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Laser glass cutting of complex contours with tailored edges

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ABSTRACT

The laser-based fabrication of glass substrates with chamfered edges and arbitrary contour geometries is reported. To achieve energy deposition along any edge geometry, a holographic beam splitter is used generating a large number of focus copies in the bulk of transparent materials. If an adapted rotation of the focus distribution is additionally used during machining, the production of substrates with arbitrary contours, such as circular or display geometries, is enabled. After the laser modification step, separation is achieved using a selective laser etching strategy. The advantages of our process are discussed using selected process results and associated laser parameters.

Keywords: Beam shaping, ultrafast optics, laser materials processing, glass processing, structured light

1. INTRODUCTION

Conventional glass cutting processes are typically limited to realize vertical glass edges.[1] It is precisely this edge that represents the substrate's greatest weak point, as straight face-edges are susceptible to chipping and cracking. At the tiny corner radii stress is accumulated in case of impacts or defects. Substrates with reduced tangential edge angles, as known from chamfered, beveled, or C-shaped edges, will therefore exhibit a higher resistance to impacts.[2,3]

Laser-based glass processing, especially single-pass, full-thickness cutting based on ultrafast laser-induced volume modifications, also leaves the substrate with a 90-deg edge. However, this technique stands out with several advantages, such as high feed rates and yields, low wear, high quality and precision, and negligible debris.[4,5] Even more important is the fact that the laser can cut complex shapes, such as e.g. smartphone display contours, and does not have to rely on rectangular geometries.[6] There is a great demand to combine the process of cutting, including mentioned advantages, and edge shaping, and to perform both steps with the laser as a subtle tool.

Recently, we have introduced "Photonic shaping tools"[7] where the focus distribution is designed to take the shape of the target workpiece. Using a holographic 3D beam splitter a large number of focus copies can be used to sample an arbitrary trajectory, for example, a chamfered or beveled edge.[3] We have used this concept to cut display glasses with arbitrary edge geometries including above mentioned cases.[8] Unlike existing concepts based on inclined[9,10] or accelerated non-diffracting beams[11,12] for tailored edge glass cleaving, our photonic shaping tools go far beyond their capabilities in terms of possible radii of curvature or variety of edge shapes.[8] Furthermore, it has already been successfully demonstrated that the substrates processed in this way exhibit enhanced mechanical properties, i.e., edge protection is in fact provided by the tailored-edge cleaving.[3] In this work we will expand this concept to cutting substrates in arbitrary contours, including circular or display geometries.

The key for a successful energy deposition at arbitrary positions and edge geometries in the bulk of the transparent material is the use of a holographic beam splitting concept.[6,13,14] The trajectories' tangential angles to the surface can be chosen almost arbitrarily. Hence all conceivable edge shapes can be realized including chamfers with 45-deg tangents.[8] As the focus distribution takes the shape of the desired edge geometry its orientation needs to be aligned during processing. We therefore apply an adapted rotation of the focus relative to the workpiece during machining which enables the production of substrates with all conceivable contours. The laser modification step is followed by the separation step, which is performed by chemical etching in the

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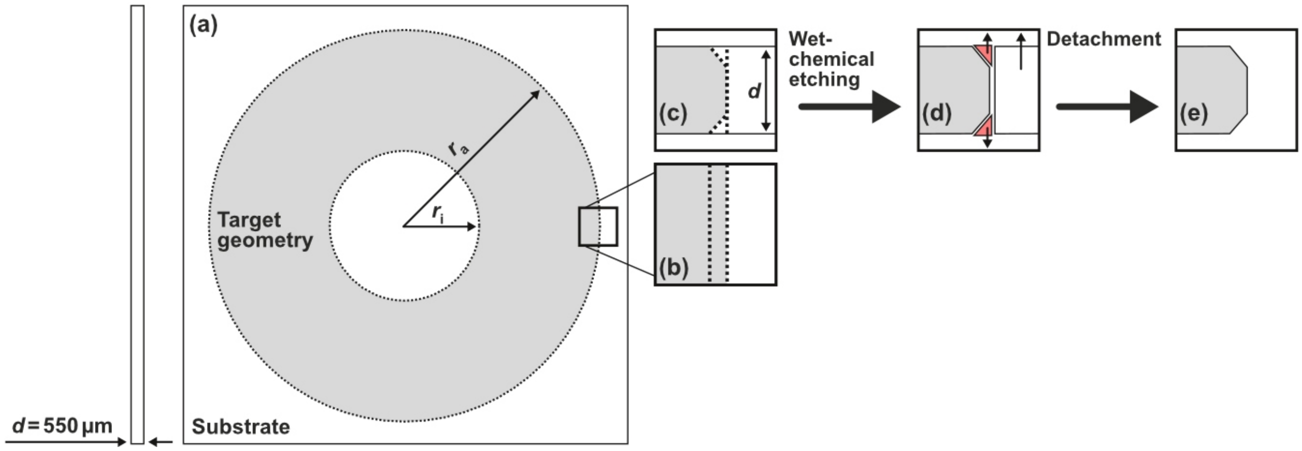

