

Article

Evaluation of Ultra-Thin Glass Cutting Edges Using an Ultrashort Pulsed-Laser Robot System

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Abstract

We report on an evaluation of cutting edge ultra-thin glass processed by a novel ultrashort pulsed-laser robot system. The system consists of a six-axis articulated industrial robot with an ultrashort pulsed laser integrated on the link after the robot's elbow. Mirrors are used for beam aligning and guiding, and a 2D galvanometer scanner and an F-Theta lens mounted on the last robot axis are used for material processing. Ultra-thin glass AF 32 eco is cut using robot motion only and combined scanner–robot motion, with additional axis rotations about the laser beam focusing in two directions. Hybrid cutting is compatible with a wide range of rotation angles, achieving cutting-edge angles from 88.9° to 119.7°. The influence of cutting-edge angles and cutting methods is further evaluated using residual stress measurements and three-point bending tests, revealing that the cutting method has a dominant impact on cutting-edge quality. To demonstrate the large-scale cutting with defining cutting-edge angles, a trapezoid is cut using the hybrid method with extra robot axis rotation, which achieves an average cutting-edge angle of 91.9°.

Keywords: ultrashort pulsed-laser robot; ultra-thin glass; cutting-edge angle; 3D processing; glass cutting

1. Introduction

Ultrashort pulsed (USP) lasers with pulse durations in the femtosecond-to-picosecond range have been widely used for precision glass processing due to their unique light–matter interaction mechanisms. Compared to conventional lasers, which provide photon energies below the glass band gap, USP lasers enable material processing through nonlinear absorption mechanisms. Owing to their extremely short pulse durations and high intensities, free electrons are generated in glass through multiphoton absorption and avalanche ionization, which facilitate glass processing [1,2]. In addition, the pulse duration is shorter than the electron–photon timescale, which suppresses thermal diffusion to the surrounding region, resulting in cold processing with a minimal heat-affected zone [3].

Ultra-thin glass (UTG), defined as glass with a thickness below 200 µm, has gained increasing attention in various applications due to its excellent optical and mechanical properties, as well as its high thermal and chemical resistance. It has been applied in microelectromechanical systems [4–6] and flexible electronics, such as foldable displays [7,8], and in photovoltaic applications [9,10]. However, the mechanical and thermal characteristics of UTG, particularly its high brittleness and high stress sensitivity, pose challenges



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to conventional glass processing methods such as mechanical scribing and cutting [11]. Various studies have demonstrated that USP lasers are suitable for various thin-glass processing applications, such as TGV (through-glass vias) drilling [12], glass microfluidic device manufacturing [13], and composite cutting [14]. Moreover, USP lasers are commonly used for direct cutting of UTG, and the factors influencing cutting quality, such as ambient medium [15], wavelength [16,17], as well as cutting methods [18,19], have been discussed.

Controlling the glass cutting edge geometry is essential for preserving the designed geometry or enhancing functionality. Recently, various methods for controlling the cutting-edge geometry have been reported. Flamm et al. [20] proposed an edge control strategy employing beam shaping and phase-only volume beam splitting. Various edge geometries, such as C-shaped, chamfered, and 90° apex profiles, were generated. Furthermore, methods for generating various cutting-edge geometries in UTG have also been reported. Itoh et al. [21] combined two CO₂ laser beams with an assisting air flow and realized C-shaped cutting edges. Hu et al. [22] developed a customizable edge geometry calculation that applies the CZT (chirped-z transform) method instead of FFT (fast Fourier transform) for 3D holographic diffraction computation. Additionally, by utilizing in situ aberration correction, the computational cost has been significantly reduced.

All of the aforementioned methods exhibit significant requirements for processing equipment. Recently, we introduced an ultrashort pulsed-laser robot (USPLR) system that combines a USP laser with a six-axis articulated robot, enabling large area 2D and even 3D micromachining [23]. Based on this concept, we conducted a comprehensive study on UTG direct cutting using the system [24]. Beyond cutting through robot movement alone, we also demonstrated a hybrid cutting method that robot axes and galvanometer scanners move simultaneously [25]. However, both previous studies investigated only 2D machining scenarios without considering oblique laser incidence. In a robotic setup, the relative orientation between the laser beam and the specimen can be adjusted with much greater flexibility, indicating that the USPLR system inherently has the potential to generate a wider range of cutting-edge geometries without requiring sophisticated additional components. Nevertheless, comprehensive investigations of oblique laser incidence, as well as systematic comparisons between the standard and hybrid approaches, remain lacking. This gap motivates the present study.

We realize the validation of cutting-edge angles of UTG in a straightforward manner using the USPLR system. The cutting edges using both robot movement and hybrid cutting method on the USPLR system are evaluated and compared. The system structure, and the methods of system tool center point definition, system characterization, glass cutting, and measurement are presented in detail in Section 2. The cutting-edge angle and the cutting quality of using both the standard and hybrid cutting are discussed in Section 3. Subsequently, to demonstrate the capability of hybrid cutting for flexible geometry fabrication, variations in cutting trajectory and the fabrication of a trapezoid are presented in Section 4.

2. Materials and Methods

2.1. Experimental

The USPLR system is illustrated in Figure 1. A 1030 nm USP laser (CB3-40W, Light Conversion) is integrated onto Link 3 of a six-axis articulated industrial robot (IRB 2600ID-8/2.00, ABB Zurich, Switzerland). A 2D scanner, comprising two galvanometer deflectors (RTAX-A15 and RTAY-A15, Newson, Dendermonde, Belgium) and a telecentric F-Theta lens with a focal length of 160 mm (JENar Silverline F-Theta, Jenoptik, Jena, Germany), is mounted at the end of Axis 6 and is responsible for laser beam deflection and focusing. Mirrors mounted on the robot links are corresponding to the beam guidance along the robot axes, enabling beam propagation from Link 3 through the subsequent links to the

scanner. The high overlap between beam propagation axis and robot axes suppresses beam misalignment during robot movement, which ensures processing precision across a large area. A two-stage cascade beam stabilization system is integrated into the system for adjusting beam alignment. Each stage consists of two mirrors with a piezoelectrical inertial actuator (PIAK10, Thorlabs, Newton, NJ, USA) pair and two cameras. Here, the first stage consists of M1, M3, CAM1 and CAM2 ($2 \times$ DMK 37AUX250, The Imaging Source, Bremen, Germany), and the second stage consists of M5, M8, CAM3, and CAM4 ($2 \times$ DMK 38UX541, The Imaging Source, Bremen, Germany), which are used to correct beam misalignment induced by the rotation of Axis 4 (For additional details on beam stabilization, see [26,27]). A confocal sensor (CL-L070, Keyence, Osaka, Japan) on Axis 6 is used for beam focus monitoring.

