Surface Probing of Ultra-Short-Pulse Laser Filament Cut Window Glass and the Impact on the Separation Behavior

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The process of laser filament cutting produces a practical nongap cut which ensures high precision in lateral dimensions at the micrometer scale. Commercially available OptiWhite soda lime silicate glass is filamented using a 1064 nm picosecond pulsed Nd:YAG laser with varying burst energies and focus positions. The filaments are characterized perpendicular to the incident laser beam using scanning electron microscopy (SEM). Maximum roughness $R_z$ evaluated with laser scanning microscopy is measured on the cut sides. The characteristic mechanical strength $\sigma$ of glass cleavage is decreased by a factor of 6 with the presence of the filaments. This $\sigma$ obtained in the four-point-bending setup decreases with the increase in energy deposited in the material by the laser. It is found that the cleaving cracks are guided by the filament only if the network of microcracks is sufficiently developed. A threshold of the cleaving guidance is linked to a critical surface modification width of 2.5 $\mu$m which corresponds to half the distance between filaments. The influences of the laser parameters, sample thickness, and sample position in respect of the focal plane on the cut quality are studied. Guidelines are given to define a suitable parameter set.

1. Introduction

The ongoing usage of complex-shaped glass products in everyday products has generated an increasing demand. Design elements made of glass, e.g. curved display glass for handheld devices or in dashboards in vehicle cockpits, are sophisticated products and often contain undercuts, small radii, or notches. The intricate products are in the direct field of view or even are part of an interactive screen and a flawless product is of high importance. The process of laser filament cutting meets these requirements due to its possibilities of high precision cutting without lacking in design freedom. The practical nongap cut allows to manufacture glass products with small tolerance in the lateral dimension and generates an unsharp cut edge, which means no post-processing is necessary. A picosecond pulsed laser beam is focused inside the glass via a specially designed optic to form an elongated laser spot. The fundamental principle of the generation of elongated material modification within the bulk material is a currently discussed topic. Linear modifications can be generated due to sensu stricto filamentation where Kerr effect occurs or due to elongated intensity distributions. The result of this study cannot bring further argument in this discussion. The linear perforations present here will be referred to as filament. Following this last explanation, the high energy of the laser induces nonlinear optical effects, which leads to the Kerr effect and repeating cycles of self- and defocusing. After each focusing cycle a plasma spot is generated, creating a void inside the material. The generation of a thorough filament starts from the point of highest laser intensity inside the glass and builds up along the beam trajectory in the direction of laser optics. The desired contour is prescribed in the material and a filament curtain is formed, which functions as a predetermined line of separation and guides the crack in the latter step of cleavage. The local energy distribution of the filamentation process, determined by the laser parameters, is the fundamental cause of the properties of a filament line. Subsequently, filament formation is setting the properties of the final cut product, i.e., cut edge quality. Proper adjustment of the energy distribution is key to obtain a semifinished glass with good separation behavior and subsequently a product of the desired quality. Despite being a research field of great interest from both the academic and industrial point of view, a detailed investigation of surface phenomena as well as the mechanical properties of a filament line has not been, to our knowledge, reported until now. The guidelines given in this article will assist in choosing suiting laser parameters and sample position for the filamentation process.
2. Experimental Section

2.1. Sample Preparation

Commercially available soda lime silicate glass OptiWhite (Pilkington Ltd./NSG Co. Ltd./ Composition [wt%]: 72.7 SiO$_2$, 13.0 Na$_2$O, 8.8 CaO, 4.3 MgO, 0.6 Al$_2$O$_3$, 0.4 K$_2$O, 0.2 SO$_3$, 0.02 Fe$_2$O$_3$) of 1.1 and 1.85 mm thickness was used as sample material. First, the sample contour with lateral dimensions of 10 mm in width and 50 mm in length was cut in a two-step process. The contour was scribed with filaments and cleaving was done utilizing the absorption of a CO$_2$ laser. The glass was heated locally at the surface due to the temperature gradient, where thermal stress is induced. As soon as the induced thermal stress exceeded the characteristic strength of the filament line the glass cleaved. After the contour was cut, the later investigated filament line was inscribed along full width at half of the length to prevent possible affection due to the cleaving process. The incidence beam of the laser was perpendicular to the flat/atmosphere side. The surfaces were named Entry-Side and Focus-Side (Figure 1). Laser filamentation was accomplished by focusing a pulsed 1064 nm Nd:YAG (Rofin - StarPicoFl) laser with a pulse duration of 10 ps and a repetition rate of 63 kHz between consecutive bursts through a SmartCleaveFI optic. One burst consisted of four pulses with identical characteristics, e.g., shape, height, and 25.0 ns distance within (see Figure S1, Supporting Information). Only every second burst train was used for filamentation and combined with the feeding speed of 157.5 mm s$^{-1}$ and a pitch of 5 μm between consecutive filaments was maintained. The nominal average power of the laser source was 50 W. However due to power loss along the beam path the final realized power on the sample was measured as 32.4 W using a thermal powermeter. Three settings for burst energy with 308.6, 411.4, and 514.3 μJ were used and referred to as 300, 400, and 500 μJ further in the text. The focal plane was set below the Focus-Side to a reference focus position for OptiWhite 1.85 mm thickness and for OptiWhite 1.1 mm thickness. This reference focus position takes into account the effect of focus shift due to the varying material thickness and is therefore comparable. Another shifted focus position for 1.1 mm thickness, 0.25 mm below the reference position, was used to estimate the sensitivity of focus conditions to the cut quality (Figure 1).

