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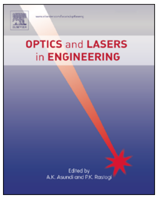

# Thermal cleavage on glass by a laser-induced plume

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ABSTRACT

We developed a thermal cleaving process on glass using an infrared–laser-induced plume. A pulsed ytterbium fiber laser with a wavelength of 1070 nm and a laser pulse energy of 40 μJ was used to produce a plasma plume on a carbon-coated sacrificial glass substrate. The induced plasma plume affected the surface of the target glass substrate and changed its optical properties locally. The laser beam that was subsequently absorbed in the modified zone induced localized heating, which led to micro-crack initiation for the glass cleaving. Various processing parameters, such as the laser's power and pulse width, and the distance between the coating layer and the target glass substrate were investigated to optimize the quality of the glass cleave. The quality of the cutting edges and cross sections with respect to these parameters were examined. Numerical simulations of the micro-crack initiation due to heat accumulation were performed to investigate the fracture mechanism and to estimate the expected glass-cleaving line. The limits and applications of the process are also discussed.

## 1. Introduction

Thin glass substrates are used as the main display component for portable mobile electronics. Their applications are gaining importance in various fields because the substrates have outstanding optical, mechanical, and chemical properties. However, glass cutting is still a challenging technique for conventional machining processes, due to random crack propagation [1–4]. A high-quality cutting surface is not easily achievable. Various machining processes, such as a mechanical tool bit [5–7], a water jet [8,9], chemical etching [10,11], and a laser beam [12–20], have been used for this purpose. One of most popular techniques for cutting glass is the conventional mechanical process involving the physical contact of tool bits. However, the problems with this approach include a considerable loss of materials and inconsistent cutting results. Additionally, the physical contact by the tool bits results in the generation of many chips and limited cutting quality. Moreover, a post-grinding process is usually necessary to remove any micro-cracks on the cutting edges. A water jet is a non-conventional cutting process that uses a water impinging jet with abrasives at high pressure. This jet can cut thick and hard materials; however, nozzle wear and contamination are potential disadvantages [8]. Chemical etching can also be used to obtain the designed shape of the glass substrate [10,11]. However, this process is not flexible, and multiple steps are necessary. A summary of these processes is shown in Fig. 1.

The laser process is one of the most competitive methods for machining brittle and thin materials, compared with other techniques having the disadvantages of micro-cracks, chip contamination, and difficult surface-quality control [3,21]. The laser process has the potential to overcome the weak points of the other processes, mentioned earlier, and its precision energy control and non-contact characteristics are suitable for cutting glass or silicon wafers [4]. However, the processing parameters offered by various laser sources must be considered and carefully incorporated into the design, due to their different laser–material interaction characteristics. The laser process for glass cleaving generally requires the generation of initial cracks through material ablation, followed by crack propagation to form the cut, which is accomplished by rapid heating and cooling of the material with laser beam irradiation. Different machining results can be expected with various lasers; wavelength and pulse width, in particular, have been shown to play key roles. With respect to the laser wavelength, lasers for glass cutting are classified into far-infrared (FIR), near-infrared (NIR), visible (VIS), and ultraviolet (UV) lasers. Additionally, a laser with a short-pulse width, such as a femtosecond laser, can also be used. $CO_2$ lasers, with a wavelength of 10.6 μm, are commonly used for glass cutting, despite the relatively large laser spot and difficulty in optical delivery [3]. When an FIR laser, such as a $CO_2$ laser, irradiates a glass surface, it can

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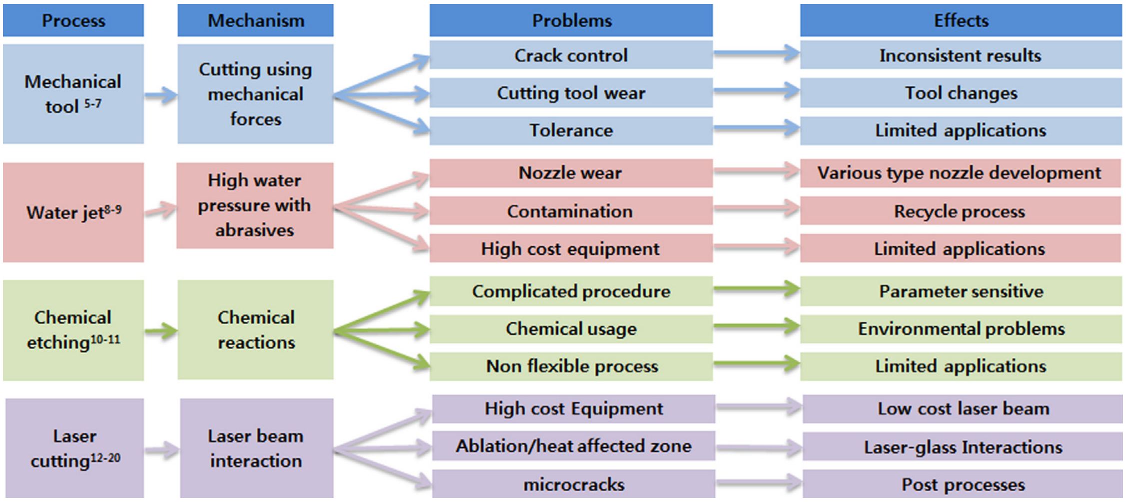

