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Laser fusion cutting of ultra-thin glass (UTG) using a profile-controlled beam for residual stress reduction

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Abstract

We have developed a method to cut ultra-thin glass (UTG) via laser fusion cutting approach. This study presents a method to reduce residual thermal stress. A focused CO_2 laser beam spot melted glass, and then the locally molten area was blown away via assisting air. Two laser beams, one circular and the other elliptical, were superposed to control the beam profile and illuminated. Photoelastic analysis and the sample fracture pattern proved that this method could reduce the residual thermal stress in glass caused by laser fusion cutting.

Keywords: Laser fusion cutting; multi-laser beam; flexible glass; ultra-thin glass (UTG); residual thermal stress

1. Introduction

Ultra-thin glass (UTG, usually having a thickness of less than 200 μm) with a large area has been commercialized. UTG has not only typical glass characteristics such as optical transparency, gas barrier property, chemical stability, and electrical insurance property, but also special advantages such as its lightweightness and flexibility originated from its thinness. Therefore, a variety of new potential applications by utilizing these advantages have been proposed such as ultra-thin fordable display (Ha et al. 2021), ultra-thin OLED lighting (Wang et al. 2021), flexible solar cells (Kim et al. 2020) etc. Although these applications are promising, the current technical gap is a lack of processing methods for UTG such as cutting, drilling, and

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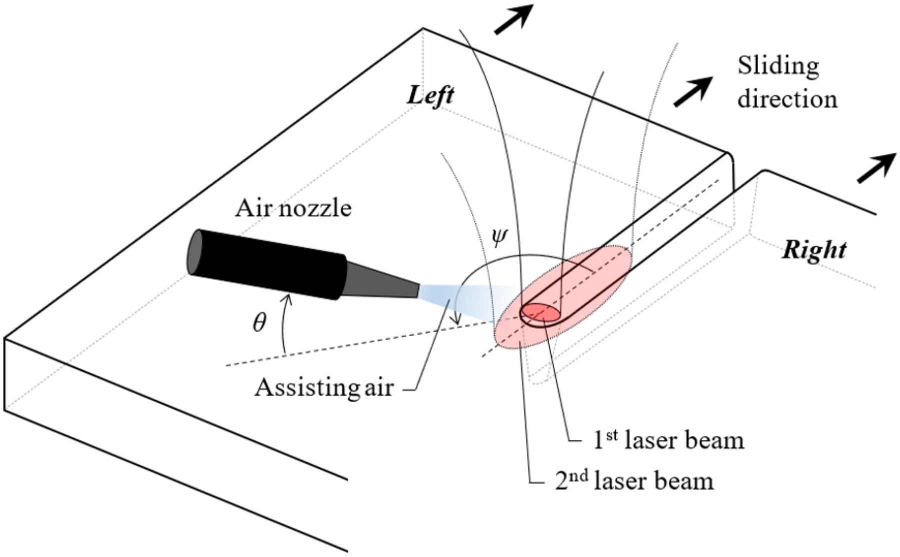

Fig. 1. Schematic of the experimental setup for the laser fusion cutting.

polishing, which prevents the UTG from being utilized in more variety of new applications. Regarding cutting, it is required to cut UTGs with a freeform geometry while keeping a high edge strength.

The thinness of UTG, in turn, causes difficulty on cutting. While there several conventional cutting methods, such as mechanical scribing and breaking (Tomei et al. 2018), laser thermal cutting (Yahata et al. 2013; Abramov et al. 2010), ultra-short pulsed laser scribing utilizing filamentation (Dudutis et al. 2020), there is still no solution to meet the requirements of the freeform cutting and high edge strength at the same time.

