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Laser line etching technique using nozzle-induced bubble jet impact for glass

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Abstract

The study proposes a new technique of laser line etching for glass. An Nd:YAG laser was applied to the backside of the glass which was partially submerged in water. A metal plate was placed below the glass substrate. Most of the laser energy is absorbed by the metal plate. The metal vaporized the water and generated a bubble jet. A rectangular nozzle whose inlet and outlet are narrow and rectangular shape was proposed to enhance the impact of the bubble jet. Material ablation occurred by softening and rupture from impact of the bubble jet. The parameters of nozzle geometry, laser power, and laser scanning speed were obtained. The proposed laser etching method was successfully demonstrated for etching a line-strip of 50-500 μm in width on a glass surface. It was found that the bubble jet of the small width nozzle inlet was well confined and created a strong jet impact on the glass surface. The proposed technique can prevent thermal damage and has great potential as an improved solution for the micro-machining of glass.

Keywords：Laser ablation, Laser etching, Bubble jet, Glass;

1. Introduction

The development of microstructure machining techniques for micro-optical elements and micro-patterns has made great progress in recent years. Conventional methods to fabricate grating displays, micro-arrays, and micro-channels are optical and electron beam lithography. Lithography is a complicated process involving mask patterning and ion etching. In recent years, an alternative technique of laser etching was proposed by Wang et al., 1999a and 1999b which has been widely applied in glass etching. The desired etching surface of the glass was placed in contact with an organic solution. The hydrocarbon solution

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absorbed the UV laser energy. The laser-induced rapid vaporization of the organic solution resulted in surface softening near the interface of the glass and the liquid. The softened materials were then expelled by the mechanical stress resulting from the rapid heating, shock waves, and bubble flow. Since the laser was applied from the backside of the transparent substrate, the technique was coined as laser-induced backside wet etching (LIBWE). In recent years, the LIBWE technique has been widely used in glass etching using an Excimer laser or Nd:YAG laser with frequency multiplication (Zimmer et al., 2003; Huang et al., 2007). The liquid gallium metal with a melting temperature of 30°C can be used as the absorbing liquid in the LIBWE technique (Zimmer et al., 2006).

Weng and Tsai, 2014 proposed an alternative etching technique using bubble jet impact. An Nd:YAG laser was applied to the backside of the glass substrate which was partially submerged in water. A metal plate was placed below the glass substrate. The metal vaporized the water and generated a turbulent bubble flow. The bubble nozzle was proposed in order to enhance the impact of the bubble jet. The glass surface was first softened and then expelled by the shock wave resulting from the jet impact. Their etching method was successfully demonstrated for etching a cavity of 5-20 μm in depth and 50-250 μm in diameter.

A full understanding of water jet and bubble development can be obtained using high-speed photography (Takamizawa et al., 2003; Nath et al., 2011). In recent years, the phenomena resulting from a liquid jet induced from a bubble close to a rigid boundary have been studied (Brujan et al, 2001; Wolfrum et al., 2003; Chew et al., 2013; Khoo et al., 2005). When a bubble occurred near a plate with a small hole, the bubble collapsed and split into a liquid jet. The liquid jet entered the hole and generated a micro-pumping effect. The bubble was generated by a laser and other means. The hole diameter of the rigid plate and the distance between the plate and the bubble were the major factors in the bubble pumping effect (Khoo et al., 2005; Lew et al., 2007).

Conventional LIBWE can be used to fabricate microarrays on fused silica plates (Ding et al., 2004). This method offered micro-channels and cavities with controllable depths. The combination of LIBWE and the scanning contour mask technique obtained high quality etching of a transparent material for a micro-optical element (Zimmer and Böhme, 2005). Most laser-line etching techniques use the LIBWE method assisted by the Galvanoscanner system (Niino et al., 2007; Schwaller et al., 2011; Zehnde et al., 2011). Most applications of LIBWE use UV laser for hydrocarbons or liquid metals as an absorbing liquid. However, using $CuSO_4$ in an absorbing aqueous solution while applying a near-infrared laser for etching a line track on a glass surface is relatively easy (Schwaller et al., 2011; Zehnde et al., 2011).

In this study, the etching technique using bubble jet impact proposed by Weng and Tsai, 2014 will be applied in line etching. The conventional LIBWE technique requires a laser absorber such as an organic solution to absorb the laser energy. In this study, an alternative laser-induced backside wet etching technique without the assistance of organic solution will be applied in etching a line track. The proposed technique will use an Nd:YAG laser to heat a metal plate underwater in order to generate the water bubbles. The idea of a bubble-induced jet pump will also be applied to the laser etching of glass. A bubble nozzle will be introduced in order to enhance the pumping effect. The material ablation mechanism of the present method is different from that of conventional LIBWE.

