Chapter 6
Effect of Laser Parameters on Laser-Induced Plasma-Assisted Ablation (LIPAA) of Glass

Upasana Sarma and Shrikrishna N. Joshi

Abstract Laser-Induced Plasma-Assisted Ablation (LIPAA) is an advanced machining process, in which, the laser beam passes through the substrate and irradiates the target metal placed behind the transparent material. The laser fluence is set above the ablation threshold of the target metal and below the ablation threshold of the transparent material. As the laser beam reaches the target metal, plasma-generated flies towards the substrate at a high speed of approximately 10^4 m/s resulting in both target and glass substrate removal. In the present work, a systematic experimental study has been carried out to study of the effects of laser parameters (scanning speed, laser peak power and pulse duration) on crater width of glass. Glass material was successfully processed using Nd:YAG laser. Microscopic studies have been carried out to understand the mechanism of ablation. Results provide useful guidelines to create features on transparent material.

Keywords LIPAA · Ablation threshold · Crater width · Transparent materials · Glass

6.1 Introduction

The glass is one of the most trending materials in scientific and industrial applications such as optics, photonics, microelectronics, display industries due to its high transparency over a wide range of wavelength. Also, glass has a very good resistance to chemical reactions, high thermal stability, and high hardness. Due to these qualities, it has become one of the most widely used materials today. In spite of its excellent properties, its brittleness and hardness make it difficult to machine. Precision and crack free machining of glass is a challenging task. Lasers are widely used in machining of brittle and hard materials. However, lasers are not suitable for processing of transparent materials such as glass, as no laser beam is absorbed for

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any thermal action to take place. Literature reports various processing techniques to fabricate different structures in transparent materials viz. photolithography [1], chemical etching [2], abrasive jet machining [3]. They are capable of processing the glass material, however, they have limited applicability as the photolithography requires high vacuum condition. Chemical etching may cause hazardous problem as etching material contains atoms of lead or sodium and thus results in production of non-volatile halogen compounds. Abrasive jet machining [3] results in rough surface and limited to larger components. Ultrasonic machining requires complex setup. However, laser has been found as a promising tool if it is applied with proper setting of laser parameters such as wavelength, laser power. It is known that laser beam must be highly absorbed to achieve ablation. For high absorption, short wavelength in the visible ultra-violet (VUV) region (high energy photons) and short pulse width in the sub-picosecond range were first attempted, but such laser faced difficulties due to its high capital cost, small beam diameter which results in low material removal rate and slow scanning process [4]. For research and other applications, the development of a new fabrication technique of glass was desired and hence, in 1998 a group of Japanese scientists invented laser-induced plasma-assisted mechanism, which can be used to process transparent materials.

Laser-Induced Plasma-Assisted Ablation (LIPAA) [5] is a high potential ablation scheme for transparent, hard and brittle material. In this process, the glass and metal sheet are placed one above the other and the plasma is formed with assistance from the metal ablation when the laser transmitted through the glass irradiates the metal. It is used to get colour printing characters, surface metallization of electrodes and even images on the glass substrate. However, the mechanism varies slightly depending upon the distance between the target metal and the glass substrate. Further improvement of the process can be witnessed using confined ablation conditions. This plasma ablates the transparent material on its rear side. It is characterized by high etching rate and no incubation effects are found. In this work, an experimental study has been carried out to apply LIPAA methodology to ablate the glass substrate. Moreover, a systematic parametric study has also been carried out. These are presented in the next sections.

6.2 Experimental

6.2.1 Experimental Setup

In the present study, a conventional Nd: YAG pulsed millisecond laser (Model: 500 W pulsed Nd: YAG CNC Laser, Make: Suresh Indu Lasers Pvt. Ltd) having a wavelength of 1064 nm is used. The frequency was set at a fixed value of 20 Hz with varying laser peak power, scanning speed and pulse duration. The laser workstation consists of the beam bending, expanding, collimating and focusing optical units and

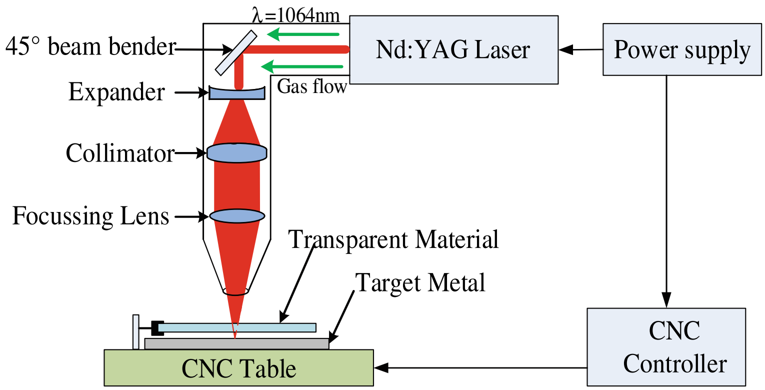


Fig. 6.1 Schematic diagram of the experimental setup

a computer-controlled x-y position stage. Figure 6.1 shows the schematic diagram of the experimental setup used for the study of LIPAA process.

