SINGLE PASS CLEAVING OF ULTRAFAST LASER MODIFIED C-SHAPED GLASS EDGES

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Abstract

We report on single-pass laser cleaving of transparent materials with C-shaped edges that exhibit 45-deg tangential angles to the surface. A holographic 3D beam splitter distributes several foci along the desired edge contours, including C-shaped edges. Single-pass, full thickness laser modifications are achieved requiring single-side access to the workpiece only without inclining the optical head. After having induced laser modifications with feed rates in the order of 100 mm/s actual separation is performed using a selective etching strategy.

Introduction

The past few years have shown how the concept of cutting transparent materials with ultrashort pulsed lasers has been industrialized. Reliable ultrafast laser platforms are equally available as adapted processing optics providing customized non-diffracting beams for full-thickness operations with m/s-feed rates [1, 2].

The glass articles with 90-deg edges, are susceptible to cracking and chipping in the event of an impact as stress is accumulated at the right-angled corners. Substrates with reduced edge angles, as known from chamfered, beveled or C-shaped edges, will exhibit higher bending stabilities [3].

Our concept which is based on holographic 3D-beam splitters enables to deposit energy along arbitrary edge contours including C-shaped edges. Associated tangential angles to the surface can be arbitrarily chosen and amount 45-deg in the present case. In particular, using our optical concept, we see clear advantages with respect to possible tangential angles to the surface and in possible radii of curvature compared to classical concepts with accelerated and elongated focal distributions [4, 5]. The processing optics operates under vertical incidence and requires single-side access to the workpiece only. The ability to introduce volume modifications along the entire substrate edge geometry within a single pass allows for laser processing in the order of a hundred mm/s. Here, the 3D-beam splitter realized by flexible digital holograms or static diffractive optical elements is designed to exploit the entire power performance of industry-grade ultrashort pulse laser systems.

The laser-based modification step is followed by the actual separation performed which can be performed by e.g., thermal, mechanical or as in the present study via chemical etching. Crack-connected type-III-regime modifications [6] enable selective etching [7] along the desired edge geometry with high etch rates. Generated tailored edges meet the demand of the consumer electronics industry regarding edge roughness, stability and throughput.

Energy Deposition Along Customized Edge Contours

The structured light community provides several interesting beam classes with focus distributions propagating along curved trajectories. Using Airy beams or non-diffracting beams tailored to propagate along accelerating trajectories glass substrate with curved edges have already been demonstrated. However, we believe that there are fundamental physical limitations that prevent curved-edge cutting with tangential angles to the surface that amount to 45-deg. Main reasons can be found in light's critical refraction angle [8] or extreme requirements to the focusing unit's NA [9].

We therefore pursue a different strategy and use holographic 3D beam splitters [9] to distribute energy in the glass volume along the desired edge geometry. The concept known from parallel micromanipulation [10] or multifocal microscopy [10] is used here to generate almost identical focus copies at arbitrary positions in the volume of a focusing unit. Examples to this can be seen in Fig 1, where simulated intensities $I(x, z)$ in an isotropic medium with $n = 1.45$ are depicted. Here, the z-axis corresponds to the propagation direction of the laser. In the first case, Fig. 1 (a), 29 Gaussian foci are split along a 45-deg trajectory. The example useful for bevel cuts exhibits low uniformity errors and a high diffraction efficiency when realized with flexible spatial light modulators (SLMs) or static diffractive optical

