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Technical Communication

Experimental and Theoretical Investigation of CO_2 Laser Drilling of Fused Silica

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Single and multiple laser pulse hole drilling in fused silica have been carried out using a CO_2 laser system operating at 10.6 µm. Laser pulse duration, pulse energy and number of pulses impinging on the silica plate have been measured in-situ for drilled holes. Hole depths, diameter and volume have been measured using a fluorescent confocal microscope and the results are compared against the predictions of a numerical model. This model considers surface evaporation as the main material removal mechanism. For the case of single pulse drilling, the depth and volume of the drilled holes are predicted accurately and the discrepancy between the model and experiments are observed to be less than 10%.

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1. Introduction

Machining of silica glass and glass-ceramics is of considerable interest for developing new technologies and devices for consumer electronics and telecommunication industries. Conventional machining methods are expensive, time consuming, labor intensive, and also lack the precision needed for modern devices. An attractive alternative method is to use lasers for machining silica. Silica has a strong absorption in the wavelength range of 9-10 µm – making CO_2 laser a robust and economically viable manufacturing tool.

CO_2 lasers have been used for machining silica for a range of applications such as fiber end shaping [1-3], damage mitigation due to short pulse laser and surface smoothening [5-6]. There are many theoretical and modeling investigations on thermal processing, residual stress generation, surface deformation due to structural relaxation and surface polishing [7, 8]. However, there is a lack in detailed studies dedicated to development of numerical model capable of predicting surface morphology due to CO_2 laser processing of silica – a consideration important for process development and predictive capabilities.

In this study, a numerical model capable of simulating the surface evolution during CO_2 laser processing of silica is presented. This model was used to predict the shape of holes produced by CO_2 laser drilling of Silica. The predictions, for single and multiple pulses drilling were compared with morphologies of laser drilled holes. The current state of applicability of the model along with its limitations are discussed in this article.

2. Experimental

The laser hole drilling of silica plates were carried out using a CO_2 laser operating at 10.6 µm from Synrad Inc. Single and multiple pulses were delivered on a glass plate placed on a X-Y stage and holes were drilled at different positions on the silica plate. The laser beam was split into three beams using two 50-50 beam splitters (as shown in the figure 1). Reflected beam from the first splitter was directed on to a roughened graphite block and scattered light was used to measure the pulse duration of the individual pulses impinging the silica plate using a photodetector from VIGO Systems (Model # PVM-10.6 1x1 BNC-NW). The reflected beam from the 2nd splitter was directed toward an energy meter (from Ophir-Spiricon, LLC) to measure the pulse energy. The transmitted beam from the 2nd splitter was directed to a focusing lens (plano-convex lens with 50 mm focal length) and focused on to the silica plate for hole drilling. In this way the pulse energy and pulse duration were measured in-situ for hole-drilling experiments. The laser drilled holes were characterized using a fluorescent confocal microscope (from Zeiss).

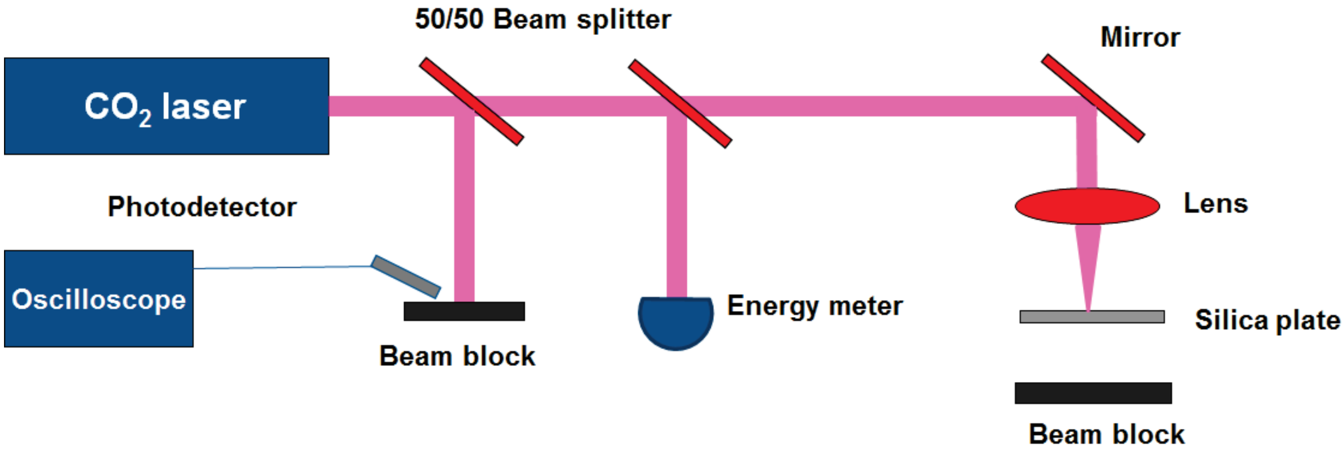


Figure 1: Schematic of experimental setup for laser hole drilling of fused silica.