In this technique, the transparent material and the metal target sheet are arranged one above the other with the glass slide above the metal sheet on a CNC table connected to a CNC controller. The profile to be cut or scanned, its dimensions and the direction of motion is given through the RD-Works software and controlled by the CNC controller. The transparent material is chosen such that it is transparent to wavelength of the homogenized laser beam. The laser beam passes through the substrate and irradiates the target metal placed behind the glass substrate. The laser fluence for this method is set above the ablation threshold of the target metal and below the ablation threshold of the transparent material. When the peak power density exceeds the ionization threshold potential of the metal surface, the generation of free electrons at the focal spot through ionization takes place in the focal region, leading to the formation of dense and optically opaque plasma. The plasma generated flies towards the substrate at a high speed (of the order of 10^4 m/s) [6]. The plasma generated further absorbs the energy of the incoming laser pulses through the laser–plasma interaction process [7]. Thus, there is a strong interaction among the laser beam, plasma and the transparent material, which results in increased fluence. This causes heating, melting, vaporization of the transparent material. The heating of the surface and eventually conduction into the material results in the generation of temperature distribution. Also when the incident fluence is very high, it results in phase transformation (melting and vaporization), which serves as the material removal mechanisms.

6.2.2 Materials

In the present a transparent material, glass slide of dimension 75 × 26 × 1.4 mm has been used. Microscopic glass slides are generally of soda–lime glass or borosilicate glass. In this work soda–lime glass was used as work material. Its chemical composition is 73 wt% SiO_2+16 wt% Na_2O+9 wt% CaO with certain additives like MgO and Al_2O_3 and its maximum transmission is in the range of wavelength 500–2500 nm approximately.

The target metal chosen was a sheet of aluminium of thickness 1 mm. An important property of aluminium is that it is a good reflector of both visible light and radiated heat. Taking into consideration this property, aluminium was chosen as the metal target for well-defined ablation to take place at the rear side of the transparent material.

6.3 Results and Discussion

Using the conventional millisecond Nd: YAG laser system, ablation on the rear side of glass has been carried out by the LIPAA technique. The experiments were carried out at fixed repetition rate of 20 Hz and with no gap between the glass and the aluminium sheet. Vertical lines were traced on both the glass and the aluminium sheet by varying the current in the range of 50–80 A, speed in the range of 2–20 mm/s and pulse duration from 0.5 to 4 ms.

Ablation on both the aluminium sheet and the glass substrate were achieved by this technique. Figure 6.2 shows the ablated aluminium sheet and glass substrate.

Ablation takes place due to the phase change of the material. Phase change of the glass material takes place due to thermal effects of the plasma. The molten glass material is removed by the plasma-induced shock wave whereas some molten metals redeposits on the crater resulting in a recast layer. Figure 6.3 shows the optical microscope image of the crater with the recast layer formed on the surface of the crater giving it a glassy appearance.