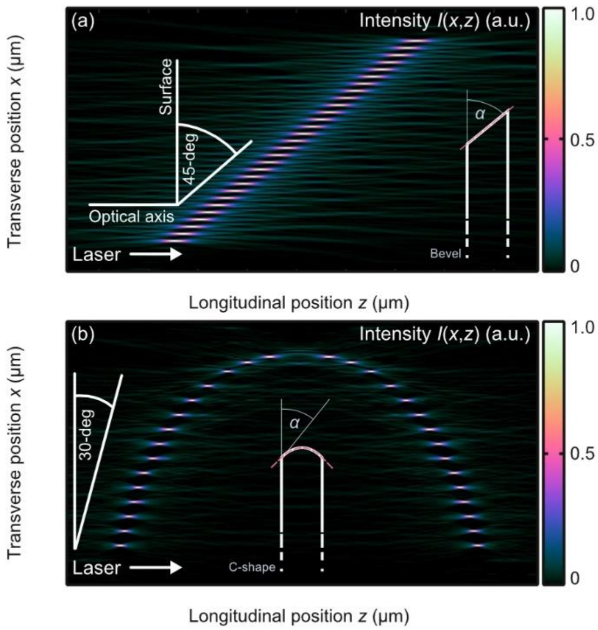

Figure 1: Examples of 3D-focus distributions for tailored edge cleaving with simulated intensities *I(x,z)* in an isotropic medium with $n = 1.45$. The *z*-axis corresponds to the laser's propagation direction. Beam splitting of 29 Gaussian foci along a 45-deg trajectory (a). Beam splitting of 30 Gaussian foci along a C-shaped trajectory (b).

elements (DOEs). With the second example shown in Fig. 1 (b) C-shape cleaving of transparent materials is enabled. In this case, 30 Gaussian spots are distributed at the desired C-shaped trajectory.

From an optical point of view, the problem of creating high intensities along advanced edge contours seems to be solved. However, for the design of the holographic 3D-beam splitter only linear optical concepts were taken into consideration. It is not revealed here in a theoretical manner what the associated modifications look like and whether they are suitable for a separation step. Although the focal distributions, i.e., the entirety of the beam-split foci, may be arranged along accelerated trajectories, the individual Gaussian foci still propagate parallel to the optical axis, cf. Fig. 1. At first glance, this situation is unfavorable for material processing, since we expect elongated modifications aligned along this axis [11, 12, 13] which, depending on the edge contour, will extend into the useful part of the workpiece. We want to clarify this notoriously complex situation experimentally by analyzing the laser-induced modifications in the next section and by applying a selective etching strategy for the actual separation.

Single-pass Tailored-edge Cleaving

Using ultrashort laser pulses emerging from a TruMicro Series laser and a simple 2f-like optical concept [9] we

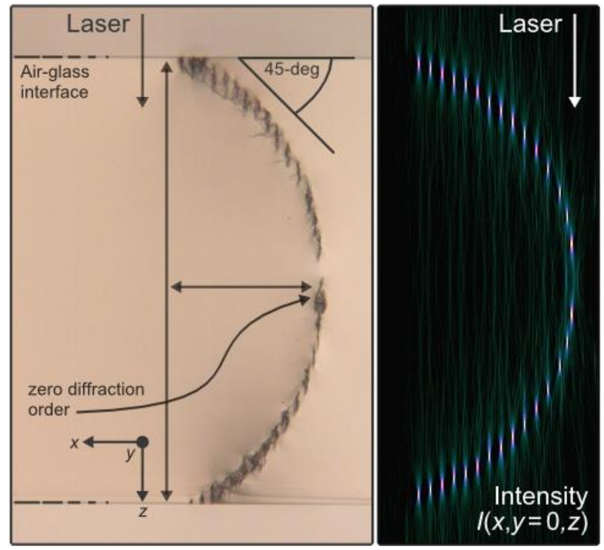

Figure 2: Microscope image of the edge of a glass substrate with laser induced modifications along a C-shape (left). Partially separated type-III-regime modifications caused by the split Gaussian foci are apparent. For reasons of comparability, we again depict the intensity profile used for machining with adapted axis scaling, cf. Fig. 1 (b), (right).

focus the presented C-shaped focus distribution, cf. Fig. 1 (b) into the volume of sheet-like glass substrates. Laser parameters were adapted to the material at hand (Corning Gorilla) to mainly generate type-III-regime modifications [6]. A microscope image taken perpendicular from the edge of a modified substrate is depicted in Fig. 2. Here, 30+1 partially overlapping modifications are visible (one additional modification is apparent due to the 0^{th} order from the SLM used in this particular experiment). These modifications were generated with laser parameters that are particularly suitable for separation by selective etching. This refers in particular to the modification size, but also to their interconnection with cracks as well as a particularly favourable access to the etching solution from the surface. However, we would like to point out once again that other separation strategies can also be effective, for example by applying mechanical [1] loads or by inducing thermal stresses from CO_2-laser radiation [8]

Our selective etching strategy is based on applying 30 wt.-% NaOH solution to the laser-modified substrate in an ultrasonic bath operating at 80°C. After an etching period of < 60 min separation is achieved [7].