2.2. Imaging Using Scanning Electron Microscopy of Modified Zones at the Surface

High-resolution imaging of Entry-Side and Focus-Side was done utilizing scanning electron microscopy (SEM; Quanta 200/FEI). Samples were sputter coated in advance to imaging to minimize charge effects and ensure high-quality images throughout. The technique allowed to precisely measure the width of the area that was affected by the filamentation process.

2.3. Roughness Determination Using Laser Scanning Microscopy (LSM)

With laser scanning microscopy (LSM; confocal LSM VK-X-160K/KEYNENCE Corporation) the surface of the cut edge was probed with high accuracy. A laser at 658 nm was focused through a times 100 magnification objective with a numerical aperture (NA) of 0.95, resulting in a spot diameter of $\approx$0.845 μm at the focal plane. An area that covered the entire thickness of the respective sample was scanned in multiple planes, starting from the lowest to the highest visible feature, with a step size of 0.13 μm between two planes. The scanned area was partitioned into areas of interest (AOI), with attention to the area just below the Entry-Side and Focus-Side, which are analyzed to obtain the value for maximum roughness $R_z$.

2.4. Mechanical Testing

Mechanical strength was tested in a four-point bending setup with a 500 N load cell (Load frame 5565/Illinois Tool Works Inc.) and a span width ratio of 1:2 with 10 mm spacing on the load traverse and 20 mm on the support traverse. Samples were

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**Figure 1.** Explanatory drawing of the prepared samples for clarification of the filamentation process and nomenclature of orientation used in this article: symbols next to the sample names were used consistently in other graphs (turquoise dots $= 1.85$ mm reference focus, orange triangles $= 1.1$ mm shifted focus); red lines represent filament location; Surface named Entry-Side is the surface which is closer to the laser optics and Focus-Side is the surface close to the focus position below the glass (e.g., reference position and shifted position as used further in this article). Dashed grey lines indicate the location of the surfaces with respect to the reference plane. Colored picture at the right represents the energy distribution of the laser beam inside the sample (purple = high energy, green = low energy). The dots and ovals overlaid on the energy distribution sketch the generated surface modification at the corresponding surface.
loaded with a constant loading speed of 0.5 mm s\(^{-1}\) until the sample broke. Measurements were carried out in two orientations for each parameter set (burst energy and focal position) to measure the force needed to cleave the sample by applying it either on the Entry-Side or the Focus-Side. The side facing the support span determined the side under tensile stress, subsequently being the origin of separation. Following the norm EN 1288-3 the bending strength was calculated from the applied force measured during the experiment. A series of 10–30 samples were tested for the different parameter sets. The filament line acted as the predetermined breaking point. The characteristic strength was determined using Weibull statistics. The errors bars were assessed using norm EN 843-5, based on the maximum likelihood method. The error bars were estimated considering the number of specimens and a fixed confidence level of 0.95.