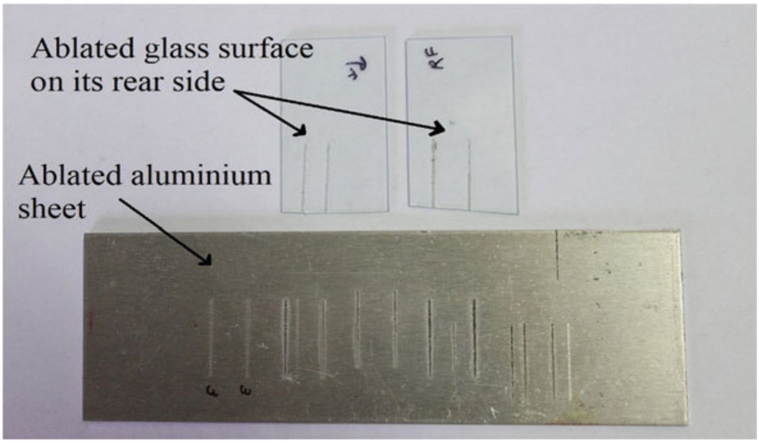


Fig. 6.2 Ablated glass substrate and aluminium sheet

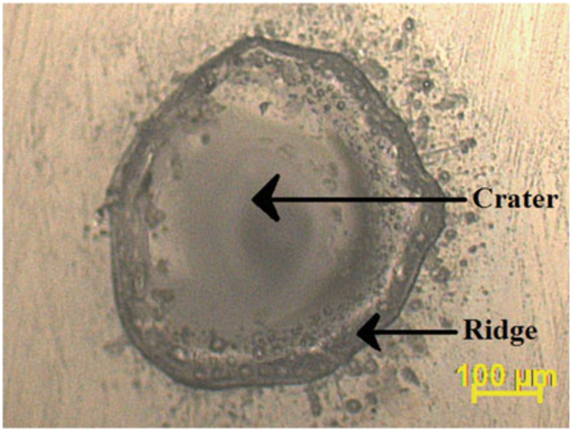


Fig. 6.3 Optical microscope image of a crater with recast layer (Current: 80 A, Scanning speed: 20 mm/s, Pulse Duration: 2 ms)

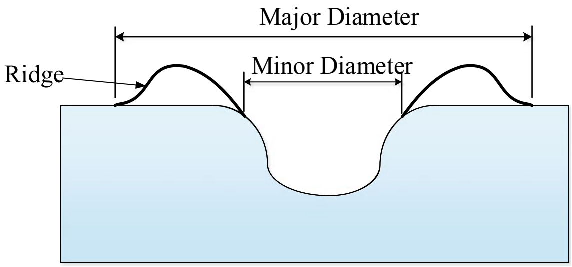


Fig. 6.4 Ridge formation on the ablated crater

It is the recast layer that results in a doughnut-shaped ridge formation around the crater. A schematic of the ridge formation is shown in Fig. 6.4. As observed in optical microscope, the major and the minor diameters are measured and for further analysis of the crater width, the average of the major and minor diameters is considered.

Mathematically,

$$Crater\ Width,\ D_{avg} = \frac{Major\,Diameter + Minor\,Diameter}{2} \tag{6.1}$$

6.3.1 *Effect of Laser Parameters on Ablated Crater Width by LIPAA*

Laser Scanning Speed. As depicted in Fig. 6.5, it can be observed that the crater width decreases with the increase in scanning speed and also decreases with the decrease in current. However, at 15 mm/s instead of decrease in crater width with the

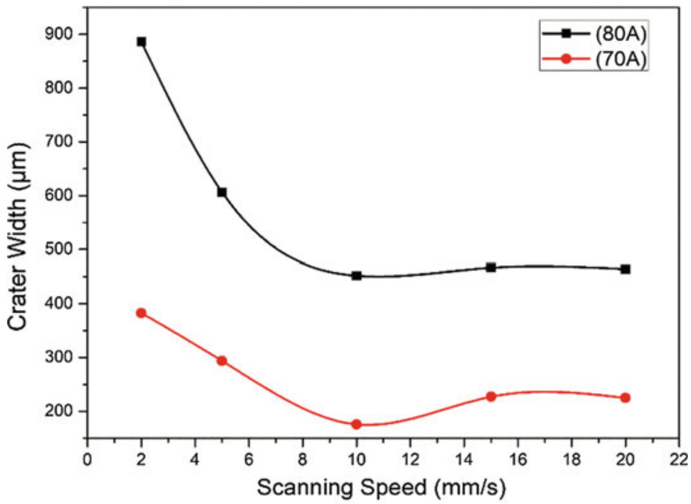


Fig. 6.5 Effect of scanning speed on average crater width

increase in scanning speed, an increase in the width is seen and further increasing the scanning speed, crater width again decreases.

The reason for such variation may be stated as, with the slowing down of the scanning speed the laser irradiation per unit area increases and hence, more energy per unit area by the laser-induced plasma. It can also be stated that with the slowing down of the scanning speed, the laser-induced plasma interacts with the glass for longer duration which results in more material removal and greater Heat-Affected Zone (HAZ). Further, at a high speed, the successive laser pulse moves far away from the former laser pulse and hence, there is no interaction between the HAZ of the two consecutive laser pulses. Therefore, increase in scanning speed results in reduced crater width. However, the reason for increase in crater width at 15 mm/s scanning speed may be stated that the deposition of the metal particles on the rear side of the glass by the former laser pulses plasma get accumulated which acts as the site for higher absorption of the plasma.

