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Tailored-edge laser glass cleaving supported by thermal separation

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ABSTRACT

A two-step laser-based concept is presented for cleaving glass substrates with tailored edges. In a first step beam shaped ultrashort laser pulses are used to modify the transparent material along chamfered or C-shaped edges. Secondly, thermal stress is applied close to the modified area by absorbing the radiation from CO_2 laser. The tensile stress thus induced on the upper side of the glass leads to the actual release. The efficacy of our approach is demonstrated by presenting selected samples with tailored shaped edges and discussing corresponding edge qualities.

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

1. INTRODUCTION

Ultra-short pulsed laser-based cutting of transparent materials with elongated focus distributions shows high advantages in terms of quality, micro-debris, tool wear and throughput.[1,2] However, the laser modification process based on non-linear in-volume absorption usually has to be followed by a second process step that separates the material at the weakened areas. Mechanical, chemical or thermal processes can be used here, whereby the application of thermal stress caused by, e.g., CO_2 laser radiation is probably the most elegant way, since another non-contact tool is also used here.[3,4] Further advantages concern reproducibility, process speeds and the fact that at least parts of the system technology required for the ultrashort pulse laser process can also be used for thermal cutting based on CO_2 lasers. For industrial implementation, the thermal separation step also stands out with low costs, especially compared to wet-chemical etching.[5,6]

In this work, a two-step process for cutting transparent materials with tailored edges is presented. First, spatiotemporally shaped ultrashort laser pulses at $\lambda \sim 1\,\mu m$ are used to non-linearly modify glass substrates along chamfered or C-shaped geometries within a single pass.[7] Here, such edge shapes are of relevance that help to protect the substrate from cracking or chipping in the event of an impact.[8] Second, CO_2 laser radiation operating at $\lambda \sim 10\,\mu m$ is applied to the surface close to the modified area. The tensile stress thus induced on the upper side of the glass due to linear absorption leads to the actual separation.

Our presentation will include details about the employed structured light concept—a holographic 3D-beam splitter—, which favors thermal separation. Additionally, we will discuss useful parameters for both radiation sources, the ultrafast laser and the CO_2 laser. We demonstrate the efficacy of our concept using selected machining examples with edges in C-shape, which high surface quality as confirmed by microscopic examination.

2. SEPARATION OF MULTI-SPOT-MODIFIED GLASSES WITH CO2 LASERS

Recently we have introduced the concept of holographic-3D beam splitters, also called "Photonic shaping tools",[9] where a large number of focus copies can be used to deposit energy at arbitrary positions in a working volume of a focusing unit.[10–12] By sampling a desired edge trajectory of a display glass with, for example, tens-of-foci, the shape and density of resulting volume modifications can be used to separate the substrate and, at the same time, to achieve a chamfered edge. So far, for the task of separation, we have exploited the fact that the laser-induced modifications (mainly of type III[13]) exhibit a higher selective etchability.[8,14] Here, we applied a 30 wt-% KOH

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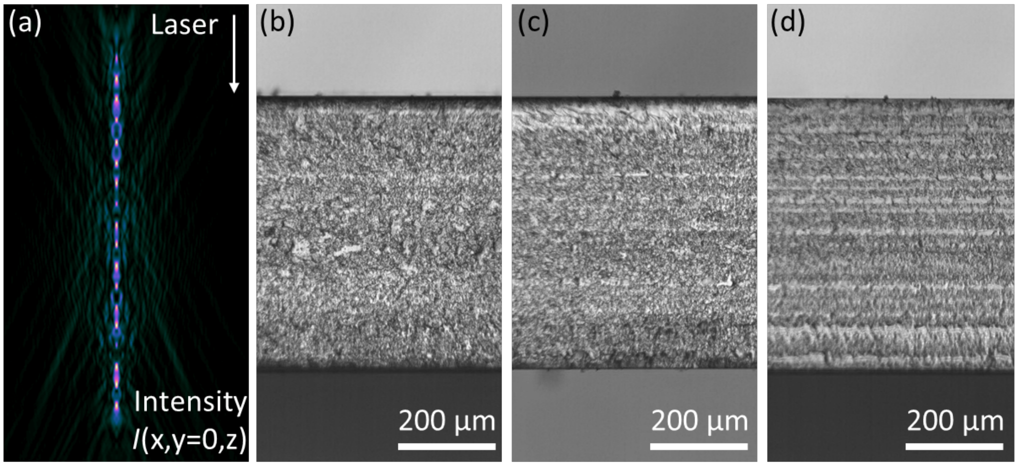

