Investigation of laser induced plasma assisted ablation of glass in presence of magnetic field

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ABSTRACT

This paper summarizes the experimental investigation of glass drilling using laser induced plasma assisted ablation. In the experiments, a nanosecond pulsed laser with a wavelength of 532 nm as the laser source and copper with 2 mm thickness as the metal substrate are used, and two permanent neodymium magnets (4500-4800 [G]) are used to apply an external magnetic field to drill holes in the laboratory slide glass. The laser fluence was selected in 4 levels of 1, 1.5, 3 & 3.5 [J/cm^2] and the characteristics of the holes produced with 50 laser shots were examined in terms of dimensions and morphology. It was observed that by applying a magnetic field, the material removal rate increases about 2 to 2.4 times in the lower fluences and 31 to 35 times in the higher fluences. In the magnetic field absence for different laser fluence, the hole depth and diameter changed from 1.6 to 32 and 10 to 100 um, and in its presence, they change from 3 to 76 and 11 to 380 um, respectively. Distribution of particles deposited on glass in the presence and absence of magnetic field is also different.

KEYWORDS

Laser, Glass, Ablation, Drilling, Laser Induced Plasma

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Introduction

Glass is known as one of the most widely used materials in various industries due to its properties such as corrosion resistance, high chemical stability, high hardness, corrosion resistance and low thermal conductivity. However, the brittleness of this material has caused its low machinability and it cannot be easily machined with conventional methods.

Laser machining is capable of machining a variety of conductive and non-conductive materials with a high depth to diameter ratio and a suitable machining speed [1]. However, glass is transparent to visible or infrared laser light, and machining with a direct laser beam is not easily possible. In the last two decades, following the efforts of researchers to machine glass with laser and to find a solution for easier machining, higher speed, lower cost and higher quality without the need for special and complex tools or conditions, the Laser-Induced Plasma Assisted Ablation (LIPAA) was introduced [2]. Laser-induced plasma assisted ablation uses the plasma resulting from the laser interaction with the material. The plasma dynamics strongly influence the machining characteristics [3]. If the plasma can be controlled or its characteristics changed, machining conditions can be improved. Plasma is an ionized medium with charged particles, so if plasma expands in a magnetic field, the plasma dynamics will be strongly affected. Accordingly, the effect of applying an external magnetic field on the morphology and dimensional and geometric properties of the hole created on the glass by laser-induced plasma assisted ablation as an innovation is studied. In the experiments, glass was drilled in the presence and absence of magnetic field.

Theoretical analysis

When a high-intensity laser is irradiated on the metal surface, melting and vaporizing is occurred, and by ionizing the vaporized material, a plasma plume is generated before the laser pulse is off. Due to the plasma shielding effect, part of the laser energy is absorbed by the plasma and the plasma plume begins to expand. In LIPAA process, two confining effects are applied to the plasma by the glass placed on the metal and the magnetic field. Regarding the confinement of plasma, the plasma pressure increases, and a shock wave is applied to glass and metal [4]. After the laser pulse is turned off, the plasma maintains its pressure and by moving perpendicular to the magnetic field direction, a force is applied to the plasma plume from the magnetic field and a current induces inside the plume, which increases the internal energy and consequently leads to increases the plasma temperature.

To describe the fluid flow, it is necessary to obtain the equations of conservation of mass, momentum, and energy [5]. Considering plasma as a fluid, if the hydrodynamic equations (Equations 1 to 3) are written in the presence of a magnetic field, the expression $\vec{J} \times \vec{B}$ as magnetic force is entered in the momentum equation (Equation (2)) and the expressions $u(\vec{J} \times \vec{B})$ as the work done by magnetic force and $\frac{|\vec{J}|^2}{\sigma}$ as Joule heating effect are entered in the energy equation, respectively. In these equations B is the magnetic field intensity, J is the induced electrical current density, σ is the electrical conductivity and u is the velocity in the direction perpendicular to the magnetic field.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial z} = 0 \tag{1}$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2 + P)}{\partial z} = (\vec{J} \times \vec{B}).\vec{a_z} \tag{2}$$

$$\frac{\partial(E + \frac{1}{2}\rho u^2)}{\partial t} + \frac{\partial\left[u(E + \frac{1}{2}\rho u^2 + P)\right]}{\partial z} = \frac{\partial}{\partial z}(k\frac{\partial T}{\partial z}) + ... \tag{3}$$

$$\frac{\partial I}{\partial z} + \frac{|\vec{J}|^2}{\sigma} + u(\vec{J} \times \vec{B}).\vec{a_z}$$