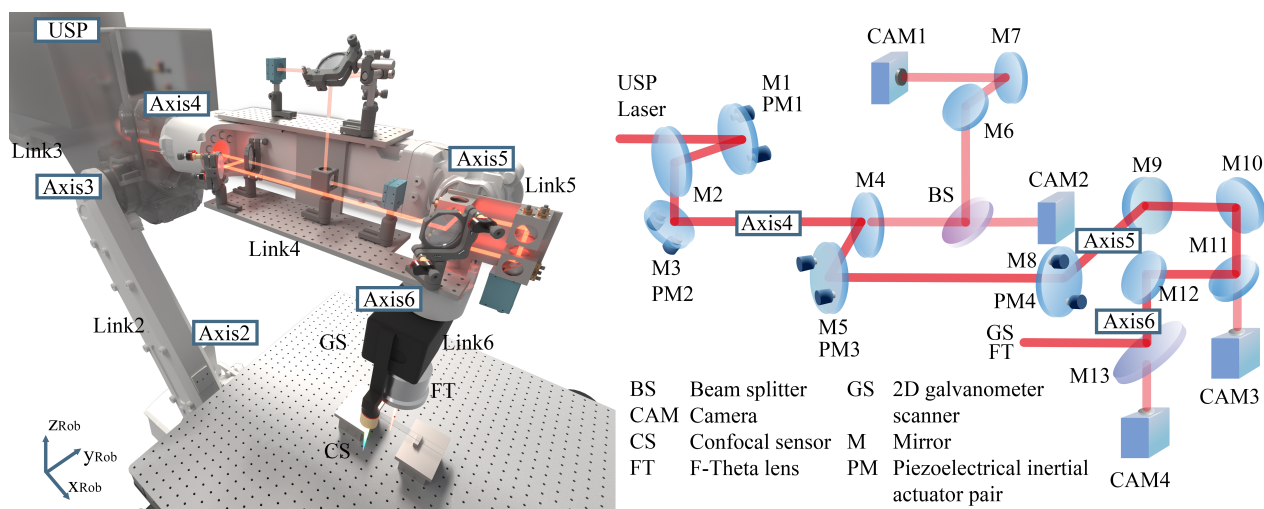


Figure 1. Illustration of the USPLR system. Axis 1 and Link 1 are located behind the table and not depicted in the figure. The USP laser is mounted on Link 3. The laser beam guided by mirrors propagated along the axes, reaching the scanner fixed at the end of Axis 6. A cascade beam stabilization module, consisting of mirrors with a piezoelectrical inertial actuator pair and cameras, suppresses beam misalignment and maintains the optimal alignment between the optimal propagating axis and the mechanical axes.

Ultra-thin glass plates (AF 32 eco, Schott, Mainz, Germany) with a geometry of $300 \text{ mm} \times 300 \text{ mm} \times 100 \text{ }\mu\text{m}$ were initially cut into pieces (measuring $15 \text{ mm} \times 100 \text{ mm} \times 100 \text{ }\mu\text{m}$) using the USPLR system for the subsequent cutting process. These long pieces were cut using various cutting strategies into segments with dimensions of $10 \text{ mm} \times 15 \text{ mm}$, wherein the 15 mm cutting edges produced under varying cutting conditions were compared. A laser scanning microscope (LSM, VK-X3000, Keyence, Osaka, Japan) was used for cutting-edge recording and measurement. The residual stress in the samples was measured using imaging polarimetry (ilis, Erlangen, Germany, StrainScope Flex). A camera (DMK 33UX546, The Imaging Source, Bremen, Germany) with a resolution of 2480×2480 (pixel size: $2.74 \text{ }\mu\text{m}$) and a polarimeter (PAX1000, Thorlabs, Newton, NJ, USA) were used for beam profile and polarization measurements, respectively.

2.2. System Preparation

2.2.1. Determination of Tool Center Point

The tool center point (TCP) is essential for maintaining positional accuracy during complex system trajectories, which is particularly critical for the USPLR system. ABB robots provide a simple function to define the TCP using four segments with various orientations, and each segment comprises translational and rotational information (for more details see ABB tutorial [28]). Based on this function, a method for determining the TCP of the

USPLR system is illustrated in Figure 2a. Beam focus is defined as the system TCP. For the first segment, the robot moves without additional rotation along the z axis, until a minimum beam diameter is captured on the camera fixed on the table. The beam diameter d_0 is defined as beam focus, and beam position (x_0, y_0) is defined as the reference, with the corresponding robot position and orientation recorded. Subsequently, the scanner is rotated in three of four available orientations a–d (see Figure 2), with each orientation corresponding to a 15° rotation about the x or y axis in the robot coordinate system. At each orientation, the robot moves along the x, y and z axis, adjusting the beam profile after rotation (x_i, y_i, d_i) to the focus diameter d_0 and the reference position. Please note that beam position within a defined positional tolerance is acceptable. The corresponding translational and rotational information is then recorded (segments 2–4).