Figure 1. Simulated intensity $I\left(x,y=0,z\right)$ of a straight multi-focus distribution (a). Microscopic images of straight glass edges thermally separated by pulsed CO_2 laser radiation (b) – (d). Corning Gorilla® samples are modified with the same multi-spot focus distribution, see (a), but with different pulse energies from the ultrafast laser.

solution to modified Corning Gorilla® glass samples and achieved detached workpieces within less than one hour.[7]

In Sec. 1 we have already briefly discussed the advantages of separation by thermal stress, in particular by CO_2 laser radiation. This process has become the state of the art when separating on straight-line modifications,[3] in particular induced by ultrafast non-diffracting beams.[12,15] Here, we would like to first address the question of whether we can achieve similar separation results when the continuous non-diffracting beam is replaced by a perpendicular focal line composed from discrete spots realized by our holographic 3D-beam splitting concept.[9,10] The employed focus distribution is depicted in Fig. 1 (a) where the simulated intensity cross section $I\left(x,y=0,z\right)$ is plotted. Here, and in the following figure, beam propagation is parallel to the z-axis. We omit clear length specifications but provide the focus length which is adapted to a substrate thickness of $d = 550\,\mu\text{m}$. On the optical axis $\mathbf{r} = (x=0, y=0, z)$ 18 local intensity maxima can be seen caused by splitting the raw beam into 18 Gaussian-like foci. The total number of spots, however, exceeds 50 as additional foci are distributed in the y-dimension. The holographic 3d-beam splitter is realized with a liquid-crystal-on-silicon-based spatial light modulator.[8] The digital hologram is arranged in a $2f$-like configuration with a large-working volume and large working distance NA-0.4-microscope objective acting as Fourier-lens.[7] Processing was conducted with 3 ps pulses from a TruMicro Series 2000 laser operating in burst-mode with a total pulse energy of $< 300\,\mu\text{J}$. For the thermal separation step a pulsed CO_2 laser system (Synrad p400, Novanta PHOTONICS) with a feed rate of $\sim 3\,\text{m/min}$ at $< 40\,\text{W}$ average power was employed. Results of thermally separated Corning Gorilla® glass samples are shown in Fig. 1 (b) – (d) where micrographs of the separated edge confirm a successful cleaving process. Achieved edge qualities will strongly depend on the applied laser parameters and the processed material. For example, at constant CO_2 laser average power and feed rate the employed ultrafast laser pulse energy E_P is impacting the edge's surface roughness which decreases from $S_a \cong 1.2\,\mu\text{m}$ to $0.8\,\mu\text{m}$ while decreasing E_P, see Fig. 1 (b) to (d). Thus, achieved roughness parameters are close to what is known from cleaving results using non-diffracting beams.[2,16]

The process parameters found for glass cutting with perpendicular edges now serve as a starting point for the first experiments to produce tailored glass edges supported by thermal separation. For this task a focus distribution was designed providing volume modifications that follow a C-shaped trajectory. Here, the trajectory's tangential angle to the glass surface amount to 90-deg in the center down to less than 45-deg at the top and bottom side, respectively. A cross section of the simulated intensity profile $I\left(x,y=0,z\right)$ is depicted in Fig. 2 (a). Again, not all foci are visible as additional focus copies are split also in y-direction.[9] A microscope recording of the modified glass edge before separation can be seen in Fig. 2 (b). Here, type-III-regime modifications[13] are clearly visible that sample the desired C-Shape. Please note, that this machining result was