3. Results and Discussions

3.1. Surface Probing with SEM

In Figure 2A the SEM images of the Entry-Side for all sample series are displayed. The sample of 1.85 mm thickness with 300 \(\mu\)J (Figure 2A1) burst energy at reference focus indicates no trace of surface modification. With increasing energy to 400 \(\mu\)J (Figure 2A2) first visible modifications occurred. The modifications vary in shape, being elliptical but also round with a piled-up bulge (arrow) around some holes. A further increase to 500 \(\mu\)J (Figure 2A3) generated much larger modifications than for 400 \(\mu\)J with round shapes and varying pronounced bulges. A precrack (arrow) links adjacent filaments. A recent study investigating laser treatment with elongated Bessel beam found similar surface modifications in the same magnitude of size and interconnecting cracks to be generated for borosilicate and aluminosilicate glass.\(^{[18]}\) The sample series of 1.1 mm thickness with reference focus shows impacts on the surface for all energies. Due to the reduction in thickness of the glass, 300 \(\mu\)J (Figure 2A4) was sufficient to form surface modifications. The surface modifications for 1.1 mm reference 300 \(\mu\)J are alternatively with or without piled-up round bulges, as described previously for 1.85 mm thickness for a higher energy of 400 \(\mu\)J (Figure 2A2). No visible precracks link the filament holes. Similarly, the 1.1 mm reference 400 \(\mu\)J sample (Figure 2A5) displayed noticeable round bulges and precracks linking the filament holes (arrow) as the 1.85 mm 500 \(\mu\)J sample (Figure 2A3). The sample filamented with 500 \(\mu\)J (Figure 2A6) burst energy presents slightly larger bulges and a crack, that bypasses some of the filament holes (arrow). At the bottom row, the 1.1 mm glass samples with shifted focus did not differ significantly from the reference focus ones. For all energy settings, the filament holes are present and round. For the 400 \(\mu\)J sample (Figure 2A8), a large brighter area next to the filament line is noticeable (arrow). This area is ascribed to an electrical charge effect of the SEM electron beam. The disturbed structure of the material can cause accumulation of electrical charge due to a partially interfered electrical conductivity.\(^{[19]}\) This indicates that the area, influenced by the laser treatment, reaches into regions’ subsurfaces. At 500 \(\mu\)J (Figure 2A9) the bright surface modifications are only visible at the edge of the image. They are similar to those for 400 \(\mu\)J (Figure 2A8) but larger in size. Figure 2B shows the SEM images for the Focus-Side. In general, the laser treatment generated surface modifications and cracks along the filament line for all studied parameter sets. In addition, expelled material in the direct environment next to the filament can be seen (arrow in Figure 2B2). This was only scarcely observed for the Entry-Side for the 500 \(\mu\)J burst energy. For the 1.85 mm reference sample treated with 300 \(\mu\)J (Figure 2B1) the round shape and bulges were similar to the reported examination on the Entry-Side. Increasing the laser energy to 400 \(\mu\)J (Figure 2B2) leads to the appearance of comparable surface deformations but with growing size and increase in the amount of expelled material. For 500 \(\mu\)J (Figure 2B3), the shapes of the
bulges change and are deformed/squeezed (arrow). The 1.1 mm reference sample series (Figure 2B4,5,6) shows surface modifications similar to the 1.85 mm series. This similarity is in good agreement as both reference series have identical distances between the Focus-Side and the focal plane itself. 1.1 mm shifted samples show filaments which vary in size, shape, and look even dented. The laser treatment with 400 μJ (Figure 2B8) caused a viscous flow of glass, generating surface modifications that still appear round but warped and larger as for 300 μJ (Figure 2B7) burst energy. The amount of expelled material in the surrounding has increased and is more spread out. Again, the bright area next to the filament line originating from the electrical charge effect of the electron beam of the SEM was noticeable. Eventually, the 500 μJ (Figure 2B9) burst energy caused a drastic disruption of the surface. Two additional lines of surface modifications to both sides of the regular filament line emerge due to the high energy deposition. The appearance of the surface modifications of each line is highly deformed. The new lines were in contact to the central one leaving a broadly modified area. Evaluating the SEM images, the width of the surface modifications was measured (reported in Table S1, Supporting Information). Depending on the modification shape, either the outer rim of the bulge or the edge of the affected area was selected as the border for the width measurement. Error bars were estimated using the standard deviation of 18 length measurements done for each parameter set. Figure 3 shows the values obtained for the width of surface modifications at both sides with the corresponding optical position. The optical position takes into account the index of refraction and its influence on the laser focus position. The distances are divided by the refractive index, $n = 1$ for air and $n = 1.489$ for the glass at 1064 nm. Indicating that the distances in air are unchanged, inside the glass they are shortened, e.g., 1.24 mm for 1.85 mm sample and 0.74 mm for 1.1 mm sample. The position of the Focus-Side of the reference samples was taken as the 0 position. Symbols are half-filled to denote the corresponding surface (top filled = Entry-Side, bottom filled = Focus-Side). Dashed lines represent a visual guide to the eye and indicate the energy sets (blue = 300 μJ, green = 400 μJ, red = 500 μJ). Entry-Side values of 1.85 mm reference focus (top-filled turquoise dots) show an increase from 1.4 μm for 400 μJ to more extensive modifications of 2.8 μm at 500 μJ burst energy. A value for 300 μJ was not determinable and is represented as (X) as the filamentation process generated no surface modifications. For all the intermediate positions, for the Entry- as well as for the Focus-Side, deformation widths increase with the laser energy. As already described in the observation of the SEM images, the burst energy of 500 μJ for the 1.1 mm shifted sample caused a three-line deformation which cannot be directly compared with the others and therefore is denoted in the graph as (oOo). Widths at the Focus-Side are comparably larger than at the Entry-Side. Moreover, all the deformation width line up versus the optical positions for each laser energy are arranged parallely. The width deformation is then within our experimental uncertainty with a quasilinear function of two parameters: the optical position and the laser energy. This states that the conditions of filament formation are determined only by energy distribution within the laser beam. Energy distribution of the laser beam was characterized using a tomographic method on a chromium-coated glass. The local energy of the laser removes the chromium and leaves a characteristic pattern. Height position of the laser is changed stepwise, and the so-generated patterns are stacked up. As a result, the characteristic profile of the energy along the propagation direction of the laser is shown in the colored picture on the right in Figure 1. The appearance of two lateral lines making a V-shape begins at the focus point. This structure is proposed to explain the formation of two lateral lines observed at the Focus-Side 1.1 mm shifted focus sample (Figure 2B9). The schematic of the position of the different sample surface modifications within the global beam path is reported in the energy distribution in Figure 1. The evolution of the energy distribution and the observed modification width is in close agreement. For the 1.85 mm Entry-Side, no surface modification was observed and it is assumed that an energy threshold exists. The energy threshold is found both in the central laser path and on the V-shape structure. Indeed, the 1.1 mm shifted focus sample 400 μJ (arrow Figure 2B8) starts to present subsurface deformations but without filament hole formation at the Focus-Side. If the sample is in close proximity to the focal plane, the energy of the outer parts of the laser beam exceeds the energy threshold to modify the material and creates additional modifications. Two characteristic modification widths are defined in Figure 3. First is the width where two modifications are going to be in contact, so where the width is equal to the pitch between two modifications, i.e., 5 μm width. Samples presenting modifications this large are more deformed and show warped shapes, indicating that they received a higher energy deposition. Second, below the critical width of 2.5 μm, the modifications do not present bulges and surface precracks. This critical width will be discussed in
3.2. Examination of the Cut Edge with LSM