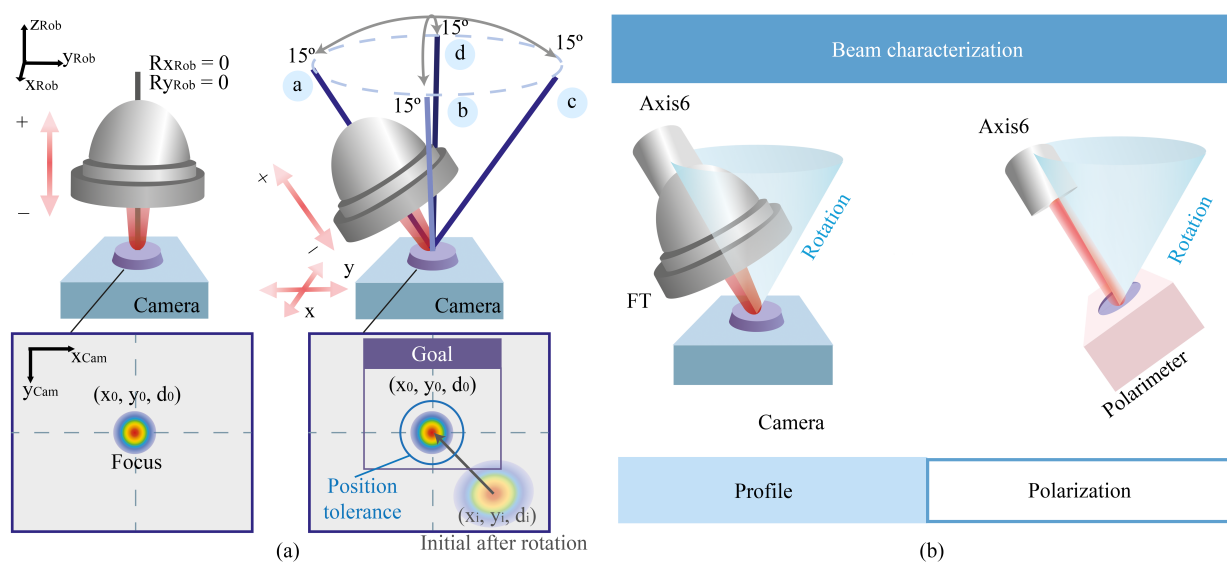


Figure 2. Illustration of the USPLR system preparation steps. **(a)** TCP determination. Left: robot moves along the z axis for determining beam focus d_0 and beam center position (x_0, y_0) . Right: scanner is rotated into three of four orientations a–d. On each orientation, the beam profile d_i and beam center position (x_i, y_i) are adjusted through robot movement to match the beam focus diameter and the reference position within a positional tolerance. **(b)** Beam characterization. **(Left):** The beam profile behind the F-Theta lens with rotation about TCP is captured by a camera fixed on the table. **(Right):** Beam polarization behind Axis6 with rotation about TCP is measured by a polarimeter, where the sensor surface vector of polarimeter remains parallel to the beam propagating axis.

2.2.2. Beam Characterization

The beam profile and polarization measurements provide a clear characterization of the system status during additional rotations about the determined TCP. The system was rotated about the TCP in the range of -15° to 15° in 5° increments around both the x and y axes (Figure 2b). The profile of the focused beam at each robot orientation was captured using a camera fixed on the table, with its sensor surface maintained parallel to the table. Applying the same rotation strategy, the polarization of laser propagating behind Axis 6 was measured with a polarimeter, with its surface vector maintained parallel to the beam-propagating axis.

2.3. Cutting Using USPLR System

The unique structure of the USPLR system enables UTG cutting in a simple and flexible manner. The cutting method is illustrated in Figure 3a. The robot moves along a predefined trajectory (in this case, along y_{Rob} direction), while the laser is activated after a time offset and deactivated before the robot reaches the end of the robot trajectory. The laser

activation duration is calculated based on the robot velocity so that the effective cutting length matches the designed length. Offsets before and behind the designed length prevent laser exposure during the unstable movement that occurs during robot acceleration and deceleration. The required offset lengths are calculated based on the robot speed.

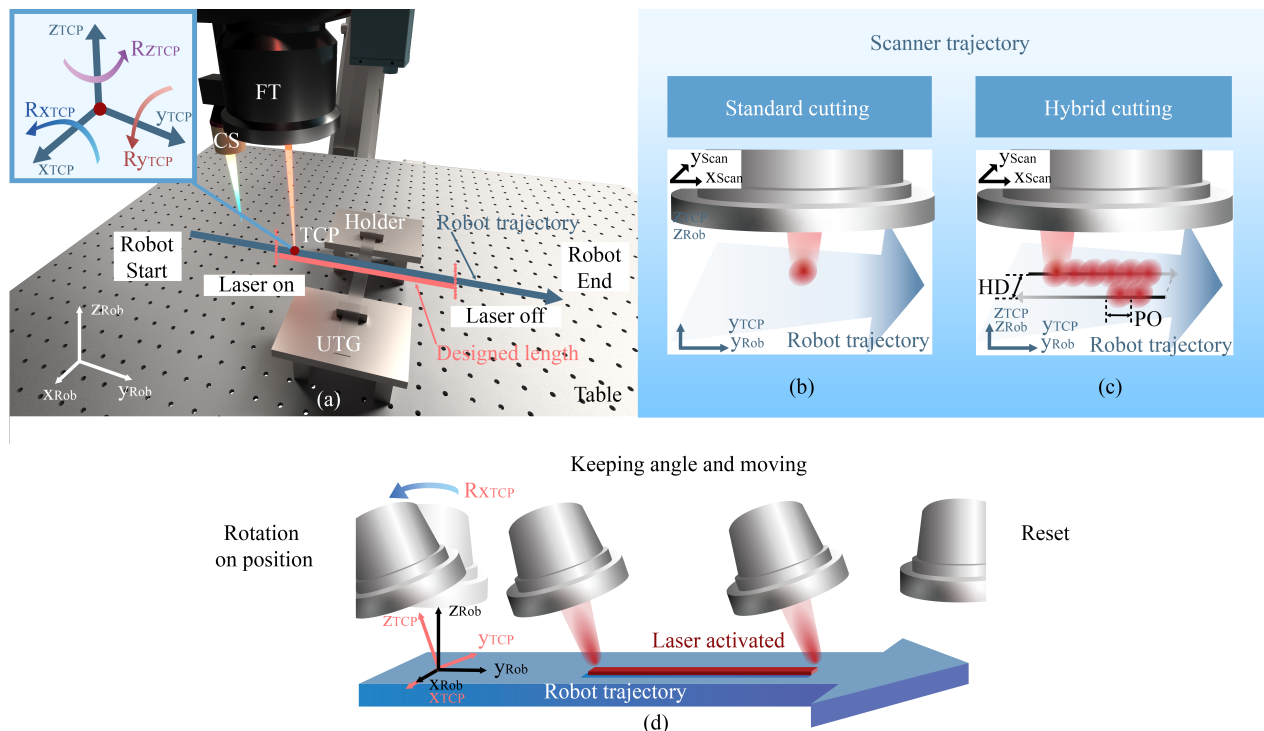


Figure 3. Cutting method using the USPLR system. (a) Laser beam focus is defined to be the TCP. Robot translational and rotational movement are referenced with respect to the TCP coordinates. Cutting along the robot trajectory, the laser is activated after a time delay once the robot motion begins and is deactivated before the robot reaches the end of the robot trajectory. UTG is held between two holders such that the robot trajectory passes through the gap. (b) Standard cutting, in which the scanner remains at its initial position while the robot follows its trajectory. (c) Hybrid cutting, where the scanner follows its own trajectory in addition to the robot movement. HD—hatch distance, PO—pulse overlap. (d) Cutting with additional rotation about the TCP. The robot rotates about R_{xTCP} and moves along trajectory with remaining orientation.

