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Cleaving tailored edges and curved surfaces of transparent materials by ultrafast lasers through advanced beam shaping concepts

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Abstract

Concepts for laser cleaving transparent materials through volume modifications and mechanical, thermal or chemical separation gained increasing recognition for a broad bandwidth of industrial use using industrial ready ultrafast lasers and application specific adapted optics. The fully controlled deterministic energy deposition into the working volume is achieved by advanced spatio-temporal beam shaping. With these concepts single-pass, full-thickness modifications with m/s-feed rates were demonstrated for plane substrates with complex inner and outer contours. Thicknesses of up to more than 10 mm at the same time with low edge roughness, low chipping and high edge stability have been achieved. Substrates with tailored edges as known from chamfered, beveled or c-shaped edges will protect the glass article by reducing cross sections and by improving impact resistance. This enables a reduction of potential edge fractures, an increased edge stability as well as the capability of e. g. curved surfaces. The efficacy of our concepts is presented by evaluating surface and edge qualities of different separated glass structures.

Keywords: ultrafast lasers; ultrafast optics; beam shaping; transparent materials

1. Introduction

Laser cutting of transparent materials through volume modifications followed by mechanical, thermal or chemical stress separation have been successfully industrialized within recent years. [1–3] This was enabled by and lead to industrial ready ultrafast laser sources, such as a TruMicro 2000 series laser platform[4], as well as adapted processing optics, e. g. TOP Cleave for laser cutting. [3] Here the deterministic energy deposition in the volume of the transparent material is achieved by a spatio-temporal beam shaping. [2,5] The advantage of these

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concepts compared to self-modulated filamentation (e. g.) is a higher degree of freedom, enabling complex inner and outer contours beyond already demonstrated single-pass modifications for material thicknesses of up to 10 mm at m/s-feed rates, see Fig 1.

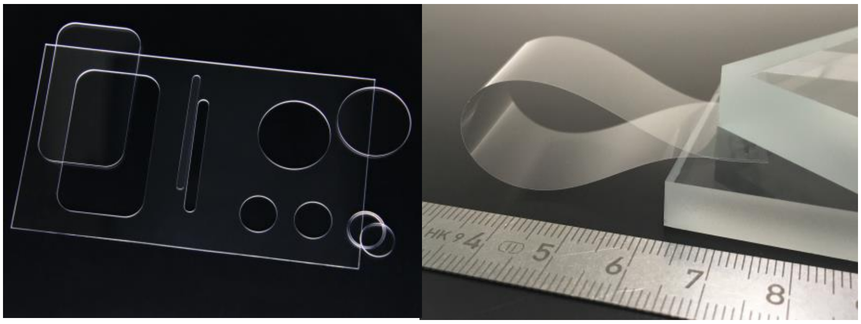

Fig. 1. Selected glass cutting examples highlighting the performance of the TOP Cleave cutting optics (left). Cutting of 10 mm-thick soda-lime glass using high energy ultrafast laser platforms, such as TruMicro 5000 series, emitting 1.5 mJ pulses (right) plus complex inner contours separated by ultrasonic bath[17] plus controlled cutting of ultrathin glass with thickness < 30 µm (right).

Most recently there is an increasing demand for these complex geometries, especially for customized glass edges structures. Beyond visual advantages these geometries improve the edge stability of the sample leading overall to a significantly decrease of fractures. Apart this specific need especially for displays there is an increasing demand for more complex geometries, such as curved surfaces as required in large quantities from medical industry for syringes, ampules, viols etc. (ampoules, e. g.).

In this paper we will present state of the art cleaving strategies for plane substrates of transparent materials. Furthermore, we will introduce enhanced industrial techniques to realize chamfer, bevels and cutting of curved surfaces. For all of these complex geometries achieved by enhanced beam shaping a strict aberration correction is required in order to compensate phase disturbances due to beam transition given by tilted or curved surfaces.

2. Tailored-Edge Cleaving

Cleaving of transparent materials as presented in Fig. 1 can be achieved by laser beam shaping, where the energy deposition is extended homogeneous over the entire material thickness. In these cases, the material is usually separated without any taper angles, hence α=90° (see Fig. 2).

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Fig. 2. Comparison of different edge geometries for reducing the edge angle α from the typical perpendicular situation (α = 90°, see straight case on the left) and to increase edge stability especially when local cracks are weakening the substrate.

However, in order to improve the quality by protecting the edge from cracks and chipping in case of an impact, it is required to reduce the edge angles, ideally to α=45° for bevels as well as chamfers. So far this was realized by mechanical processes which were supposed to be replaced by a laser driven process since this would allow to avoid high effort post processing such as polishing, e. g.Even more sophisticated is the realization of a c-shaped glass edge, as energy needs to be deposited along an accelerating trajectory with local tangential angles alpha = (90 … 45)° (or even less). For this, non-diffracting beams are state of the art[5].