Figure 4 shows the cross section of the cut edge of the different sample series measured with LSM. The Focus-Side is located on the right and Entry-Side on the left. Separation was initiated from Focus-Side and the cleaving crack propagated toward the Entry-Side. Areas close to the Entry-Side appear darker due to light reflection side effects. The position of the 1.1 mm shifted series was relocated with respect to the focus shift. 1.85 mm 300 \( \mu \)J sample (Figure 4(3)) shows a scattered fracture pattern starting from the focus side, reaching 0.55 mm into the material. The scattered appearance fades out and the rest of the sample shows a characteristic glassy fracture. The increase to 400 \( \mu \)J did not change the appearance significantly, but the length of the scattered fracture area increases and covers 1.5 mm of the sample (Figure 4(2)). Only a smaller portion of glassy fracture is observed. Eventually, with 500 \( \mu \)J energy, the scattered fracture pattern covers the complete cross section (Figure 4(1)). The appearance of the cut surface was shown to be comparable for other glass systems. \(^{3,18}\) 1.1 mm reference focus series displays the same visible features as previously described for 1.85 mm series. The area of the scattered fracture pattern is also 0.55 mm for the 300 \( \mu \)J sample (Figure 4(6)), whereas 400 and 500 \( \mu \)J show a complete scattered fracture pattern (Figure 4(4,5)).

The appearance of the cut edge surface of 1.1 mm shifted focus is similar to the other series. With 0.9 mm, nearly the full cross section for the 300 \( \mu \)J sample (Figure 4(9)) is covered with the scattered fracture pattern. Samples filamented with 400 and 500 \( \mu \)J burst energy (Figure 4(7,8)) show a continuous scattered fracture along the entire thickness. In the bottom-left corner (Figure 4(10)), the surface of 1.1 mm 300 \( \mu \)J sample after separation is exhibited. The filament line can be seen next to the cut edge on the right glass piece. All samples with a glassy surface (Figure 4(2,3,6,9)) present a similar offset between filament line and cut edge. The final cut edge can deviate for more than 20 \( \mu \)m, impairing the dimensional accuracy significantly. The formation of filaments begins from the Focus-Side and proceeds toward the Entry-Side. Therefore, further from the focus point, lower the amount of deposited energy. A consequence is that further from the focus point, smaller the length and the number of associated microcracks. As the separation was initiated via the Focus-Side, the cleaving crack propagated as intended along the microcrack network, creating the scattered fracture pattern. However, as the abundance of associated microcracks decreases, the cleaving crack cannot be guided efficiently any longer. At this point a long-range unguided crack forms and propagates through the remaining glass toward the Entry-Side. The characteristic broken glass surface seen in the cross-section images is the result of this last unguided crack propagation. An explanation could be that the cleaving mechanism switches from subcritical propagation through the microcrack network to a regular crack growth. The limit between the scattered fracture area and the broken glass surface is located at the same position for all the samples treated with 300 \( \mu \)J burst energy. That suggests a guided cleaving threshold from which filaments can still exist but disrupt the glass inadequately to control the crack propagation. The guided cleaving threshold shifts further away from the focus point as the laser energy increases, indicating that both