Experimental setup

The soda-lime glass was used as a transparent material. Copper was used as the metal substrate behind the glass. Q-switch Nd: YAG pulsed laser with 12 ns pulse duration, 532 nm wavelength, and 8 mm beam diameter was used. A lens with a focal length of 50 mm was used to focus the laser beam. To create a transverse magnetic field, two permanent neodymium magnets with an intensity of 4500 to 4800 Gauss were used. The focus spot of the laser was at the interface between glass and copper. In the experiments, 50 laser shots were irradiated on glass in 4 levels of laser fluence 1, 1.5, 3, and 3.5 J/cm^2 in the presence and absence of a magnetic field.

Results and discussion

The depth and diameter of the holes at various laser fluences and in the presence of the magnetic field and its absence are shown in Figure 1. Based on the results, it is clear that increasing the laser fluence increases the depth and diameter of the hole. This increase is due to more evaporation of the metal and the formation of a larger plasma. Larger plasmas absorb more laser energy, resulting in higher temperatures and pressures, leading to increased material ablation in larger dimensions. The diameter and depth of the holes created in the presence of the magnetic field are greater than the case where the holes were created in the absence of the magnetic field. Comparing the depth and diameter of the holes, it is clear that in the presence of a magnetic field, the average inlet diameter is 2.4 times and the maximum depth of the holes is 1.98 times when there was no magnetic field.

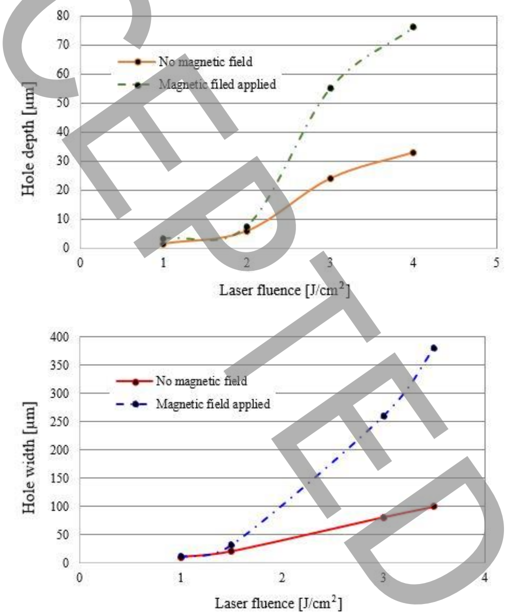

Figure 1: Hole depth and hole width variation via Laser fluence with and without magnetic field

The circularity of the hole diameter can be considered as the ratio of the minimum diameter to the maximum Feret diameter at the hole entrance. The diameter of the Feret is the distance between two parallel and tangent planes on the hole profile. If the minimum diameter to maximum diameter ratio is closer to 1, the hole inlet profile is closer to the circle. by applying the magnetic field, circularity is slightly decreased. This is due to the increase in temperature and pressure of the plasma in the presence of a magnetic field and as a result the transfer of more heat to the glass and also the deformation of the plasma in the magnetic field.

As shown in Figure 2, the ratio of the amount of ablation produced in the presence of a magnetic field to its absence at low energies and close to copper threshold is about 2 to 2.5 times, but with increasing energy, this ratio has increased to 35 times.

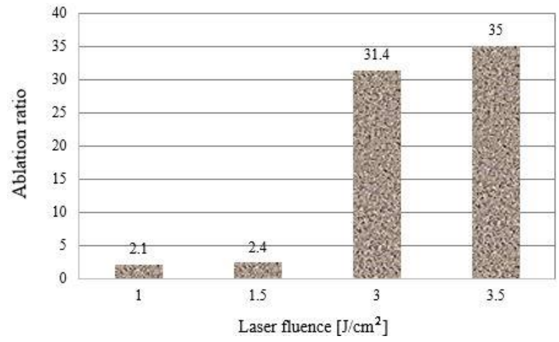

Figure 2: Ablation Ration in magnetic field presence to its absence

Conclusions

In this study, the magnetic field effect on glass ablation by laser induced plasma assisted ablation has been studied experimentally. Experiments have been done for different values of laser fluence in presence of magnetic field and its absence. The results showed that by applying an external magnetic field, maximum hole depth, inlet hole diameter and the amount of ablation increases. With increasing laser energy, due to the formation of larger plasma, the effect of the magnetic field on the plasma is greater and the material removal rate increases sharply.

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