The authors have developed the laser fusion cutting method for UTGs (Itoh et al. 2022). When the laser fusion cutting is applied to glass, there are the following advantages: First, the ideal rounded shaped edge, which has never achieved scribing and breaking approach, is formed as glass is heated and softened during the laser fusion cutting. Then, the rounded edge is created by the cutting process, post-chamfering process of the glass edge will not be required. Second, the defect-free edges having a high flexural strength is expected. The typical concern is that laser fusion cutting will induce the large thermal residual stress to the glass, which will lead to cracking during or after cutting. Thus, this method has not been applied to glass yet, except for silica glass having less thermal expansion coefficient than the other glass. However, the author considered that the laser fusion cutting might be applicable to UTGs, as the material is so thin that it will take less time for the laser-induced heat to be penetrated enough in the depth direction. Therefore, the thermal stress generated might be reduced. It is essential to demonstrate the strategy to cut UTGs via laser fusion cutting and to understand its basic mechanisms for the future utilization.

This study is aimed for demonstration of high quality cutting of UTGs via laser fusion cutting, particularly focused on reduction of residual thermal stress.

2. Experimental

A CO_2 laser beam ("1st laser beam") was emitted from an oscillator (C-40, Coherent Inc.) with a wavelength of 10.6 µm, power of 5–20 W, was enlarged using a set of lenses, delivered, and focused onto the glass specimen using a lens. Fig. 1 shows the schematic of the experimental setup. UTG samples were placed on a

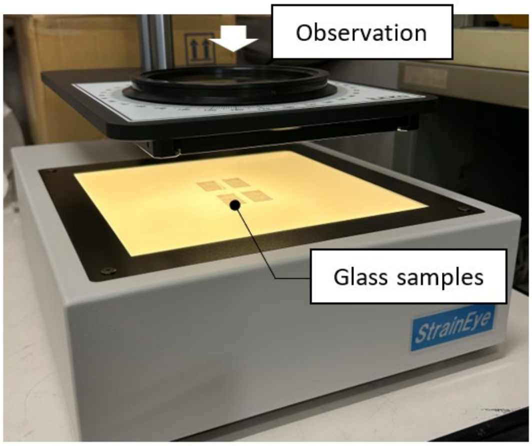

Fig. 2. Photograph of polarimeter used to evaluate residual stress in glass.

one-dimensional mechanical stage and translated along the cutting direction (y-axis). To blow away the molten part indu ced by the laser irradiation, an assist air jet through a nozzle with an inner diameter of 0.2 mm with angles of (ϑ, ψ) aimed to control the cut glass edge shape was prepared and applied toward the molten part. Particularly, in this study, ϑ was fixed at 45° because the air nozzle diameter was so small that the coaxial application of the laser beam and air was difficult. Another CO_2 laser beam ("2nd laser beam") emitted from an oscillator (Evolution 100, Synrad Inc.) was delivered and focused through a cylindrical lens and illuminated onto the surface nearby the molten spot. The 2nd laser beam spot was elliptical with a size of 1.3 by 3.9 mm in order to smoothen the temperature gradient caused by the 1st laser beam.

Alkali-free glass sheets (Willow, Corning Inc.) with a thickness of 100 µm was used. After the laser fusion cutting, the sample was sectioned by using a glass scriber. Then, the sectional image of the glass edge was captured by a laser microscope (LEXT OLS4000, Olympus Corp.) and a scanning electron microscope (SEM, JSM-IT200, JEOL Ltd.). To quantify the retardation values, a polarimeter (LSM-4401LE, Luceo Co., Ltd.), the setup of which is shown in Fig. 2, was utilized.

3. Results and discussions

Fig. 3 shows the SEM image of the cut UTG. At the edge of the UTG, rounded shaped edge was formed. Fig. 4 shows the residual stress map observed by a polariscope in the case of (a) 1st laser beam only, and (b) 1st and 2nd laser beams. Also, Senarmont angles, which shows the amount of the stress, were added in the figure. Typically, the relation between the observed retardation value and principal stress difference in materials can be expressed as

$$C = \frac{Re}{\sigma \cdot t} \quad (1)$$

where *Re* represents retardation (also proportional to the Senarmont angle), *C* photoelastic coefficient, *σ* principal stress difference, *t* sample thickness. As a result, the stress value in the *Right* sample was decreased ~50% by 1st and 2nd laser beam irradiation. Currently, further optimization of parameters is ongoing.