Figure 6.6 shows the optical microscope images of the rear surface of the LIPAA processed glass material taking aluminium as the metal target at two different scanning speeds 10 and 5 mm/s.

Laser Peak Power. It has been observed in Fig. 6.7 that with the increase in current corresponding to a laser peak power there is an increase in the average ablation depth. The reason for such variation may be that as the pump current increases it induces higher population inversion, which gives greater stimulated emission and hence increase in output power.

The relation between current change and power change is linear and is given by

$$P = \eta V I \tag{6.2}$$

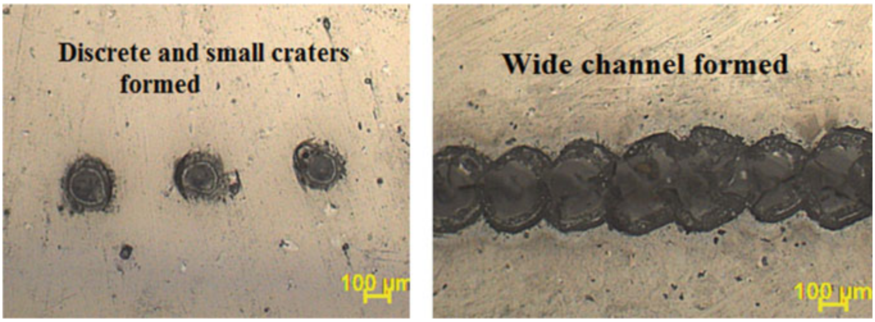
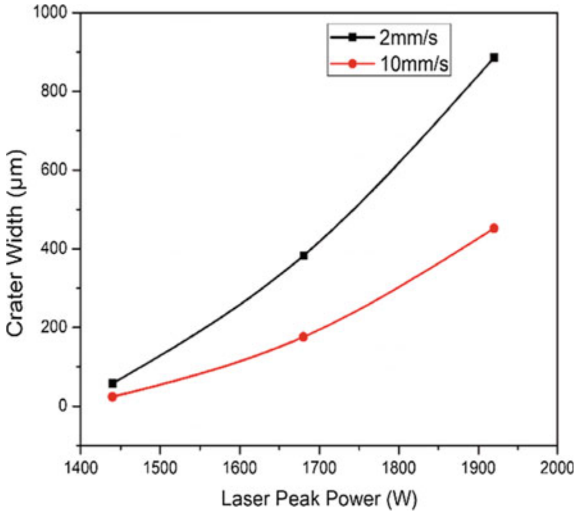


Fig. 6.6 Optical microscope images of the rear surface of the LIPAA-processed glass material with 0 μm distance between the glass and the aluminium sheet, 70 A current and **(a)** 10 mm/s **(b)** 5 mm/s scanning speed

Fig. 6.7 Effect of laser peak power on average crater width



where

P Pulse power
n Radiation efficiency
I Current input.

Hence with the increase in current, laser peak power is increased and more plasma is generated as the laser irradiates with the metal behind the glass. The generated plasma has a greater thermal effect on the glass material and more material removal resulting in wider crater width. However, the ablation geometry not only depends on the current but also on the metal used. Figure 6.8 shows the optical microscope images of the rear surface of the LIPAA processed glass material taking aluminium as the metal target at various laser peak power levels.

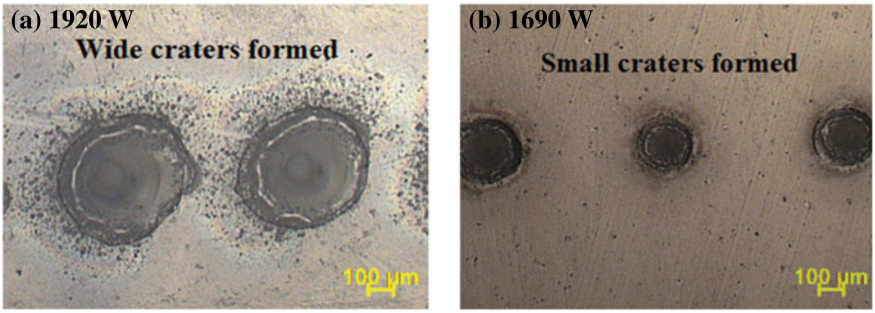
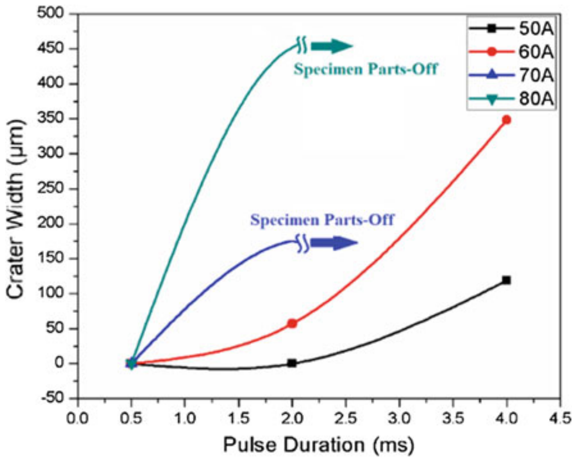