Beyond the robot trajectory, the scanner movement also plays a significant role in the cutting process. Two recently reported cutting strategies are applied in this work. In standard cutting, the scanner remains stationary, keeping the laser beam at its initial position in the scanner coordinate system while the robot moves (Figure 3b) [24]. In contrast, hybrid cutting involves simultaneous robot motion and scanner movement, where the scanner follows a predefined trajectory during the robot movement. The scanner trajectory is continuously repeated during the laser activation time duration. The parameters, namely, hatch line numbers and length, hatch distance (HD), pulse overlap (PO), scan speed and jump speed are configurable according to the specific requirements of the processing material (Figure 3c) [25].

Rotation of the system allows the cutting-edge angle to be varied. As shown in Figure 3a, additional rotation around the x and y axis (R_{xTCP} , R_{yTCP}) about the defined TCP is allowed. The active rotation around the z direction (R_{zTCP}) is restricted to maintain a consistent alignment between the robot TCP and scanner coordinate systems. In the cutting process, the scanner rotates about the TCP to the specified angle and then initiates the motion, keeping the orientation until the robot reaches the end of its trajectory (Figure 3d).

For multi-trajectory processing, resetting the system to the initial orientation at the end of each trajectory prevents collisions during axes movement.

2.4. Analysis of Cutting Edge

2.4.1. Cutting-Edge Angle Measurement

The beam focus remains on the surface of the glass specimen using the confocal sensor. The resulting cutting-edge angles were measured by the method illustrated in Figure 4a. Glass segments with a geometry of 10 mm × 15 mm were cut using various cutting parameters. The upper portion of the cut-through segment was used for angle comparison, where the angle between the front side and the cutting edge is defined as the cutting-edge angle. Please note that the angles on the inlet side were considered in the experiment (cross section view A-A) and cutting direction is along y_{Rob} .

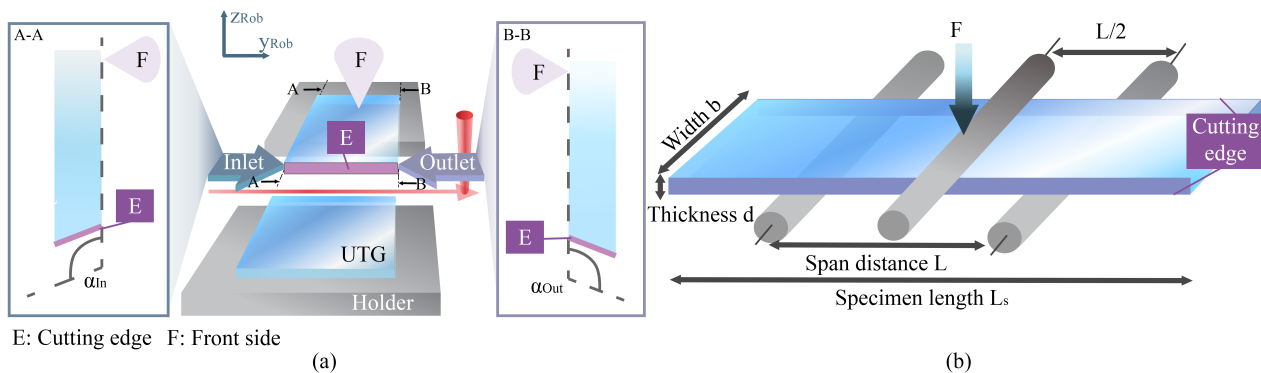


Figure 4. Cutting edge analysis methods. (a) Measurement of cutting-edge angle. The inlet side was considered in the analysis. The angle between the glass front side and cutting edge is defined as the cutting-edge angle. (b) Three-point bending test. The long sides of the specimens were cut using various cutting parameters.

2.4.2. Bending Test

To investigate the influence of the cutting-edge angle on cutting quality, a three-point bending test (EZ Test, Shimadzu, Kyoto, Japan) was utilized to compare the flexural strength of the produced cutting edges (Figure 4b). A span distance of 70 mm and the loading rate of 5 mm·s^{−1} were used in the experiment. Both sides with a length of 100 mm were cut with the evaluated parameter and the width was measured individually using the LSM. The flexural strength is calculated according to [25,29]:

$$\sigma = \frac{3FL}{2bd^2}, \quad (1)$$

where F is the maximum load, L is the span distance, b is the specimen width and d is the specimen thickness. Three samples were generated for each parameter.

2.5. Flexible Cutting of UTG

To evaluate the cutting process using the USPLR system, different robot trajectory orientations are considered (Figure 5a). The default robot trajectory (LNo.1) was rotated by 45°, −45° and 90° around the home position, generating LNo.2–4, respectively. Cutting without additional rotation ($Ry_{TCP} = 0^\circ$) and with a rotation of 15° about the y_{TCP} ($Ry_{TCP} = 15^\circ$) was performed for all trajectories. Please note that the TCP coordinate system rotates according to the defined robot trajectory, such that y_{TCP} remains parallel to the corresponding robot trajectory. For example, as shown in Figure 5a, y_{TCP} is parallel to the trajectory in cutting along LNo.1, the same as along LNo.3.