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The diagram in Figure 4 shows the cross section of the cut edge of 1.85 mm series, 1.1 mm reference, and 1.1 mm shifted focus (within a series: top: 500 \( \mu \)J; middle: 400 \( \mu \)J; bottom: 300 \( \mu \)J). Enumeration is shown in round shape. The 1.1 mm shifted sample series is displayed with respect to the reference plane. The 300 and 400 \( \mu \)J “guided cleaving thresholds” indicate to which point an accurate crack guidance is assured. The picture in the bottom-left corner shows the Entry-Side for 300 \( \mu \)J 1.1 mm reference sample after separation and highlights the deviating crack propagation when cleaving is not completely guided along the entire cross section.
the focus position and laser energy influence the guided cleaving threshold position. The samples for which the guided cleaving threshold is inside the thickness of the glass are 1.85 mm reference 300 and 400 μJ, 1.1 mm reference 300 μJ and 1.1 mm shifted 300 μJ (respectively in Figure 4(3,6,9)). They are also the samples for which no precracks between adjacent filaments were observed in the Entry-Side SEM images in Figure 2A. They correspond also to samples with a modification width lower than 2.5 μm, defined as the critical width (shown in Figure 3). The existence of pre-cracks on the opposite side of the initiated cleaving is then a feasible and nondestructive method to evaluate if the cut edge will follow the prescribed filament line. Additional understanding of the aforementioned microcracks may help to describe the cleaving mechanism and can be examined by roughness measurement of the cut surface.[21,22]

### 3.3. Evaluation of the Maximum Roughness $R_z$

For better evaluation of the quality of the cut surface, the maximum roughness $R_z$ was measured across the sample thickness (Figure 5). For the sake of completeness, the arithmetical mean roughness $R_a$ was evaluated simultaneously and exhibited similar trends with values <2 μm. Here only $R_z$ is further discussed as it gives direct information on the length of the longer microcracks, which is the relevant parameter when considering fracture mechanics with Griffith’s criterion.[23] The value of $R_z$ gives the possibility of estimating the tendency of the crack to propagate straight through the material (high $R_z$) along the filament or deviating from it (low $R_z$). In the graphs, the distances are relative to the glass sample with the Focus-Side always located at zero. All graphs use the same color code with blue dots = 300 μJ, green dots = 400 μJ, and red dots = 500 μJ and the same symbols as previously used, e.g., in Figure 3 (dashed lines are visual guides to the eye). Hollow symbols indicate that a glassy fracture pattern is present. The glassy fractures are often curved, making the estimation of their roughness difficult. The value of $R_z$ for these glassy areas is set to 0.5 μm as it could be estimated at 660 μm for 300 μJ burst energy in Figure 5A at the edge between the scattered fracture pattern and the glassy area. $R_z$ is determined by taking the mean value of 11 single-line measurements parallel to the surface of the sample and defining then an AOI. Borders of the AOI are stated by the error bars belonging to the distance axis in Figure 5. Standard deviation for each evaluated AOI is used as error bars for $R_z$ and allows an estimation of the topological homogeneity. The observations shown in Figure 5 present several global trends. $R_z$ and its standard deviation are higher near the surface of the sample on both the Entry- and the Focus-Side. That suggests that the lesser confinement of the laser energy near the surface induces a more complex network of longer microcracks. At the opposite, the roughness in the sample center is lower and more homogeneous. The contrast between the central and the subsurface regions increases with the laser energy and between the samples in the order 1.85 mm reference, 1.1 mm reference, and 1.1 mm shifted, showing that the confinement effect is more critical when the deposited energy is higher.[24] The highest roughness of 18 μm is observed for the Focus-Side of the 500 μJ 1.1 mm shifted sample, which is in good agreement with the surface modifications presenting three lines (000, Figure 2B). The exact relation between the size of the microcracks and energy is assumed to be more convoluted at higher laser energy as the maximum roughness $R_z$ at the surface is greater than the width shown in Figure 3 and higher than the distance between the filaments. A rather large area is affected/weakened by the laser treatment below the surfaces. The central part of the samples presents a relative constant roughness with similar $R_z$ values, which increases with applied laser energy. For lower laser energy a crossover from scattered fracture pattern to glassy fracture is observed. The glassy fracture does not necessarily mean that no filament exists but that the cleaving crack is not guided by the filament modifications. At the guided cleaving threshold position, $R_z$ lies between 3 and 4 μm. This critical limit value of $R_z$ is lower than the distance between each filament. This could then explain why the guidance terminates. Indeed, the network of microcracks generated in the surrounding of one filament does not overlap the micro-crack network of the next filaments. The propagation of a guided cleaving crack is not favored to the propagation of a conventional plain glass cracking behavior. It is expected that the microcrack network that we just