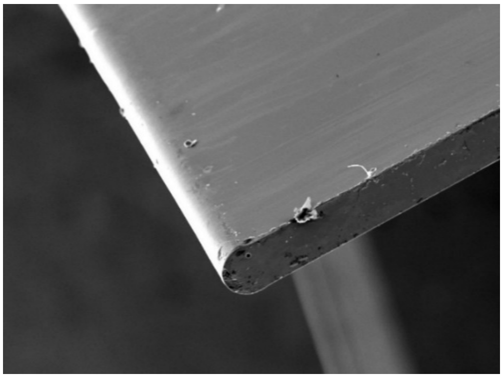

Fig. 3. A SEM image of the cut glass. The thickness of the glass is 100 µm as a scale.

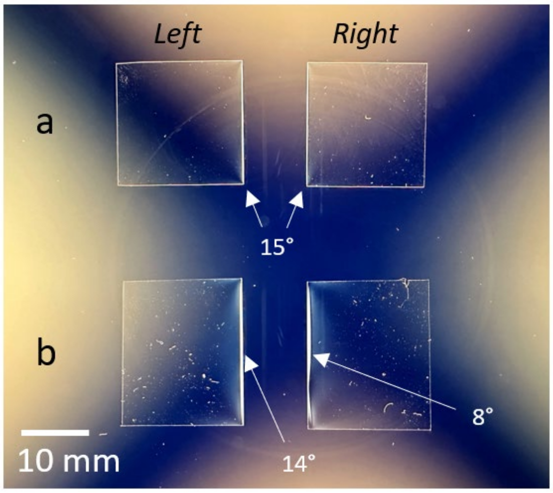

Fig. 4. Residual stress distribution measured by the polarimeter in the case of (a) 1st laser beam only, and (b) 1st and 2nd laser beams.

Fig. 5 shows the sectional views of glass edges in the case of (a) 1st laser beam only, and (b) 1st and 2nd laser beams. Both glass edges have the similar shape. Therefore, the 2nd laser with the applied power in this study doesn't affect the edge shape. On the other hand, in Fig. 5a, the hackle mark can be seen at the edge of the glass (as pointed by the arrow), which is probably caused by the residual stress. However, in Fig. 5b, no hackle mark was seen at the edge. These fracture patterns when created during sample sectioning, are also one of the evidence that the residual stress is relieved by the 2nd laser beam irradiation.

4. Conclusions

UTGs were successfully cut by laser fusion cutting together with residual stress reduction. Residual thermal stress was reduced by superposing the 2nd beam, which is larger than the 1st beam, and overlapped and illuminated. At least, we achieved to reduce the residual stress ~50%, and the fu rther optimization is ongoing.

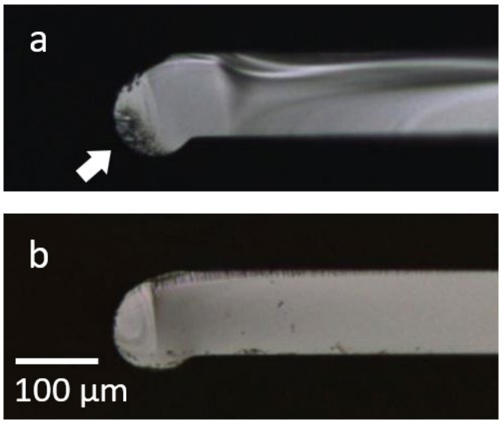

Fig. 5. Sectional views of glass edges in the case of (a) 1st laser beam only, and (b) 1st and 2nd laser beams on *right* sample.

Acknowledgements

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