The USPLR system enables the fabrication of complex geometries with a defined cutting-edge angle through additional TCP rotation. The cutting procedure is illustrated in Figure 5b. A trapezoid with a base length of 65.9 mm, a top length of 24.5 mm, a height of 37.2 mm and a base angle of 60° was cut out. Following the cutting rule introduced in Section 2.3, the y_{TCP} remains parallel to the corresponding trajectory, with an additional rotation of 15° about the y_{TCP} . For the cutting-edge angle measurement, the trapezoid was cut using the USPLR system along the trajectories shown in the inset of Figure 5b.

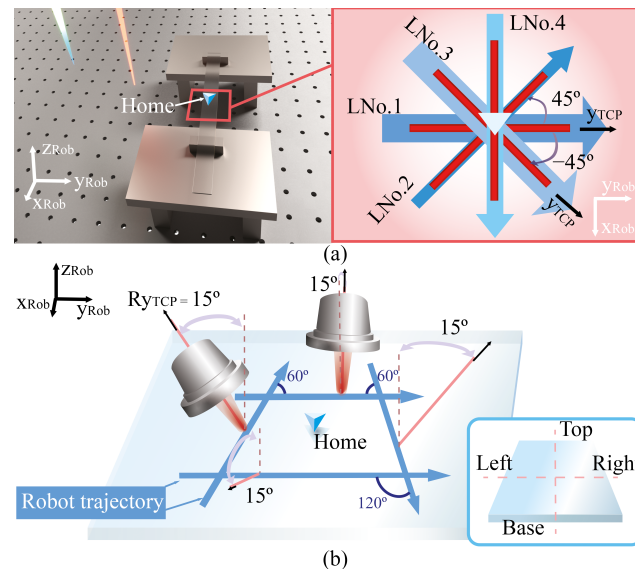


Figure 5. Complex cutting with a defined cutting-edge angle. (a) Cutting with various robot trajectories passing through home position. Three trajectories (LNo.2–4) are compared with the default robot trajectory LNo.1, each rotated by 45° relative to the previous trajectory. (b) Cutting trajectories of the trapezoidal geometry with defining cutting-edge angle. For each side, y_{TCP} is parallel to the corresponding robot trajectory, with the remaining $Ry_{TCP} = 15^\circ$. Inset: The sample was cut along lines for edge angle measurement and the edge angles were measured.

3. Results and Discussion

3.1. Characterization of the USPLR System

Rotating the robot about a point located outside the laser beam focus causes the beam to become defocused after the rotational motion, resulting in increased deformation of the beam profile. Therefore, defining the laser beam focus as the tool center point (TCP) is essential for accurately calculating and controlling both the translational and rotational motions of the robotic system. Beam profiles with and without TCP determination after rotating robot axes are shown in Figure 6a. A stable beam profile is observed after adjusting the system TCP using the method described in Section 2.2.1, whereas a significant ellipticity is found when rotating axes about an unsuitable TCP. Defining the beam focus as the system TCP, the beam defocusing and beam position deviation during complex system movements are reduced, thereby ensuring the process precision. Figure 6b involves the beam diameters measured after TCP adjustment with rotation in the range of $(-15^\circ, 15^\circ)$ around both the x and y axis. Please note that the initial robot orientation is defined as $Rx_{TCP} = 0^\circ$ and $Ry_{TCP} = 0^\circ$. An increase in beam diameter is observed as the rotation increases from the initial orientation, while combined rotations about both axes produce a more pronounced diameter expansion. The diameter at 15° rotation along both axes exhibits a substantial deviation compared to other orientations. This is attributed to the small angle between the beam-propagating axis and the normal surface of the sensor, which leads to distortion in the captured images. Excluding this orientation, the mean diameter of remaining orientations is $58.4 \mu\text{m}$ with a standard deviation of $3.0 \mu\text{m}$.

In addition, polarization exhibits a dependency on the robot orientation (Figure 6c). Single x and y axis rotation induces a counter-clockwise rotation of laser polarization. A nearly circular polarization (ellipticity = -36.35°) is observed at the initial orientation, whereas the ellipticity decreases as the rotation angle increases. At the same time, the orientation angle also varies as the TCP is rotated. The translational and rotational motions of the robot are achieved through combined rotation of six axes, during which the mirrors mounted on the robot links are also rotated. The deviation of incident angle during system movements is unavoidable and consequently leads to variations in polarization.

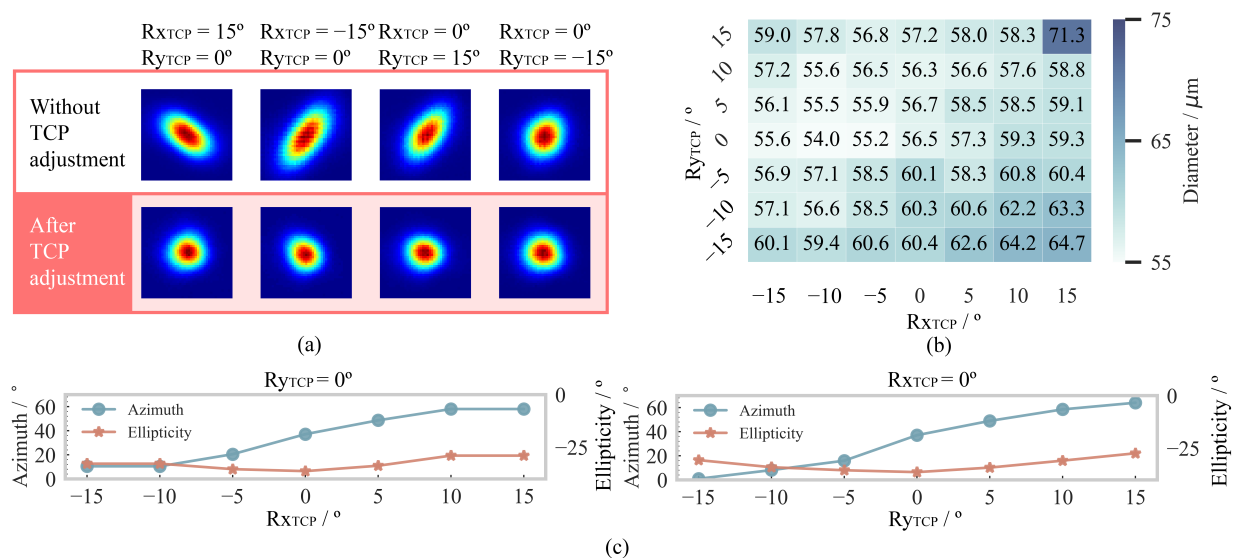


Figure 6. System preparation and beam characterization. (a) Beam profile before and after TCP adjustment. (b) Beam diameter with system rotation around x_{TCP} and y_{TCP} axis after TCP adjustment. (c) Laser polarization with rotation around a single axis. A counter-clockwise rotation is assigned a negative sign.