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**Figure 5.** Maximum roughness $R_z$ spatially resolved across the thickness of A) 1.85 mm reference focus, B) 1.1 mm reference focus, and C) 1.1 mm shifted focus. (color code of energy settings: blue = 300 μJ, green = 400 μJ, red = 500 μJ). Hollow symbols indicate characteristic glassy fracture, grey vertical dashed lines represent Entry-Side and Focus-Side. An increase in burst energy causes higher $R_z$ values. $R_z$ is greater at the Entry-Side and Focus-Side. Sample centers present smoother regions.
3.4. Mechanical Strength of the Filaments Line

Results of the four-point bending measurements and subsequent evaluation using Weibull statistics are shown in Table S2 and S3, Supporting Information. As shown, many differences are observed between the Entry-Side and the Focus-Side. Filaments do not always reach through the complete sample, and precracks between adjacent filaments are not always present. The roughness also shows a strong anisotropy between both sides. Therefore, it is critical to describe separately the results between the mechanical strength measured by initiating the cleaving from the Entry-Side or Focus-Side. For comparison, plain glass without filaments was also tested in the same setup and its characteristic strength is determined at 130 MPa. Here, the edges of the plain glass were cut by filamentation. This plain glass value is equivalent to the strength of the final product. It is similar to the strength of a postpolished, scribe and break cut glass, as recently reported.

Figure 6 shows the results obtained by applying the tensile stress on the Focus-Side. The filaments on this side all present bulges and precracks connecting the filament holes (Figure 2B). All the characteristic strengths are contained in a relatively small interval between 22 and 29 MPa. The two reference samples, which received an identical quantity of energy from the laser on that specific side, present a similar decreasing trend of their strength with increasing burst energy used. The small shift between the two thicknesses did not display significant differences. The shifted sample has an almost constant characteristic strength of 23 MPa. The slightly higher value for 500 μJ burst energy is attributed to the three lines deformation, which also caused an increase in the error bars. It is in this series that the most prominent surface modification and roughness were observed. The practically constant strength value and roughness were observed. The practically constant strength value suggests that a saturation of the weakening of the glass was reached. However, at the Entry-Side the highest discrepancy of the aspect was observed in the SEM images (Figure 2A). The drastic difference of characteristic strength from 117 to 25 MPa, shown in Figure 7, reflects the discrepancy. The points joined by dashed lines correspond to the samples where a precrack is observed in the SEM pictures in Figure 2A. They are comprised in the same interval and follow the same trend than the results obtained for the Focus-Side (Figure 6). In this case, the microcrack networks have the same weakening effect on the characteristic strength. The samples where such a precrack is absent (Figure 2A2, A4, A7, encircled in Figure 7) or where the filament hole is absent (Figure 2A1, X in Figure 7) have significantly a higher characteristic strength. In that specific case the presence of microcrack networks did not influence the weakening of the glass strength drastically. Their characteristic strengths are close to the values obtained for plain glass without the filament measured at 130 MPa. If the presence of the filament seems to not have a strong effect on the characteristic strength in certain cases, it has a significant effect on the statistic distribution. The determined Weibull modulus for all the filamented conditions is high reaching, even to a value of 44 (see Table S3, Supporting Information). Higher values of the Weibull modulus mean that the breaking points are better predetermined, allowing a better control of the stochastic effect. No further logical trend could be identified between the samples and the measured Weibull modulus. The observations on the characteristic strength underline the importance of the properly chosen laser energy and focus position to generate complete effective filamentation to maintain an optimal cleaving behavior and assure high-dimensional accuracy of the cut pieces.

![Figure 6](image6.png)

**Figure 6.** Characteristic strength $\sigma$ needed to break the filament line by applying tensile stress at the Focus-Side versus burst energy. Displayed values were obtained by applying Weibull statistics on the results of four-point bending measurements; The point denoted with ($\sigma\sigma\sigma$) corresponds to the sample with a three-line deformation. The points linked by dashed lines correspond to the sample where a precrack links adjacent filaments.