Fig. 6.8 Optical microscope images of the rear surface of the LIPAA-processed glass material with 0 µm distance between the glass and the aluminium sheet, 15 mm/s scanning speed and laser power of **(a)** 1920 W **(b)** 1690 W

Pulse Duration. As observed in Fig. 6.9, the average crater width increases with the increase in pulse duration. Also with the increase in current an increase in the width is seen. But at a higher value of current, i.e. 70 and 80 A, the glass parts-off into two pieces on reaching a pulse duration value greater than 2 ms. When low pulse duration is used deeper holes are produced whereas for high pulse duration wider holes are ablated.

The reason may be such that, when the laser irradiates the metal sheet, it absorbs the heat energy, melts, gets vaporized and plasma is generated. Longer pulse duration interacts with the metal for a longer period of time and hence expanded plasma is generated with high initial velocity. Thus, it has a greater and longer thermal effect on the glass material which, in turn, gets melted and vaporized resulting in a wider ablation. Also, higher the pulse duration, higher is the pulse energy. This is also a reason for increase in width with the increase in pulse duration. It is given by the relation

Fig. 6.9 Effect of pulse duration on average crater width



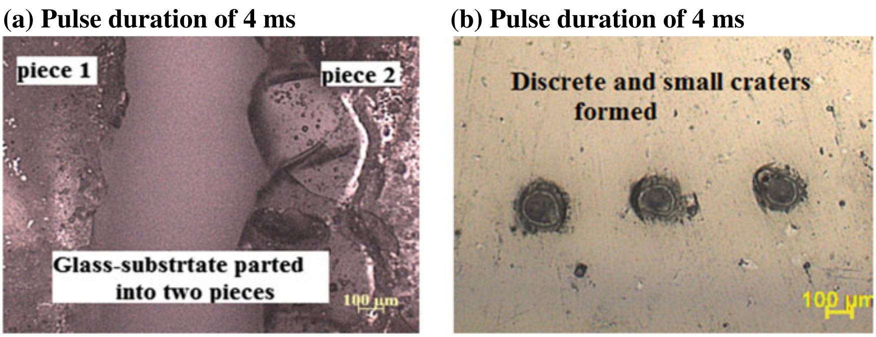


Fig. 6.10 Optical microscope images of the rear surface of the LIPAA-processed glass material with 0 μm distance between the glass and the aluminium sheet, at 70 A current and pulse duration of **(a)** 4 ms **(b)** 2 ms

$$\tau = 0.88\,\frac{E}{P} \tag{6.3}$$

where

τ pulse duration
E pulse energy
P peak pulse power.

Figure 6.10 shows the optical microscope images of the rear surface of the LIPAA-processed glass material taking aluminium as the metal target at different pulse duration.

6.4 Conclusions

In this study, laser-induced plasma-assisted ablation (LIPAA) on glass material with aluminium as the metal target was performed using a conventional millisecond Nd: YAG laser having a wavelength of 1064 nm. In the scope of present process conditions, from the experimental investigations and microscopic studies, the following conclusions can be drawn.

- When the scanning speed of the laser increases, the average crater width decreases. The average crater width at the same scanning speed was higher for a higher value of current. At higher scanning speed, LIPAA does not produce continuous channel. Therefore, higher scanning speed are usually not recommended for the fabrication of channels in practice.
- The increase in the current value results in increase in the crater width. Also, at a constant current value, when the scanning speed decreases the width reduces.
- With the increase in the pulse duration, it has been observed that the crater width increases. Also, at a constant pulse duration, higher the current applied higher is

the crater width. However, at the current values of 70 and 80 A, the glass parts-off into two pieces at pulse duration greater than 2 ms. It is due to the longer interaction of the laser pulse with the metal which results in the generation of expanded plasma with high initial velocity. Also higher the pulse duration, higher is the pulse energy. This is also one of the reasons for increase in width with the increase in pulse duration.

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