2.1. Inclined focus distribution

In general, from an engineering point of view, it is preferred to have a vertical orientation of the processing head relative to the workpiece. Thus, the obvious approach is to incline the focus distribution optically by applying controlled tilt aberrations. Using this concept, non-diffracting beams can be generated with incliniation angles of ~10° to the non-diffracting beam. An inclined non-diffracting beam can be achieved either by introducing this aberration to the corresponding optical field or simply by transverse misalignments to the focusing unit. Although these angels are relatively small (of up to ~ 10° in vacuum, corresponding to ~ 7 ° in glass) the optical realization is quite simple. Hence complex setup, such as rotational axis systems, can be avoided[25]. It has to be mentioned that these tilt angels are, besides an already noticeable effect for edge protection, sufficient for the separation of inner contours for material thicknesses of more than 100 µm [25,26].

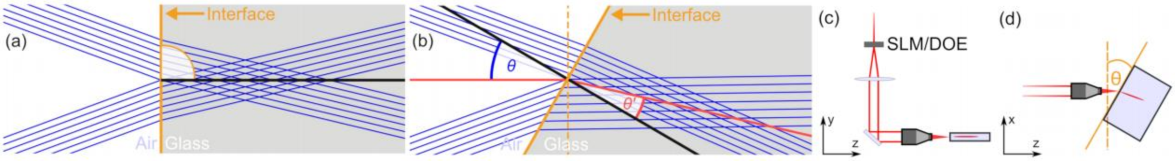

Fig. 3. Ray optical representation of the non-diffracting beam's focus situation for incident illumination θ = 0 (a) and for inclined illumination θ > 0 (b).[21] Corresponding schematic of the optical setup with an SLM or DOE as axicon-like element implemented into a 4f-setup (c) with definition of the inclination angle θ (d).[21] In this concept the refraction angle θ' (b) can be identified with the edge angle definition of Fig. 4, thus α = 90° − θ'.

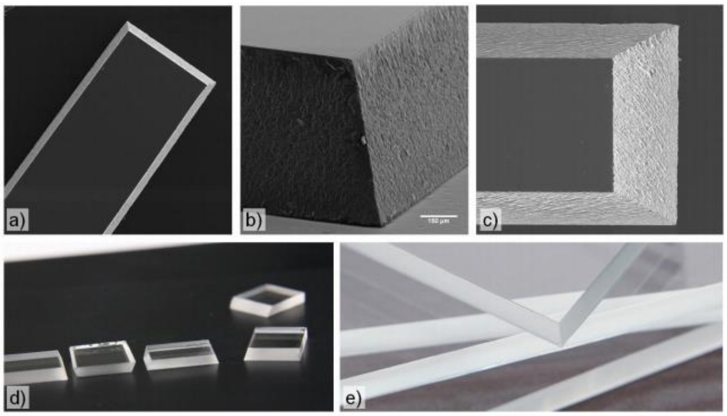

Fig. 4. Samples cut from glass sheets by Bessel-like beams .a-d) Corrected for 30° tilt of the surface, resulting in an angle of 20° of the cleaved surface, Corning Gorilla® thickness 500 µm (a,b), SCHOTT Borofloat thickness 1 mm (c), 2 mm (d). e) Cutting without tilt, SCHOTT Borofloat, thickness 5 mm. Roughness was determined to Sa ∼ 1 µm.

For focus inclination angle beyond 10° the processing head needs to be tilted. Due to limitations, given by Snell's law (Fresnel coefficients respectively) and the refractive index mismatch, angels of up to θ'~35°, see Fig. 3 (b) can be achieved. As can be seen by the surface-aberrated focus distribution a sensitive aberration compensation is required, ideally with phase-only elements. (see Fig. 3(c)). Corresponding processing results are depicted in Fig 4 where mechanically separated samples are shown. Achieved surface roughness without post processing were in the order of ~1 µm, θ'~ 20° (up to 30° have been also demonstrated).

2.2. Cleaving of curved-surfaces

The phase aberration correction for tilted surfaces mentioned in the previous section can be expanded to Curved surfaces, too, depending on the actual interface shape and local radii. In the simplest case the surface corresponds to cylinder, completely determined by cylindrical radius and refractive index n. This relatively simple geometry is of interest for potential application in medicine industry (ampoules, vials e.g.). A characteristic interference pattern is achieved when focusing non-diffracting beams behind these surfaces, see Fig. 5 (top row versus second row). Obviously, the energy deposition is only possible to a limited extent, depending on the radii.

As a first order approach this effect can be corrected by applying a cylindrical lens [20]. Basically, a cylindrical lens is implemented directly in front of the axicon-like element. The non-diffracting beam is shaped and the aberration correction is applied. Hence this is possible with only two standard components. However, we prefer a diffractive realization as holographic element with multiplexed functionalities due to its flexibility[5, 20] since the adjustment effort is significantly reduced and implementation into an industrial processing optics is straight forward. The effect on the energy distribution can be seen in Figure 5 row 3. For more details see [29].