3.2. UTG Cutting with Varying Robot Orientation

Glass was cut using both the standard method and hybrid methods. Based on previous studies [24,25], UTG was successfully cut in a simple 2D cutting scenario. The influence of laser parameters of both methods on cutting quality is shown in Table 1. Since our target is to validate the cutting-edge angle using the USPLR system while achieving better cutting quality, the laser parameters that yielded the best cutting quality (without cracks in both short and long specimens) in the standard and hybrid processes were applied in this experiment, and differ between both cutting methods. Additionally, the scanner moves along the scan trajectory as illustrated in Figure 3c with a scan speed of $1500 \text{ mm} \cdot \text{s}^{-1}$ and a jump speed of $1000 \text{ mm} \cdot \text{s}^{-1}$ in hybrid cutting. The number of hatch lines was two, with a hatch distance of $16 \mu\text{m}$. To ensure statistical reliability, three samples were generated for each parameter.

Figure 7 shows the cutting result using both methods with TCP rotation around x and y axis from -15° to 15° . Please note that three samples were cut for each condition. In the standard cutting, all samples were cut through across all the TCP orientations. However, samples tend to generate cracks by cutting with additional rotations (Figure 7a inset 2). In contrast, the hybrid method, which provides a more homogeneous energy distribution, significantly suppresses crack generation. All the cut-through samples produced by the hybrid method were crack-free. However, glass was cut through only at a part of the robot orientations. Across all the satisfying orientations, the rotation allows the cutting-edge angle to be validated. The hybrid cutting method yields a wide and continuously distributed parameter range, while the standard method produces inconsistent and unreliable cutting

results. Comparing the cutting edges produced by both methods without rotation, a molten region is observed on the edge produced by the standard cutting method due to the high accumulated energy in the processing area (Figure 7a inset 1), whereas a sharp edge with a minimum heat affect zone was achieved in the hybrid cutting (Figure 7b inset 2). The reason is that the additional scanner movement reduces local heat accumulation and maintains the cold-ablation mechanism [30] in the processing region. In addition, hybrid cutting results in a distinct relation between TCP orientation and cutting-edge angle. Rotating around the y direction leads to a significant validation of cutting-edge angle. An 89° angle is realized with a 15° rotation around the y axis (Figure 7b inset 3), while the -15° rotation around the y axis produced a cutting-edge angle of 120° (Figure 7b inset 1). It is observed that the angle difference between the TCP rotation and the resulting cutting edge remains comparable when the TCP is rotated about the y axis solely. In contrast, additional rotations around the x axis significantly diminishes processing stability. Neither stable cutting nor a clear relationship between TCP rotation and cutting-edge angle are observed for either cutting method. Notably, we observed a more significant instability in the robot motion at the 5° rotation around the x axis, which results in a reduction in cutting quality. The incident angle strongly influences the energy distribution on the workpiece surface [31,32]. In the experiment, the TCP y axis is aligned to the robot trajectory, the projected beam footprint along the cutting direction remains unchanged during TCP rotation around the y direction. Consequently, the energy distribution in this direction maintains a normal Gaussian profile comparable to that of the laser beam without rotation. In contrast, rotation around the x axis induces an elongation of the beam profile along the cutting direction. This distortion changes the local energy distribution and ultimately reduces the achievable cut-through range.

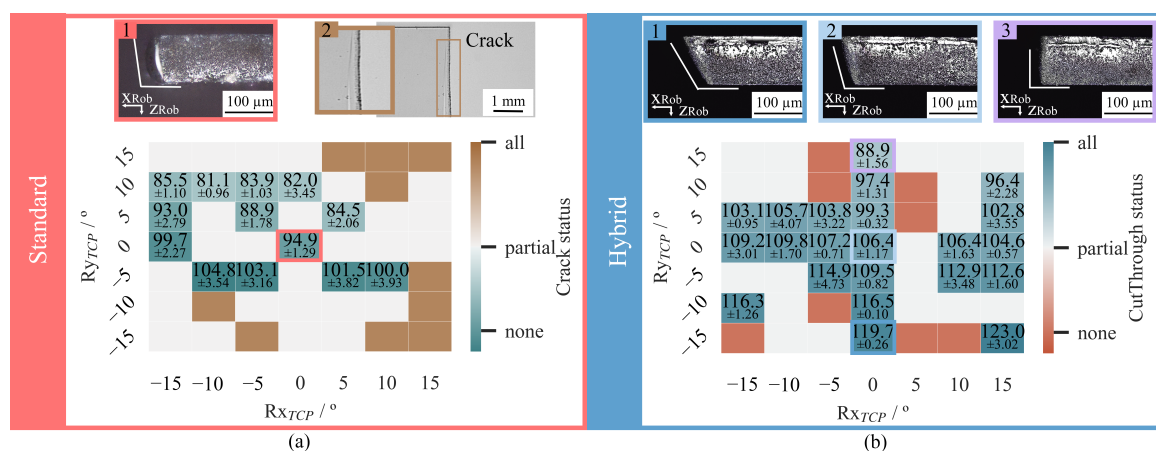


Figure 7. Cutting results using (a) standard method and (b) hybrid method with additional TCP rotations from -15° to 15° along both x and y axis. The mean values of inlet angles were measured, wherein the crack-free edges produced by the standard and the thru-cut edges produced by the hybrid method are shown in blue. Please note that the saturation in blue indicates only the variation in cutting-edge angles.

Table 1. Influence of processing parameters on cutting performance for the standard and hybrid methods.

Method	Rep. Rate/kHz	Pulse Energy/ μ J	Pulse Duration/ps	Robot Speed/ $\text{mm}\cdot\text{s}^{-1}$	Cut-Through	Crack Short Spec.	Crack Long Spec.
Standard	200	80	1	30	No	—	—
	200	120	1	20	Yes	No	Partial
	200	120	1	30	Yes	No	Partial

Table 1. Cont.