3. Results and discussion

A 3D numerical model capable of predicting evolution of surface morphology during laser machining was developed using COMSOL software. The inputs to the model are laser processing parameters such as power, time of exposure, relative motion between laser and substrate, spot size and energy profile of the laser beam. Silica has strong absorption at 10.6 µm wavelength, absorption depth is around 4 µm at high temperatures [9]. This allows in the treatment of CO_2 laser as heat flux and solving heat transfer model to compute temperature evolution. The reflection of laser as function of polarization and angle of incidence was included [10]. The temperature dependent thermal properties were included in the model [11, 12]. The material removal mechanism included in the model is surface evaporation. The heat loss due to evaporation was included [13]. The velocity of surface recession was calculated as function of surface temperature using the methodology published in laser drilling literature [14, 15]. The material removal was implemented using moving mesh approach. This model does not include temperature dependent complex refractive index of Silica. It does include wave interaction with evolving surface such as multiple reflections and diffraction. Material removal by melt ejection becomes important at higher intensities [16] and this model does not include this removal mechanism.

This laser machining model was used to simulate single and multiple pulse drilling. The surface morphology predicted by the model was compared to the experiments. Schematic of laser drilling model along with simulated morphology of laser drilled hole are shown in Fig. 1. The laser is propagating along z axis and is focused to a spot diameter of 54 microns on the top surface of the silica cylinder. The initial flat surface of the plate is parallel to XY plane. The laser has TEM_{00} mode and was linearly polarized in Y direction. The morphology of hole drilled by 200 µs pulse containing ~1mJ pulses, up to 5 pulses, was simulated and compared with experiments. In these models it was assumed that the silica plate cools down to room temperature before incidence of next pulse. The comparison of simulated and measured depths and volume of material removed is shown in Fig. 2 and Fig. 3 respectively. The cross-sectional profiles of holes, in XZ and YZ plane, for single and multiple pulse cases are shown in Fig. 4 (a-e).

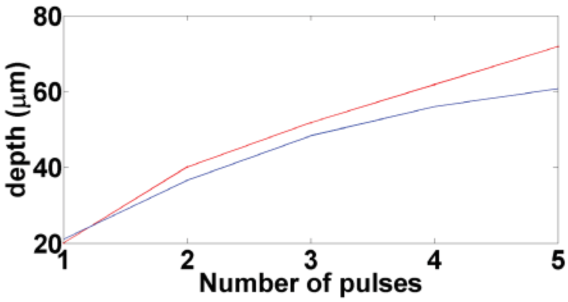


Figure 2: Comparison of depth of drilled holes; blue curve are the simulation results and red curve is the experimental values.

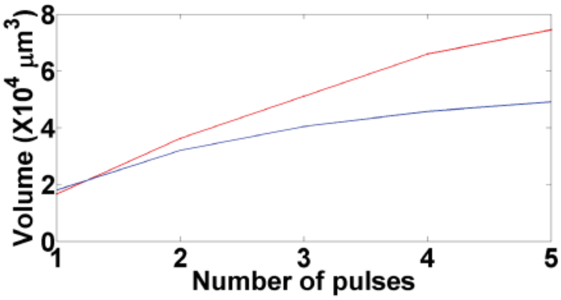
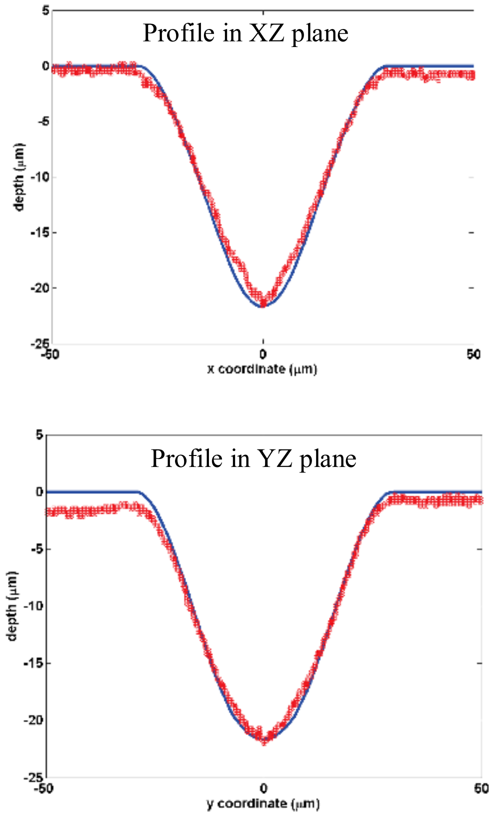
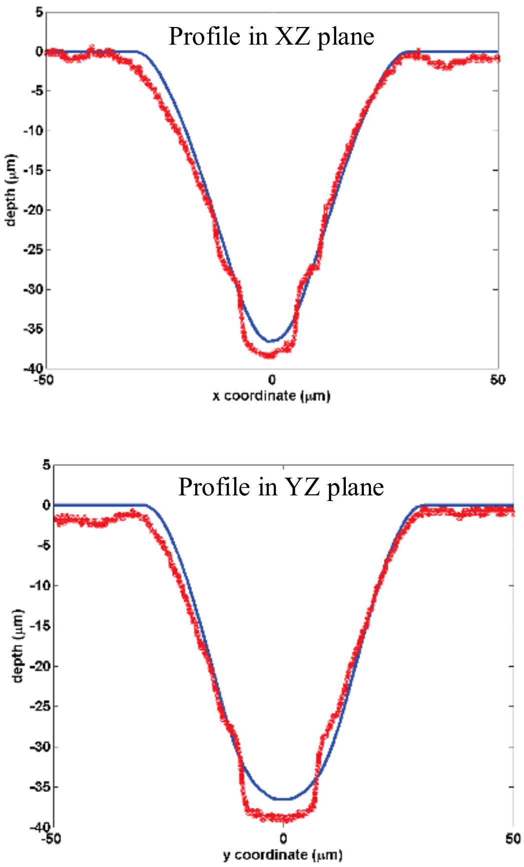