![Figure 7](image7.png)

**Figure 7.** Characteristic strength $\sigma$ needed to break the sample by applying tensile stress at the Entry-Side versus burst energy. Displayed values were obtained by applying Weibull statistics on the results of four-point bending measurements. The point with a cross (X) corresponds to the sample where filaments did not reach through the material. The encircled points correspond to the samples where no precracks are observed (partially guiding filaments) and values joined by dashed lines are those for which such a precrack existed (fully guiding filaments).
3.5. Linking Mechanical Strength with Laser Energy Deposition

A direct comparison between the laser energy distribution and the mechanical strength of the filament lines is difficult as this energy depends both on laser energy and on sample position. However, it was demonstrated that the width of deformation could be related to the energy deposited by the laser (Figure 3). Moreover, the width of surface modification has the advantage to be observable prior to the cleaving. The relationship between characteristic strength \( \sigma \) and the width of the surface modification is shown in Figure 8. The overall shape respects well the trend of Griffith’s criterion where the characteristic strength decreases with the size of the initial crack.\(^{[23]}\) If no surface modification is present or is below the critical width of 2.5 \( \mu m \), it seems that the impact of the laser treatment was not sufficient, where there is only a minor weakening of the material. The samples with \( \sigma \) higher than 74 MPa are identified to show no precracks between adjacent filaments in the SEM images on the side submitted to the tensile stress. The sudden drop of \( \sigma \) at the critical width of 2.5 \( \mu m \) demonstrates the importance of the presence of the easy observable precracks. For widths at the tensile side between the critical width of 2.5 \( \mu m \) and the contact limit of 5 \( \mu m \), \( \sigma \) decreases from 38 to 22 MPa. A higher deformation width does not further weaken the characteristic strength of the filament line, even for the 500 \( \mu m \) 1.1 mm shifted focus, marked with (oOo). The presence of a minimum strength is characteristic of the presence of microcracks. The stress field is divided on microcracks, allowing local plastic flow and then delaying the brittle behavior.\(^{[23]}\)

The strength needed to separate a filament line can be estimated quickly by observation of the surface modification. If the separation condition was to be optimized, not only must the strength be considered but also if the cleaving crack will be guided accurately along the filament line by the microcrack network. This condition is fulfilled when the deformation width is greater than the critical width at the opposed side where cleaving is initiated. All considered, an optimal cleaving behavior is obtained when the cleaving is initiated on a side presenting surface deformations in contact and ends on a side where the surface deformation width is higher than 2.5 \( \mu m \).

4. Conclusion

The experiments revealed that the laser treatment generated surface modifications, reaching from uniform round shapes to highly ruptured areas. The width of surface modification increased with the deposited energy and can be utilized as an indicator to optimize laser parameters and sample positioning without the need for destructive measurements. The critical width of the surface modification at the opposed side of cleaving initiation has to be above 2.5 \( \mu m \) to ensure complete effective filamentation, i.e., accurate crack guidance. Obtaining complete effective filamentation is essential to avoid cleaving crack deviation and maintain high precision in the lateral dimension of the final cut product. Here it is also demonstrated that the width of the surface modifications is linked directly to the quantity of energy deposited by the laser. Therefore, it takes into account the effect of laser energy as well as the effect of sample positioning.

The evaluation of the cut surface shows that the size of the microcracks at the sample center determines the cleaving guidance and therefore effective filamentation conditions. Microcracks with a length lower than 3.5 \( \mu m \), 70% of the distance between filaments, cannot overlap anymore to the adjacent filament preventing cleaving crack guidance. From this observation a generalization is possible. It is expected that if the distance between filaments is reduced, smaller microcracks will be needed to cleave. As microcracks are intrinsically needed for the cleaving process, it additionally implies that the cut edge roughness cannot be lower than 70% of the distance between filaments.

In terms of the characteristic strength \( \sigma \) the critical width is again a reliable indicator. An incomplete filamentation caused a drastic increase of the strength, close to the critical strength of a filament cut glass, if the cleavage is initiated on an insufficient modified side. The characteristic strength is decreased by a factor up to six when the surface modifications are in contact. In general, an increase in deposited energy on the side where the cleavage is initiated lowers the separation strength. If high-dimensional accuracy of the final cut product is not a critical requirement, a partial filamentation will still lower the separation strength by a factor of four.