Method	Rep. Rate/kHz	Pulse Energy/ μ J	Pulse Duration/ps	Robot Speed/mm $\cdot$ s $^{-1}$	Cut-Through	Crack Short Spec.	Crack Long Spec.
Standard	200	120	7	20	Yes	Partial	–
	400	80	1	30	Yes	No	No
	400	80	7	30	Yes	Partial	–
Hybrid	200	80	7	20	No	–	–
	200	120	1	20	Yes	Yes	–
	200	120	7	20	Yes	No	No
	200	120	7	30	No	–	–
	400	80	1	20	Yes	No	Partial
	400	80	1	30	No	–	–

Note: Yes = successful cut-through; No = unsuccessful cut-through; Partial = partial crack propagation; – = not applicable. Please note that the maximum laser pulse energy of the system at 400 kHz is 80 μ J. Parameter applied in the study are bolded.

3.3. Mechanical Behavior Analysis

The residual stress in glass cut using both methods is shown in Figure 8a. Since the residual stress in the material is lower compared to the cutting edge, all the stresses exceeding 10 MPa are represented using the same color as 10 MPa, the maximum stresses are listed in Table 2. Please note that one sample was used for each rotation angle. The residual stress was evaluated over a measurement length of 5 mm. In the hybrid method, a maximum stress of 47.2 MPa was observed at a 15° rotation around the y axis. However, the standard cutting method exhibits residual stress that is three times higher at the same orientation. The oblique laser beam has a negligible effect on the residual stress of both cutting methods. As shown in Figure 8, the hybrid cutting suppresses stress penetration into the material. Residual stress is able to be observed more than 1 mm behind cutting edge using standard cutting, whereas the stress remains confined to the near-field region of the cutting edge in hybrid cutting. The pronounced residual stress at the cutting edge together with the deeper stress penetration in the standard cutting, explains the results shown in Figure 7a, where only a portion of the samples were cut through without crack formation using standard method with additional rotation.

Table 2. Maximum stress on the glass sample after cutting with additional rotation about the TCP using both methods.

Method	$R_{yTCP} = -15^\circ$	$R_{yTCP} = 0^\circ$	$R_{yTCP} = 15^\circ$
Standard/MPa	152.2	166.1	169.9
Hybrid/MPa	41.1	37.3	47.2

Both cutting methods exhibit local stress concentrations along the cutting edge. In the case of the standard cutting method, the higher residual stress is attributed to increased local heat accumulation, which promotes melting and subsequent cooling. The resulting temperature gradients and stress relaxation during cooling lead to residual stress in the processed glass [33]. Comparing the optical micrograph and the measured residual stress at a rotation of 15° around the y axis in hybrid cutting (Figure 8b), high stresses are observed at locations where the chipping appears, which penetrate from the chipping along the structure into the material. We assume that chipping is the primary source of residual stress in hybrid cutting, while thermal effects predominantly govern residual stress formation in standard cutting.

Specimens with a length of 100 mm that were cut with various TCP rotations were used in the three-point bending test. Since additional rotations around the x axis reduce process stability, a stable cutting process is observed using hybrid cutting with rotation solely around the y axis. Furthermore, no stable cutting parameters were found for rotations around either the x axis or the y axis using the standard method. Since long specimens require higher process stability in comparison to short specimens, we applied the stable processing range of hybrid cutting as well as standard cutting without rotation for the long specimens. The results are shown in Figure 9. Cutting edges produced by the standard method exhibit a large variation in flexural strength, with a median value of 36.0 MPa. In contrast, hybrid cutting achieves a significantly higher median strength at the same robot orientation, measured as 44.9 MPa. The maximum standard deviation in hybrid cutting is 4.5 MPa, which is half of that observed in the standard cutting method. Furthermore, no dependency is observed between the cutting-edge angle and the resulting flexural strength. The maximum median strength of 49.0 MPa is obtained at a rotation of -10° , while the minimum median value of 44.9 MPa is observed at the initial orientation. A flexural strength of 370 MPa for AF 32 eco was reported for internal scribing using a Bessel beam followed by a mechanical breaking process [34]. Although direct laser cutting generally results in lower flexural strength, the USPLR system enables flexible UTG processing without requiring sophisticated additional optical components.

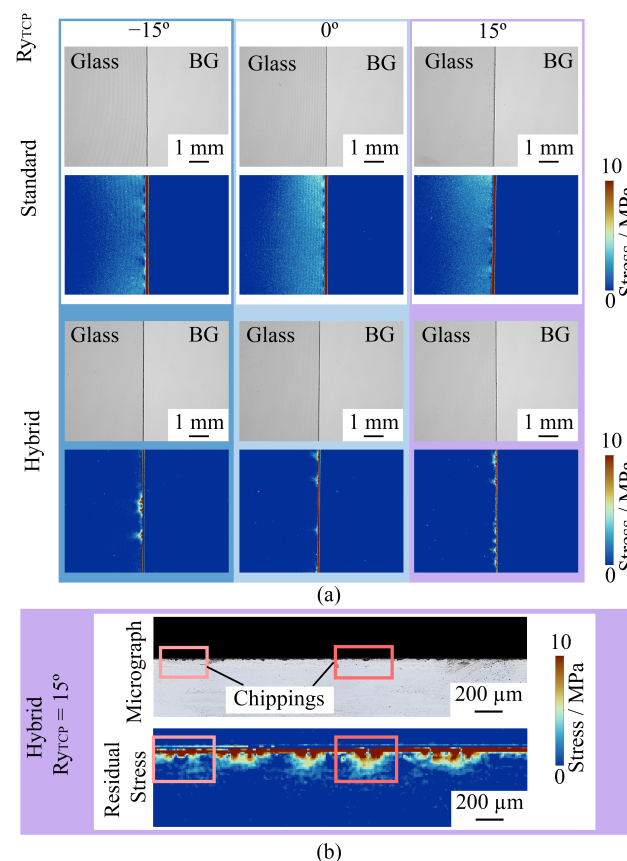


Figure 8. Measurement of residual stress in the UTG after cutting. (a) Comparison of residual stress of standard cutting (Top) and hybrid cutting method (Bottom). Please note that glass samples are placed on the left side only. BG—background. (b) Chipping induces stress penetration in glass. The stresses exceeding 10 MPa are represented using the same color as 10 MPa.