| Process | Mechanism | Problems | Effects |
|---|---|---|---|
| Mechanical tool [5-7] | Cutting using mechanical forces | Crack control | Inconsistent results |
| | | Cutting tool wear | Tool changes |
| | | Tolerance | Limited applications |
| Water jet[8-9] | High water pressure with abrasives | Nozzle wear | Various type nozzle development |
| | | Contamination | Recycle process |
| | | High cost equipment | Limited applications |
| Chemical etching[10-11] | Chemical reactions | Complicated procedure | Parameter sensitive |
| | | Chemical usage | Environmental problems |
| | | Non flexible process | Limited applications |
| Laser cutting[12-20] | Laser beam interaction | High cost Equipment | Low cost laser beam |
| | | Ablation/heat affected zone | Laser-glass Interactions |
| | | microcracks | Post processes |

**Fig. 1.** Various glass-cutting processes and their characteristics.

ablate the material directly and make an initial groove. After the initial production of the notch line, cutting from the surface groove can be achieved by applying an external physical force [22]. Other laser sources can be used to propagate the initial cracks to cut the glass fully; this is achieved by thermal stress induced by heating and cooling. However, the beam size and the quality of the $CO_2$ laser beam are limited to producing high-quality ablation on the glass. A UV laser also has a high absorption rate in glass, and its beam quality is relatively good due to its short wavelength [23]. Ablation of a glass surface can produce well-defined edges or an ablated micro-structure in which the ablated material can be precisely removed. However, the power of a UV laser beam is limited, and the volumetric material removal rate is relatively low. Therefore, UV lasers are not appropriate for cutting large, thick glass substrates. During the past two decades, ultrashort lasers, such as picosecond or femtosecond lasers, have been used for various material processes. The ultrashort pulses provide non-linear characteristics, such as multiphoton absorption, and can be used to induce material modification, not only on the surface of the glass material, but also inside the material [24]. When the laser beam is focused inside the glass material, ablation and crack formation occur. This can be advantageous for producing a high-quality cutting surface, because the initial crack is inside the material; thus, micro-crack-free edges can be obtained from the process. However, the power of the ultrashort lasers is still limited for many industrial applications. Additionally, hybrid methods using two different types of laser sources or a laser and another non-conventional process have been developed to overcome the disadvantages of using a single laser source [16,25]. NIR lasers or VIS lasers, with nanosecond laser pulses, provide relatively high power (pulse energy) and reasonable beam quality with a small, focused laser spot. However, due to the wavelength-dependent characteristics regarding the target substrate, the application of an NIR or VIS laser beam source may not be feasible. The absorption rates of IR and VIS lasers are low, compared with other wavelengths, so it is rather difficult to initiate laser–material interactions.

In this study, we investigated thermal cleavage on glass using a micro plume induced by irradiation with an IR pulse fiber laser. This laser offers advantages, such as reliable beam quality and a lower cost. An NIR beam with a nanosecond laser pulse width has a low absorption rate in glass; therefore, it is difficult to initiate melting or ablation on a glass surface. To overcome this difficulty, we used a laser-induced plasma plume to improve absorption on the target glass substrate. The quality of the cutting edges and cross sections, with respect to various parameters, was examined for fracture control on the target glass substrate. Additionally, a numerical study of the thermal stress and temperature profiles was carried out to reveal the cleaving mechanism of indirect laser glass cutting and to evaluate the appropriate thermal cleaving parameters.

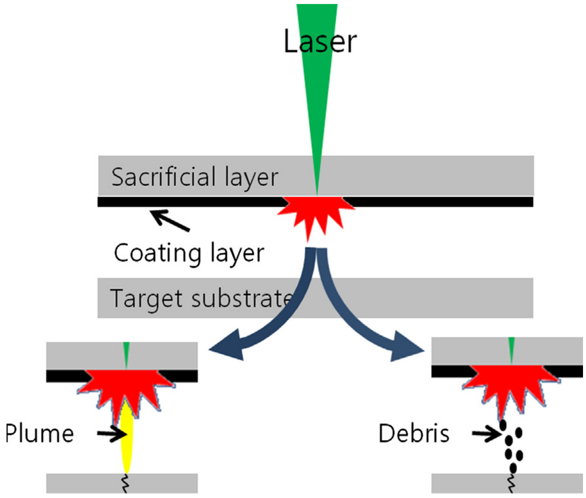

**Fig. 2.** Schematic diagram of indirect laser cleaving.

## 2. Mechanistic theory of thermal cleavage using a laser plume

Fig. 2 shows a schematic diagram of the indirect laser glass-cleaving process. An absorption layer with a black carbon coating on a sacrificial glass substrate was placed on the target glass substrate with a gap of a few hundred microns using a micro-spacer. An NIR laser pulse interacted with the absorption layer, and a plasma plume with nano/micro particles was generated. The plasma plume with nano/micro particles was transferred onto the target glass substrate. The laser-induced plasma plume changed the optical properties of the target glass substrate locally. The absorption rate of the subsequent laser pulses in that region increased, and efficient absorption occurred. Localized rapid heating and cooling were achieved, which led to the generation of local micro-cracks and their directional propagation, resulting in the cleaving and cutting of the target glass material.