Figure 1. Schematic of the glass sample's target geometry and corresponding processing steps. An annulus with r_a = 110 mm and r_i = 20 mm in 550 µm Corning Gorilla® glass is aimed. The laser process foresees the induce volume modifications with a holographic 3D-beam splitter along the annulus contour with a single pass (a). Here, a three-axis processing is required where the workpiece is rotated under the processing optics. The optics, on the other hand, can be moved to different radial positions and to ensure working in the correct focus position (z-axis). A chamfered edge shape is aimed (d), (e), which is achieved from wet-chemical etching (d). Detaching is realized by choosing a focus distribution that generates additional modifications (b), (c) that prevend interlocking of the annulus part with the substrate, see (d), (e).

present case. Here, we exploit the fact that bulk modifications, in our case of type III,[15] exhibit increased selective etchability.[16,17] The presented laser machining concept produces glass substrates with high feed rates that convince with high surface and edge quality, as well as improved mechanical properties. We will demonstrate the advantages as well as the limitations of the concept by means of selected process results.

2. CLEAVING GLASS DISKS WITH CHAMFERED EDGES

Without loss of generality, as target geometry a circular disk with central circular hole, a so-called annulus, is chosen, see Fig. 1. Processing is done in a Corning Gorilla® glass substrate of $d = 550$ µm thickness. Due to the simple geometry of the annulus a three-axis processing is sufficient (linear stages for radius position and working distance (z-axis), rotational axis for the workpiece). In this particular case the rotation of the focus distribution is not required. For more complex contours such as smartphone display shapes, possibly with notches, a four-axis machining concept is needed. Preferably, the processing optics or the beam shaping element within the optical path is rotated during the relative movement of workpiece and optics.

Our photonic shaping tool[7] is employed to deposit energy in the volume of the substrate and to generate type-III-regime modifications at the trajectory that defines the chamfer. Here, tens-of-focus-copies from a holographic 3D-beam splitter are distributed in the working volume of an NA-0.4-focusing unit from a TruMicro Series 2000 laser.[8] Details about this structured light concept are provided in Refs. 3,7,8. Using a focus distribution that is generating volume modifications along the chamfer shape only, will result in difficulties at the separation process. The end-use part will grip into the surrounding substrate through the chamfer shape in such a way that it will be impossible to detach it, see schematic in Fig. 1 (c). For this reason, additional spots are added to the focus distribution which will facilitate separation as a larger volume is etched. Our workpiece is no longer interlocked in the substrate and can be detached upwards/downwards, see red glass parts in Fig. 1 (d) and also (e). The special case outlined in the figures for the outer contour also applies to the detachment of the inner contour (central circular hole).

After all obstacles to the detachment of the contour have been removed, cf. Fig. 1 (d), for the separation step a wet-chemical etching strategy is applied. The entire substrate is placed in a heated etch solution of 30 wt-% KOH.[16] The separated workpiece is depicted in Fig. 2. Here, the glass annulus can be seen with high quality chamfered edges at the inner as well as the outer contour. A measured height profile of the glass edge recorded