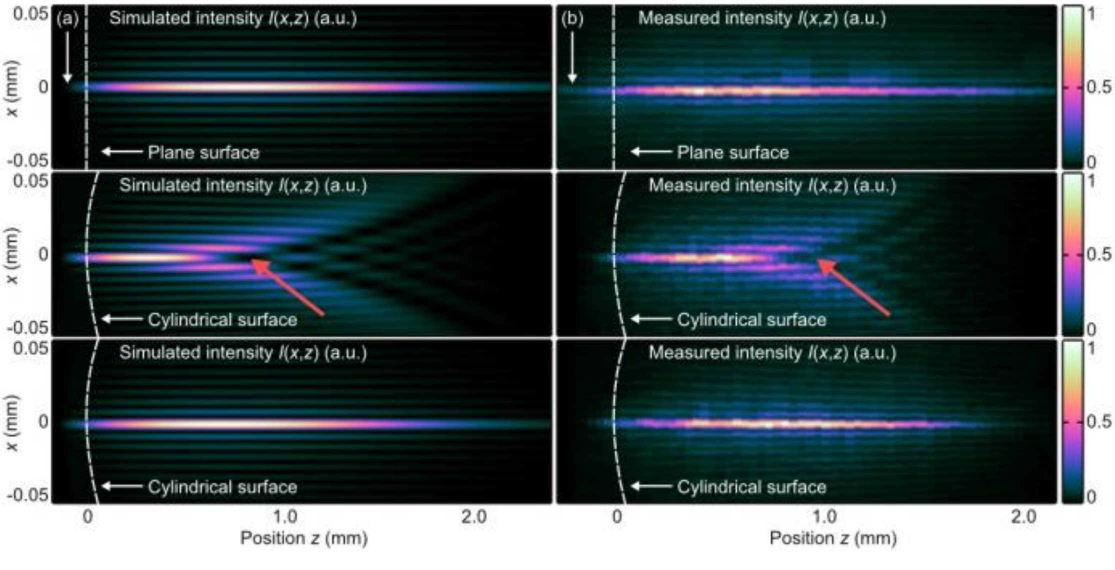

Fig. 5. Simulated (a) and measured (b) intensity cross sections I (x, z) of non-diffracting beams propagating behind a plane interface (top row), a cylindrically curved interface without aberration correction (second row) and with applied aberration correction (third row). Please note, the excellent agreement of distinct intensity features such as on-axis intensity modulations, see red arrows in second row.

2.3. Outlook towards C-shape geometries

Coming back to the initially mentioned chamfer-shape geometries, we would like to present a structure in 550 µm-thick Corning Gorilla glass achieved by an advanced optical concept which is currently under development. We show the sample in Fig. 6 which was laser modified with an optical head requiring single-side access only and achieved an effective cutting speed in the order of hundreds of mm/s. The final chamfer geometry was achieved from applying an ultrasonic bath-assisted selective etching concept and is shown in Fig 6.[18]

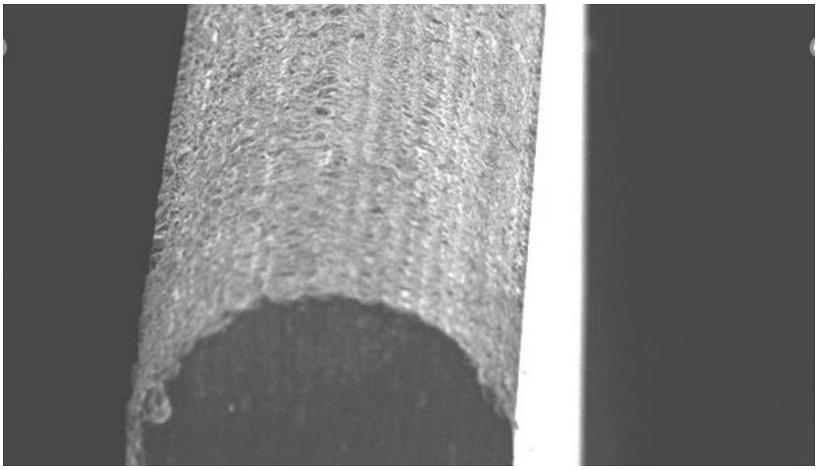

Fig. 6. C-shape sample cut. Volume modification by TruMicro series lasers, cleaved by selective etching.

3. Conclusion

In this paper we summarized the most recent results for single-pass laser cutting of transparent materials based on TruMicro series lasers in combination with the TOP Cleave cutting optics. Further novel machining concepts for cutting of tailored edges and curved surfaces have been discussed including adapted phase-corrected non-diffracting beams as enabler of industry-ready materials processing strategies.

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