengthened (d) |
|---|---|---|---|
| Repetition rate | kHz | 20 | 200 |
| Pulse energy | µJ | 70 | 100 |
| Pulse duration | ps | 6 | 1 |
| Rayleigh length (Air) | µm | Beam Shaped | 68 |
| Translation speed | mm/s | 50 | 220 |
| Number of passes | - | 1 | 1 |
| Definition of cut surface | - | Through permanent modifications | Based on transient effects |

Fig. 7. Separation of glass, thickness 700 µm. Direction of beam propagation indicated. (a) LSM measurement of cleaved edge achieved by modulated beam shape. (b) Dark field image of modification inscribed inside glass. (c) Microscopic mage of cleaved edge achieved by modulated beam shape. (d) Microscopic image of cleaved edge achieved by standard focusing of Gaussian beam. (e) Processing parameters corresponding to pictures (a – c) and (d) respectively.

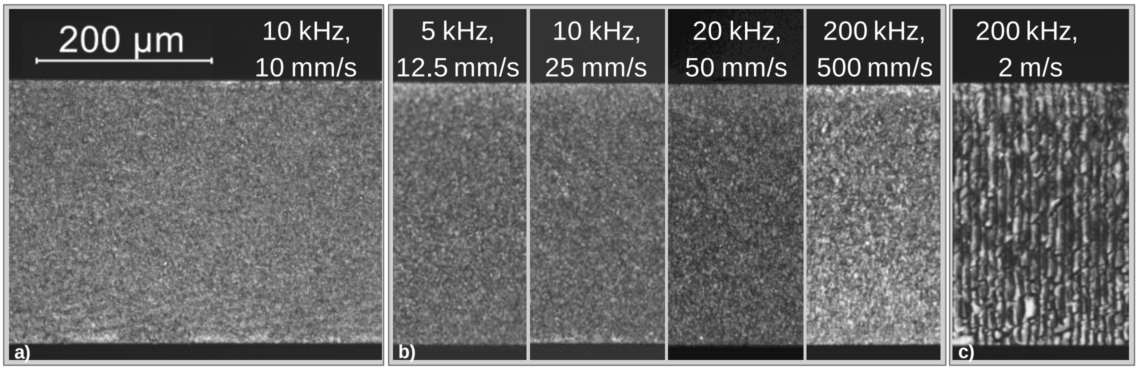



Fig. 8. Scaling of inscription speed for separation Corning Eagle® glass with 300 µm thickness, shaped beam, pulse duration 6 ps. (a) Translation of 1 µm, (b) of 2.5 µm and (c) of 10 µm between successive modifications.

As a further example demonstrating the potential of beam and pulse shaping, we inscribed modifications extending from the entrance to the rear side of the sample in a single pass suitable for selective laser etching (Fig. 10). The contour was inscribed in the chemically strengthened glass, afterwards etched in KOH-solution with an etch rate of about 5 µm/min at a selectivity exceeding 100/1. The samples were not separated during etching, but ink penetrated into the gap over the whole circumference and thickness (Fig. 10c). After pushing the inner part out, the inspection of the hole by SEM revealed a straight edge of high quality (Fig. 10d,e)

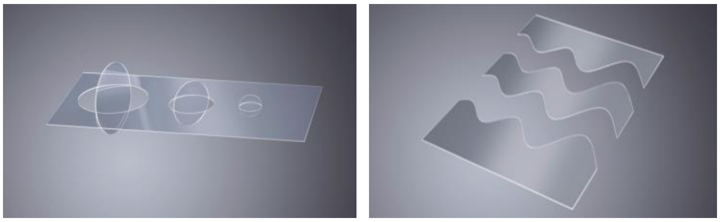


Fig. 9. Examples for separation Corning Eagle® of 300 µm thickness with shaped beam with UF laser at 6 ps pulse duration

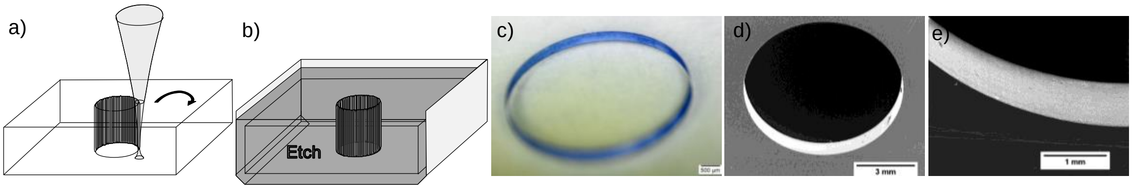



Fig. 10. Single pass selective laser etching of chemically strengthened Corning Gorilla® glass with thickness 700 µm based on elongated modifications (a) Schematic of inscription and (b) of etching process. (c) Image showing ink penetration after etching. (d) SEM image of etched hole and (e) of detail

## 5. Conclusion

The results presented demonstrate the potential of tuning the energy deposition of ultrafast lasers by adapting the pulse energy, duration and interval in addition to beam shaping. A mirror-like surface quality could be achieved in a self cleaving single pass process based on a modification resulting from accumulation effects. Robust processing suitable even for complex contours allowing separation in a process after modification was enabled by permanent elongated modifications of small lateral extend by means of beam shaping and adaption of temporal pulse parameters. The results from this experimental work facilitate the development of powerful industrial tools and processing strategies.

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