The result of the etching step is provided in Fig. 3 where a scanning electron microscope confirms a successful separation in desired geometry. Tangential edge angles to the surface amount to 90-deg in the center, down to even less than 30-deg close to entrance / exit surface, see inset. Surface quality was evaluated with laser

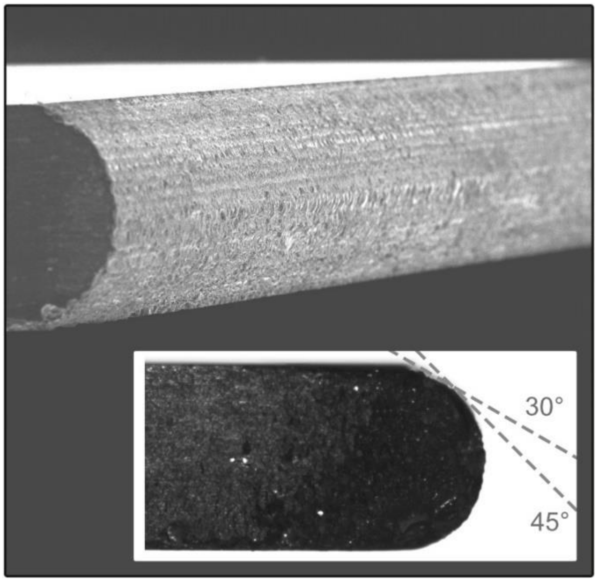

Figure 3: Scanning electron microscope image confirming the successful processing of the glass substrate with an edge contour in C-Shape. The inset provides a light microscope recording with tangential angles to the modified contour proving $\alpha < 30°$.

scanning microscopy resulting in mean surface roughness values that amount to S_a < 2µm (area evaluation).

To demonstrate the versatility of our concept, a menu of further glass substrates with tailored edges are presented in Fig. 4. Here, 550µm-thick Corning Gorilla glass was processed resulting in a C-shaped and a chamfered edge depicted in (a) and (b), respectively. Examples shown in subfigures (c) and (d) do not fulfill our motivation, cf. Sec. 1, of a protected edge, but are nevertheless shown to provide an impression of the new degrees of freedom our processing approach allows for glass processing.

At this stage of our investigation, we cannot provide proof of enhanced mechanical properties as these investigations are currently still in progress. However, they are already showing very promising results and we will provide updates on edge strength and break resistance, soon.

Conclusion

We reported on the cleaving of glass substrates with various edge contours including C-shapes using ultrashort laser pulses and a 3D holographic beam splitting concept. The single-pass, full thickness laser modification step enables to generate tailored edges with tangential angles to the surface of 45-deg. Using TruMicro Series ultrafast laser platforms feed rates in the order of 100 mm/s become possible. The modified glasses in this study were separated by chemical etching. Other separation strategies are conceivable. A study on the mechanical behavior will be provided soon.

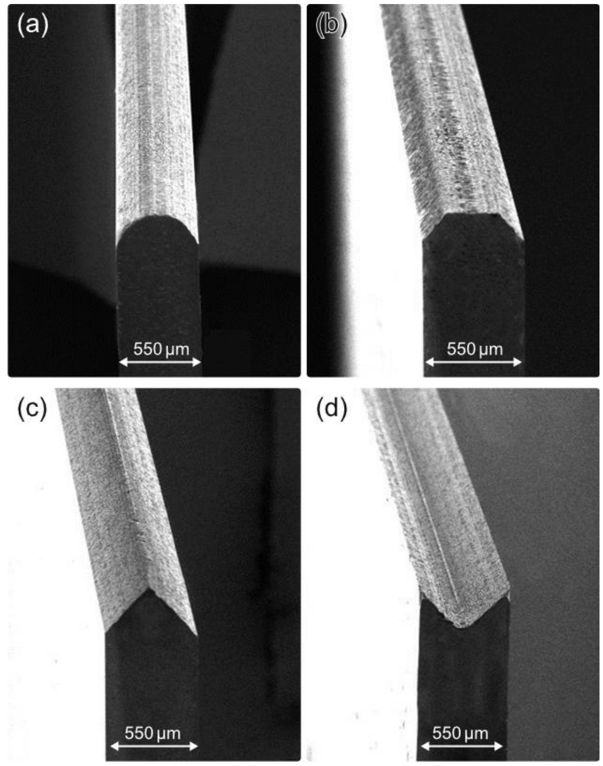

Figure 4 Glass substrates with a menu of tailored edges generated by single-pass laser modifications and chemical etching.

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