An ultraviolet laser is needed in the conventional laser ablation of glass. However, for the proposed technique using the bubble jet to etch the glass surface, a simpler laser such as a near-infrared laser will satisfy the etching requirement. This innovative approach offers great potential for the laser etching of glass.

2. Principe of laser etching

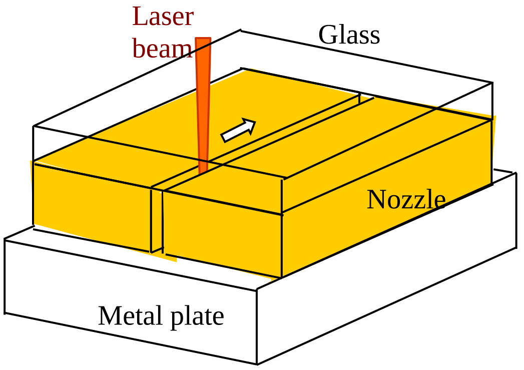
Figure 1 shows the configuration of the laser line etching system. For this study, the glass substrate is placed in water. The desired etching surface is in contact with the water and the laser is applied from the backside of the glass substrate. A pulsed Nd:YAG laser is used in this study. The glass is AMLCD Eagle^{2000} fused silica glass produced by the Corning Company (Taiwan). The glass thickness is 0.63 mm. The wavelength of the Nd:YAG laser is 1,064 nm. The focal length of the objective lens is 100 mm and the minimum diameter of the laser's focused beam is 40 μm.

A bubble nozzle is placed below the glass substrate and in direct contact with the glass surface. The bubble nozzle whose inlet and outlet are a narrow rectangular shape is proposed in order to enhance the impact of the bubble jet. A metal plate made of SUS304 stainless steel is in direct contact with the nozzle inlet. The laser's focal plane is on the surface of the metal plate. The bubbles flow through the nozzle and induce a jet impact which ablates the glass surface.

The Nd:YAG laser power measurement at the metal plate under the glass and water decreases by 10%, meaning that 90% of the laser energy is absorbed by the metal plate. The metal vaporizes the water and generates a turbulent bubble flow. The laser power used is minimal, therefore, the laser ablation effect on the metal plate can be ignored.

According to the study on the cavity etching of glass by Weng and Tsai, 2014, the bubbles generated from the surface of the metal plate are the main contributor to the etching process. When the laser is applied to the stainless steel through the glass and water, it can induce rapid heating due to the strong absorption properties of the stainless steel. The bubble is initiated from the plate surface and then the bubble size increases rapidly. The bubble detaches from the metal plate and rises at rapidly. The bubbles generated from the metal plate must be conducted and concentrated on the desired etching position. A cylindrical or conical bubble nozzle can enhance the strength of the bubble jet impact and confine the jetting direction. Material ablation occurs by softening and ruptures from impact of the bubble jet. The glass surface becomes roughened due to the impact of the bubble jet.

In this study, the nozzle is a narrow rectangular shape as shown in Fig. 1 and Fig. 2. The bubble nozzle can confine the bubble jet to the desired etching region, thereby yielding the best etching geometry. When a bubble moves close to a rigid boundary, the bubble will collapse and produce jetting. The parameters of nozzle geometry are the nozzle outlet width W and the nozzle depth H, which dominate the impact effect of the bubble jet. The outlet width of the nozzle must be larger than that of the laser beam in order to prevent damage to the nozzle.



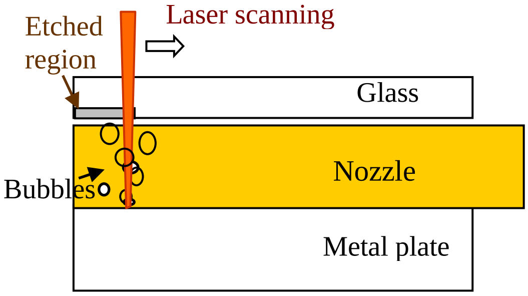


Fig. 1 Configuration of the laser line etching system using nozzle-induced bubble jet impact.

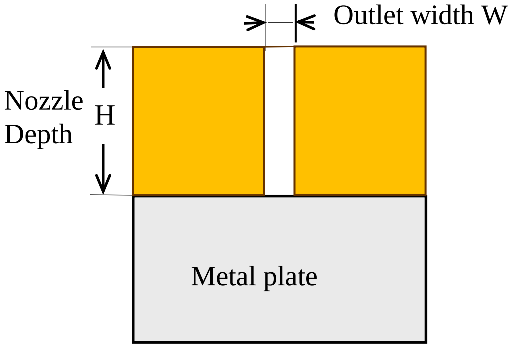


Fig. 2 Configuration of bubble nozzle and metal plate

3. Experimental results of laser etching

The laser line etching system as shown in Fig. 1 was used to etch the glass surface. Figure 3 represents the optical micrograph of the ablation track obtained with a laser power of 10 W, repetition rate of 2 kHz, and scanning speed of 0.5 mm/s. The nozzle depth was 2 mm and the outlet width was 0.6 mm. The etched width was approximately 70 µm and the straightness of the etched strip track was very good. Figure 4 represents the optical micrograph of the ablation track for laser scanning speeds of 0.5, 1, 1.5, and 2 mm/s at a laser power of 25 W. The nozzle depth was 2 mm and the outlet width was 0.4 mm. We found that the slower the scanning speed, the more remarkable the ablation track was.