The present results indicate that the cutting method exhibits a predominant influence on cutting quality using the USPLR system. In addition, the residual stress and flexural strength results obtained using the hybrid cutting method indicate that the change in

laser polarization during rotation has no significant impact on UTG cutting using the USPLR system.

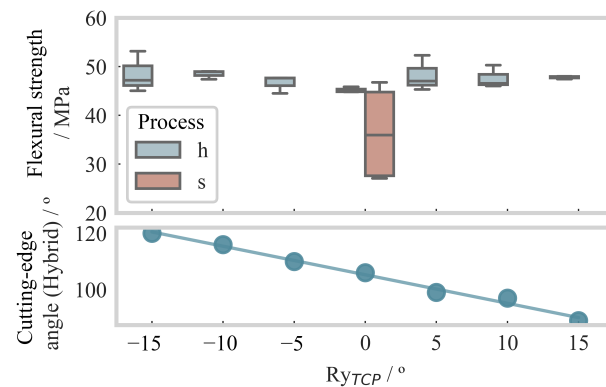


Figure 9. Three-point bending test of long specimens (h—Hybrid cutting; s—standard cutting).

4. Demonstration

Hybrid cutting with a rotation of 15° around the y axis exhibits a high median flexural strength together with the lowest standard deviation. Therefore, this cutting configuration was selected for the subsequent experiments involving varying robot trajectories and trapezoidal geometry cutting.

Since the laser beam is guided by mirrors through the robot axes, the mirrors rotate simultaneously with the robot axes during the movement, which induces the change of focus profile and laser polarization. To evaluate the influence of the robot trajectory, UTG was cut along four trajectories, as illustrated in Figure 5a, using the hybrid method both with and without additional rotation. The y axis of the TCP remained parallel to the robot trajectory. The cutting-edge angles are summarized in Table 3. Large angle deviations were observed by cutting with additional rotations, both at the same trajectory and between various orientations. The average cutting-edge angle of all the trajectories was 106.8° , with a standard deviation of 0.91° without rotation. Applying rotations, the average was 91.9° with a standard deviation of 1.49° . A trapezoid was cut with additional rotation (Figure 10). The cutting-edge angle of each side is shown in Figure 10b. The average of the angle is 91.9° with a standard deviation of 0.82° . The low deviation of cutting-edge angle observed in both the robot trajectory variation and the geometry cutting experiments demonstrates that the USPLR system is capable of cutting UTG on a large scale while reliably defining the cutting edge.

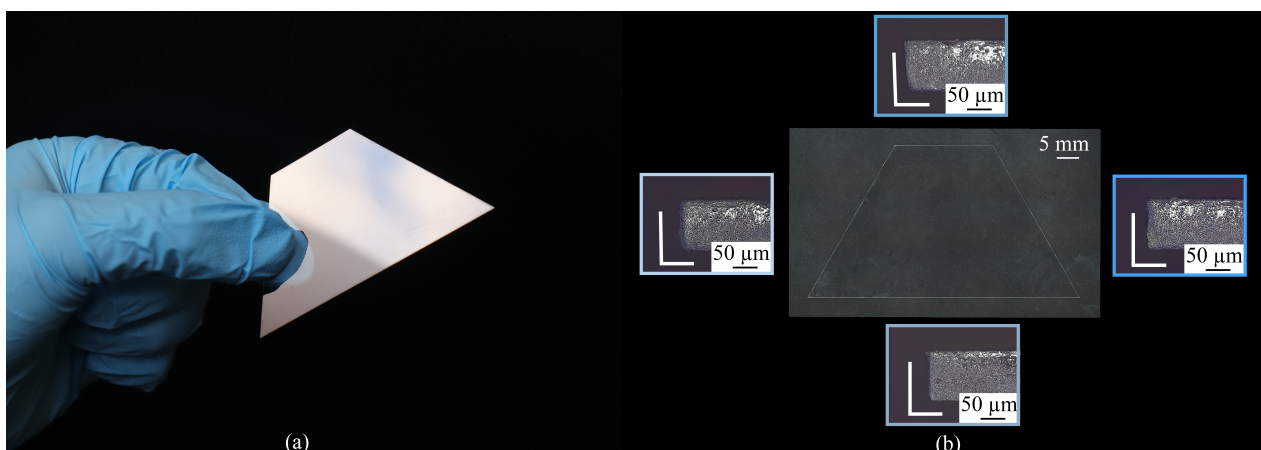


Figure 10. Trapezoid cutting using the hybrid method with additional rotation. (a) Overview (b) Cutting edges on each side.

Table 3. Cutting-edge angle using the hybrid method with additional rotation about the TCP.

Rotation (°)	LNo.1		LNo.2		LNo.3		LNo.4	
	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.
0	106.4	0.95	107.2	0.19	107.3	1.00	105.9	0.48
15	88.9	1.27	93.3	1.38	91.6	1.06	90.8	0.41

5. Conclusions

We developed a method for varying the cutting-edge angle of UTG using an ultrashort pulsed-laser robot system. By defining the beam focus as the system TCP, the UTG was cut using both standard and hybrid cutting methods. Applying TCP rotation during the hybrid cutting process, various cutting-edge angles can be achieved. Cutting edges with angles from 89° to 120° were achieved by applying rotations from −15° to 15° around the y axis. However, rotation around the x axis reduces process stability. Residual stress three times higher was observed in the material using standard cutting, while a maximum residual stress of 47.2 MPa was obtained using the hybrid method. Most of the stress was induced by chipping on the cutting edge during hybrid cutting. Furthermore, long specimens were cut with and without additional rotation and used in a three-point bending test, where a higher flexural strength was observed for hybrid cutting. Compared to the cutting-edge angle, the applied method presents a predominant influence on the cutting-edge quality.

In addition, UTG was cut using hybrid cutting with varying robot trajectories for trapezoidal geometry fabrication. A low-angle deviation was observed in both experiments, demonstrating the capability of the USPLR system for large-scale cutting of complex geometries while controlling the cutting-edge angle.

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