The results of this study may be applicable to other glass systems. Indeed, similar surface modifications during filamentation are found for borosilicate and aluminosilicate glass.\(^{[18,28]}\) The optimization of the focus position to bring the necessary energy homogeneously on a larger interval will reduce significantly the difficulties of sample positioning.
Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Keywords
crack guidances, filament cleaving, laser cutting, surface modifications, surface roughnesses, ultra-short-pulse laser filamentsations

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[1] C. Hermanns, J. Middleton, Proc. of Photon Processing in Microelectronics and Photonics IV, Vol. 5713, SPIE, San Jose, CA 2005, p. 387.
[2] J. Serbin, G. Oulundsen, Information Display 2017, 33, 38.
[3] M. Kumkar, L. Bauer, S. Russ, M. Wendel, J. Kleiner, D. Grossmann, K. Bergner, S. Nolte, in Proc. of Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XIV (Eds: A. Heisterkamp, P. R. Herman, M. Meunier, S. Nolte), Vol. 8972, SPIE, San Francisco, CA 2014, p. 897214.
[4] S. Nisar, L. Li, M. A. Sheikh, J. Laser Appl. 2013, 25, 42010.
[5] S. Abbas Hosseini, P. R. Herman, Rofin-Sinar Technologies LLC, US Patent US20130126573A1 2013.
[6] S. Abbas Hosseini, J. Un Na, G. Albelo, Rofin-Sinar Technologies LLC, US Patent US20150034612A1 2015.
[7] J. Lapointe, R. Kashyap, Sci. Rep. 2017, 7, 499.
[8] J. Dudutis, R. Stonys, G. Račiukaitis, P. Gečys, Opt. Express 2018, 26, 3627.
[9] J. Dudutis, P. Gečys, G. Račiukaitis, Opt. Express 2016, 24, 28433.
[10] J. Lopez, K. Mishchik, B. Chassagne, C. Jauva-Leger, C. Höninger, E. Mottay, R. Kling, in ICALOE 2015: 34th International Congress on Laser Materials Processing, Laser Microprocessing and Nanomanufacturing, Laser Institute of America, Atlanta, CA 2015, pp. 60–69.
[11] A. Couairon, A. Mysyrowicz, Phys. Rep. 2007, 441, 47.
[12] J. Rolle, L. Bergé, G. Duchateau, S. Skupin, Phys. Rev. A 2014, 90.
[13] K. Cveček, S. Dehmel, I. Miyamoto, M. Schmidt, Int. J. Extrem. Manuf. 2019, 1, 42001.
[14] S. Richter, F. Naumann, F. Zimmermann, A. Tünnermann, S. Nolte, Appl. Phys. A 2016, 122, 1.
[15] J.-C. P. Diels, J.-C. Diels, W. Rudolph, Fundamentals, Techniques, and Applications on a Femtosecond Time Scale, Elsevier, Amsterdam 2006.
[16] J. U. Thomas, F. Lentes, A. Ortner, J. Schatz, M. Kluge, Schott AG, US Patent US20200087192A1 2020.
[17] L. Sudrie, A. Couairon, M. Franco, B. Lamouroux, B. Prade, S. Tzortzakis, A. Mysyrowicz, Phys. Rev. Lett. 2002, 89, 186601.
[18] K. Mishchik, R. Beuton, O. Dematteo Caulier, S. Skupin, B. Chimier, G. Duchateau, B. Chassagne, R. Kling, C. Höninger, E. Mottay, J. Lopez, Opt. Express 2017, 25, 33271.
[19] E. G. Gamaly, S. Juodkazis, K. Nishimura, H. Misawa, B. Luther-Davies, L. Hallo, P. Nicolai, V. T. Tikhonchuk, Phys. Rev. B 2006, 73, 214101.
[20] M. Grehn, T. Seuzting, M. Höfler, N. Griga, C. Theiss, A. Mermillod-Blondin, M. Eberstein, H. Eichler, J. Bonse, Opt. Mater. Express 2014, 4, 689.
[21] R. C. Bradt, J Fail. Anal. Preven. 2011, 11, 79.
[22] S.-J. Wu, H.-C. Hsu, W.-F. Lin, Trans. Can. Soc. Mech. Eng. 2016, 40, 923.
[23] W. D. Kingery, H. K. Bowen, D. R. Uhlmann, Introduction to Ceramics, Wiley, New York, 1976.
[24] K. Mishchik, JLMN 2016, 11, 66.
[25] V. I. Kondrashov, L. A. Shtova, V. A. Litvinov, V. V. Surkov, Glass Ceram. 2002, 58, 303.
[26] F. Roumili, S. Benbahouche, J.-C. Sangleboeuf, Friction 2015, 3, 65.
[27] K. Cveček, JLMN 2017, 12, 115.
[28] J. Li, E. Ertorer, P. R. Herman, Opt. Express 2019, 27, 25078.