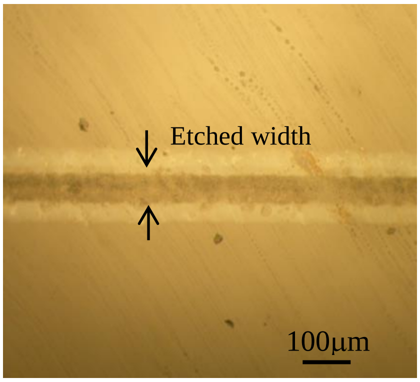


Fig. 3 Optical micrograph of ablation track obtained with a laser power of 10 W and a scanning speed of 0.5 mm/s.

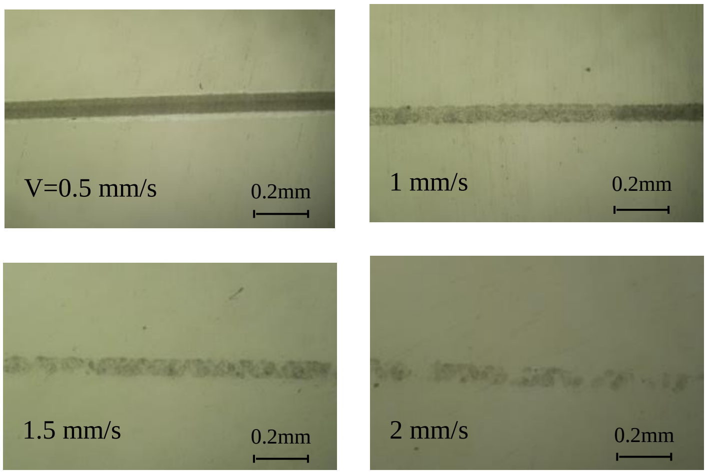


Fig. 4 Optical micrograph of ablation track for different laser scanning speed.

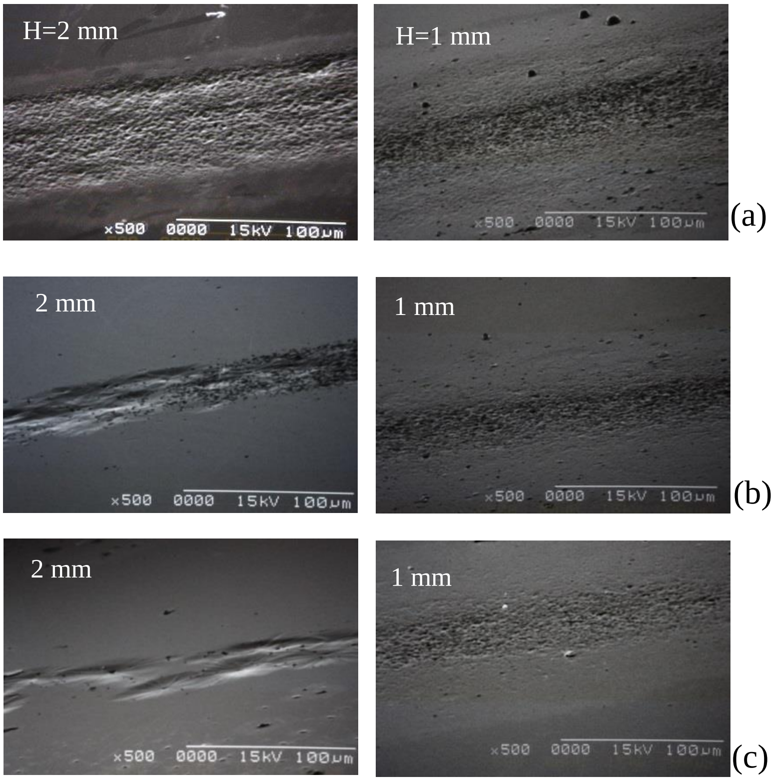


Fig. 5 SEM images of the etched surface obtained with nozzle depths H of 2 mm and 1 mm for a laser power of 25 W and scanning speed of (a) 0.5 mm/s, (b) 1.0 mm/s, and (c) 2.0 mm/s.