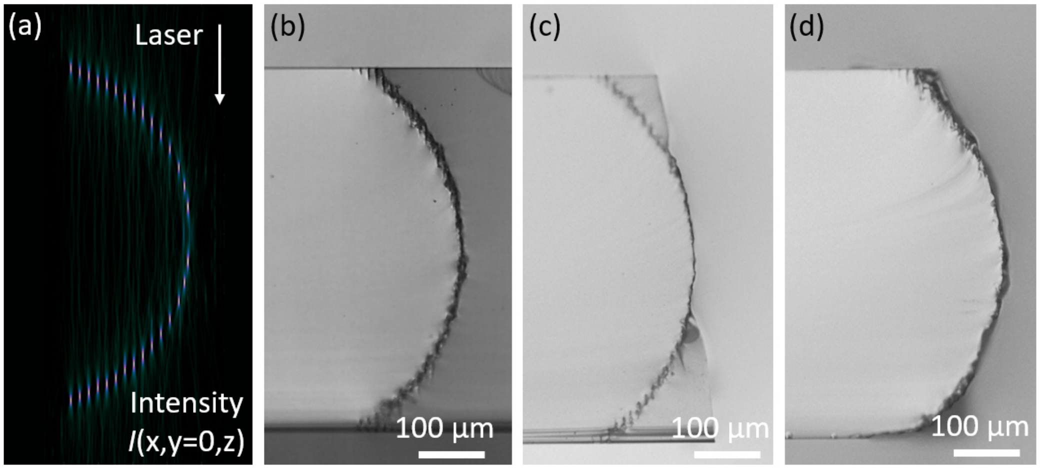

Figure 2. Simulated intensity $I\,(x, y = 0, z)$ of a C-shaped multi-focus distribution (a). Microscopic cross section image of a C-shaped multi-spot modification before separation (b). Microscopic cross section images of thermal separated C-shaped glass edges achieved with different laser parameters (c), (d).

achieved from a single laser pass. In Fig. 2 (c) and (d), results of the thermal separation process are illustrated. The applied CO_2 laser radiation is similar to the experiments discussed in Fig. 1. In the first case, see (c), pulse energy is sufficient to realize the separation, but insufficient for a complete separation along the desired C-shape. The spatial extension of the modifications is too small for the entirety of modifications to connect through cracks during the applied thermal stress. An increase in pulse energy allows thermal separation of the substrate in C-shape almost completely along the entire substrate thickness, see (d).

With the machining results presented here, we do not claim to have found the optimum. However, these show promising initial trials, with the associated laser parameters providing the basis for further investigations. However, we see a clear correlation between the pulse energy used, the spatial pulse distance and the required average power of the CO_2 laser radiation. A certain fill factor in our focus distribution (ratio of spot size to spot distance) will, for specific laser parameters, cause the resulting modifications to provide crack guidance along the target edge geometry. The corresponding pulse energy will scale the size of modifications and will facilitate separation. However, as can be seen from Fig. 2 (d) will also reduce edge quality. Intuitively, regarding the CO_2 laser power, there will be an upper limit that needs to be applied to the substrate. We assume that the thermally induced stress has to exceed a crack limit, which corresponds to the maximum tensile stress a modification is able to withstand.

Although the quality of our process results is still a way from those achieved by chemical separation,[7,8] we still see high potential here. This is especially due to the fact that post-treatment by mechanical grinding and polishing[17] is not excluded. The preforming that we can achieve with our double-laser process should significantly reduce the effort required for accuracy and process times of the grinding tools. Optimal chamfering of transparent workpieces could therefore also be achieved by combining laser processing and mechanical post-treatment.

3. CONCLUSION

We have demonstrated that display glass substrates volume-modified from ultrafast 3D-focus distributions can be separated by applying thermal stress. Starting from process parameters found for cutting straight glass edges, we modified Corning Gorilla® samples along C-shaped edge trajectories and achieved singulation after the radiation from a CO_2 was linearly absorbed at the surface. The resulting tensile stress at the surface caused crack guidance along the desired C-shape if a certain modification fill factor is realized. The fabricated samples demonstrate that thermal separation represents an alternative to selective laser etching techniques. There are clear advantages in terms of throughput, costs and required system technology. Qualitative disadvantages, that currently still exist, could be overcome by combining the laser process with mechanical post-processing.