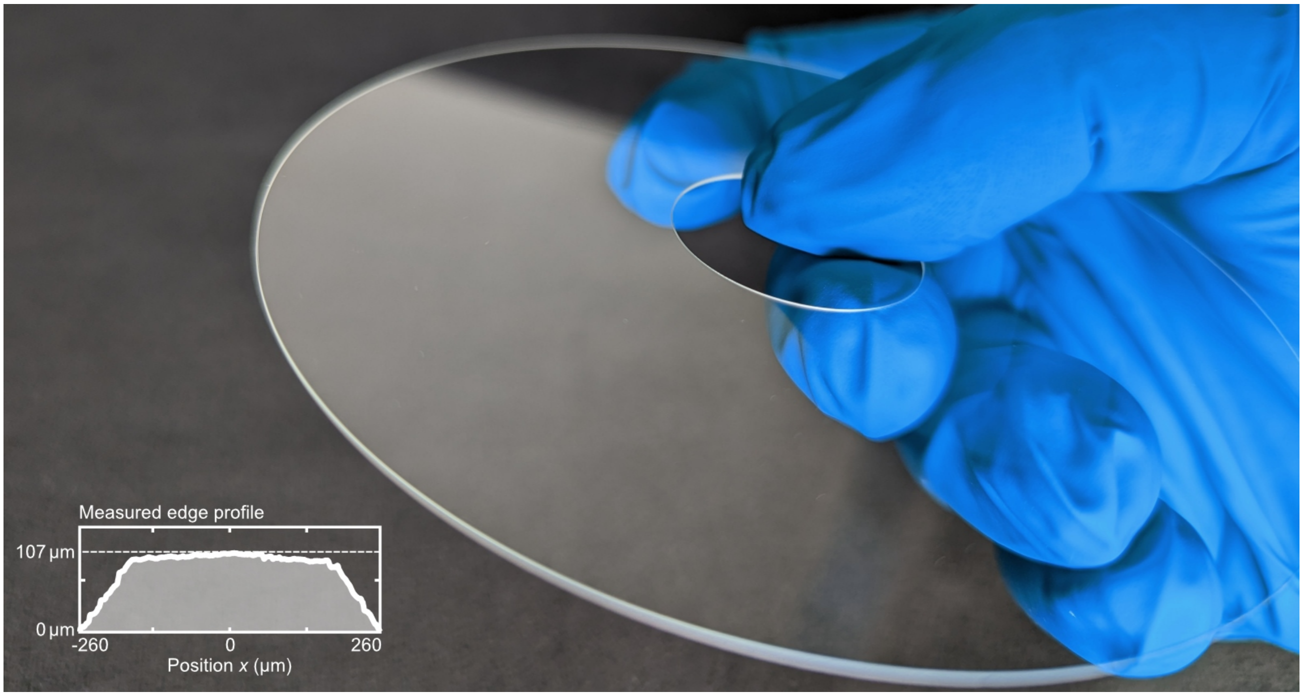

Figure 2. Fotograph of a 550 µm-thick annulus made of Corning Gorilla® glass. Outer and inner radius amount to $r_a = 110\,\mathrm{mm}$ and $r_i = 20\,\mathrm{mm}$, respectively, cf. Fig. 1. The glass edge of outer and inner circle takes the shape of the chamfer with 45-deg tangential angle to the surface as confirmed by the height profile measurement, see inset.[3] After the single-pass laser modification step separation was achieved by wet chemical etching with 30 wt-% KOH.[16]

with laser scanning microscopy is also provided in this figure, see bottom left. It confirms a successful edge chamfering with nearly 45-deg tangential angle to the top and bottom surfaces. We would like to point out once again, that for the laser modification process only a single pass was required. The substrate needs to be accessed from a single side only and no workpiece flipping is required.

For the conducted experiment presented in this work a liquid-crystal-on-silicon-based spatial light modulator was used as central beam splitting element.[6] The clear advantage of flexibility during process development comes at the expense of a limited suitability to high optical powers and a significant amount of unmodulated light that needs to be filtered or implemented into the focus distribution.[3] In the future a stationary optics solution will be available that allows for high-NA focusing in large working volumes and with large working distances.[8] A rotational module already known from the TOP Cleave-2 PRO cutting optics will allow to rotate the central beam splitter realized as diffractive optical element during processing of complex contours.

3. CONLCUSION

We have demonstrated that our recently developed processing strategy for cutting transparent materials with tailored edges can be applied to process glass substrates along complex inner and outer contours. Solving the problem of detachment requires slight modifications to the focus profile. By using holographic 3D-beam splitters, additional degrees of freedom to deposit energy at arbitrary locations in a working volume are obtained. This concept can be used to modify such glass areas that mechanically prevent workpieces to be separated. Modified areas, in turn, can be removed by increased selective etchability to facilitate the detachment of the end-use part from the substrate. We also outlined the requirements for an industry-grade laser-optical solution which will be available in the near future.

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