Figure 5 shows the SEM images of the etched surface of the glass obtained with nozzle depths H of 2 mm and 1 mm, and outlet width of 0.4 mm. The laser power was 25 W and the scanning speeds were 0.5, 1.0, and 2.0 mm/s. The quality of the etched surface was very good.

The relationships between the etching width, laser power, and laser scanning speed for the nozzle with an outlet width of 0.4 mm are shown in Fig. 6. The nozzle depths were 2, 1.5, 1.0, and 0.5 mm. We found that the etching width was not more than 1.2 mm and that slowing the laser scanning enhanced the etching width. The etching width, at high laser power, for the longer nozzle with depths of 2 and 1.5 mm were greater than that of the shorter nozzle with depths of 0.5 and 1.0 mm. When the laser power was higher, the etching width was larger.

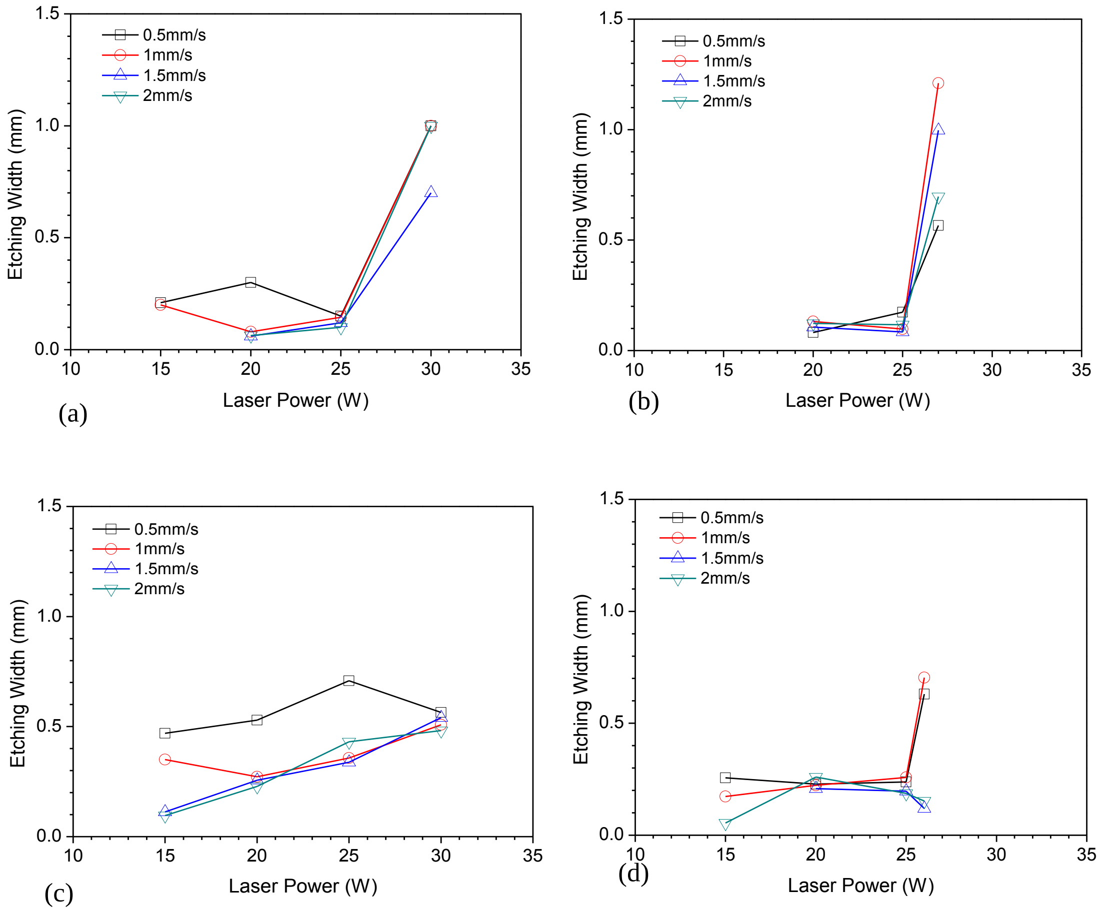


Fig. 6 Etching width on glass for the nozzle with an outlet width of 0.4 mm at nozzle depths of (a) 2 mm, (b) 1.5 mm, (c) 1 mm, and (d) 0.5 mm

4. Conclusion

The proposed laser etching method is successfully demonstrated for etching a line-strip of 50-500 μm in width on a glass surface. The needed laser power does not exceed 30 W. The impact of the bubble jet roughens the glass surface and increases the absorption of laser energy. The softened glass material is expelled by the shock wave resulting from the jet impact. The rectangular nozzle whose inlet and outlet are narrow and rectangular in shape is found to enhance the strength of the bubble jet impact and confine the jetting direction. The proposed technique can prevent thermal damage from the laser and has great potential as an improved solution for the micro-machining of glass.

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