REFERENCES

1. R. Meyer, M. Jacquot, R. Giust, J. Safioui, L. Rapp, L. Furfaro, P.-A. Lacourt, J. M. Dudley, and F. Courvoisier, "Single-shot ultrafast laser processing of high-aspect-ratio nanochannels using elliptical bessel beams," *Optics letters* **42**(21), pp. 4307–4310, 2017.
2. M. Jenne, D. Flamm, K. Chen, M. Schäfer, M. Kumkar, and S. Nolte, "Facilitated glass separation by asymmetric Bessel-like beams," *Optics Express* **28**(5), pp. 6552–6564, 2020.
3. R. Grundmüller and H. Schillinger, "Method of and apparatus for laser based processing of flat substrates being wafer or glass element using a laser beam line," Nov. 25 Nov. 25 2015. European Patent 2,754,524.
4. C. Ungaro, N. Kaliteevskiy, P. Sterlingov, V. V. Ivanov, A. B. Ruffin, R. J. Terbrueggen, and N. Savidis, "Using phase-corrected bessel beams to cut glass substrates with a chamfered edge," *Applied Optics* **60**(3), pp. 714–719, 2021.
5. M. Kaiser, M. Kumkar, R. Leute, J. Schmauch, R. Priester, J. Kleiner, M. Jenne, D. Flamm, and F. Zimmermann, "Selective etching of ultrafast laser modified sapphire," in *Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XXIV*, **10905**, p. 109050F, International Society for Optics and Photonics, 2019.
6. J. Gottmann, M. Hermans, N. Repiev, and J. Ortmann, "Selective laser-induced etching of 3D precision quartz glass components for microfluidic applications—up-scaling of complexity and speed," *Micromachines* **8**(4), p. 110, 2017.
7. M. Kaiser, H. Dounassre, M. Kahmann, J. Hellstern, J. Kleiner, C. Tillkorn, and D. Flamm, "Chamfered-edge laser cleaving of transparent materials," in *Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XXII*, **11991**, pp. 32–41, SPIE, 2022.
8. D. Flamm, M. Kaiser, M. Feil, M. Kahmann, M. Lang, J. Kleiner, and T. Hesse, "Protecting the edge: Ultrafast laser modified C-shaped glass edges," *Journal of Laser Applications* **34**(1), p. 012014, 2022.
9. D. Flamm, J. Hellstern, M. Kaiser, M. Kahmann, J. Kleiner, and C. Tillkorn, "Light along curves: Photonic shaping tools," *Adv. Opt. Techn.* **12**, 2023.
10. P. J. Valle and M. P. Cagigal, "Analytic design of multiple-axis, multifocal diffractive lenses," *Optics Letters* **37**(6), pp. 1121–1123, 2012.
11. L. Zhu, M. Sun, M. Zhu, J. Chen, X. Gao, W. Ma, and D. Zhang, "Three-dimensional shape-controllable focal spot array created by focusing vortex beams modulated by multi-value pure-phase grating," *Optics Express* **22**(18), pp. 21354–21367, 2014.
12. D. Flamm, D. G. Grossmann, M. Sailer, M. Kaiser, F. Zimmermann, K. Chen, M. Jenne, J. Kleiner, J. Hellstern, C. Tillkorn, *et al.*, "Structured light for ultrafast laser micro-and nanoprocessing," *Optical Engineering* **60**(2), p. 025105, 2021.
13. K. Itoh, W. Watanabe, S. Nolte, and C. B. Schaffer, "Ultrafast processes for bulk modification of transparent materials," *MRS bulletin* **31**(8), pp. 620–625, 2006.
14. M. Kumkar, M. Kaiser, J. Kleiner, D. Grossmann, D. Flamm, K. Bergner, and S. Nolte, "Ultrafast laser processing of transparent materials supported by in-situ diagnostics," in *Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XXI*, **9735**, p. 97350P, International Society for Optics and Photonics, 2016.
15. D. McGloin and K. Dholakia, "Bessel beams: diffraction in a new light," *Contemporary physics* **46**(1), pp. 15–28, 2005.
16. K. Chen, M. Jenne, D. G. Grossmann, and D. Flamm, "Generalized axicon-based generation of nondiffracting beams," *arXiv preprint arXiv:1911.03103* , 2019.
17. P. Bukieda, K. Lohr, J. Meiberg, and B. Weller, "Study on the optical quality and strength of glass edges after the grinding and polishing process," *Glass Structures & Engineering* **5**, pp. 411–428, 2020.