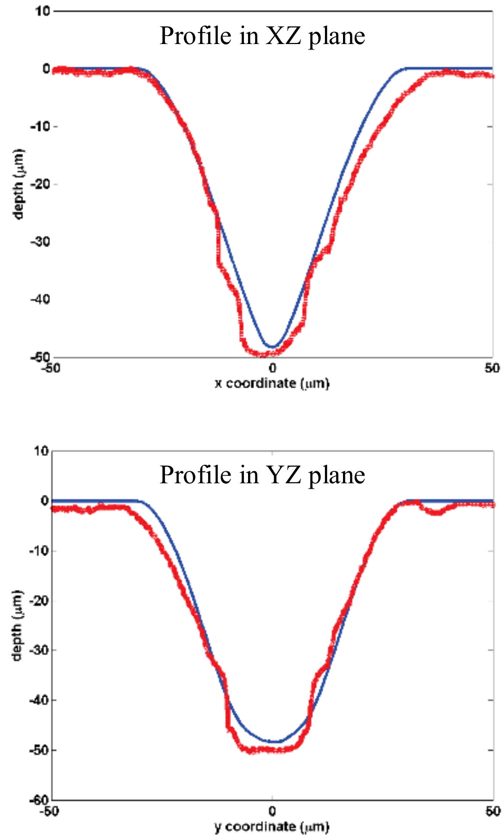
Figure 3: Comparison of depth of drilled holes; blue curve are the simulation results and red curve is the experimental values.



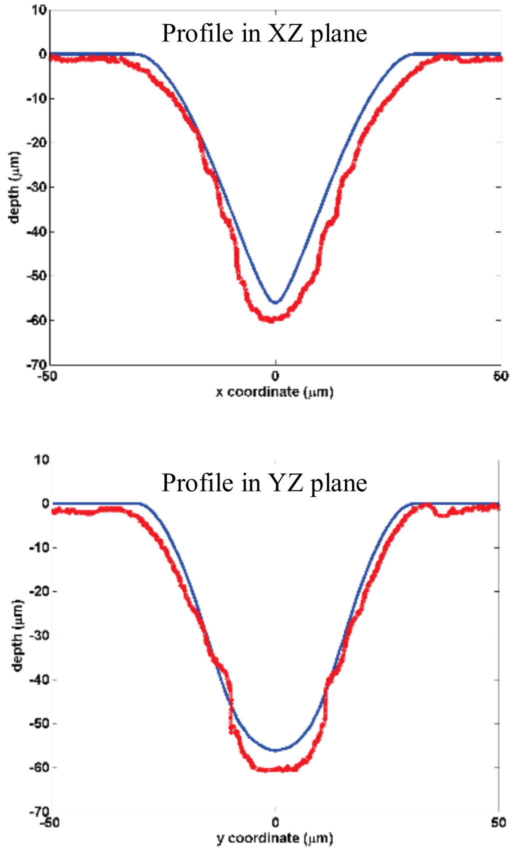
(a) Laser drilled hole with one pulse



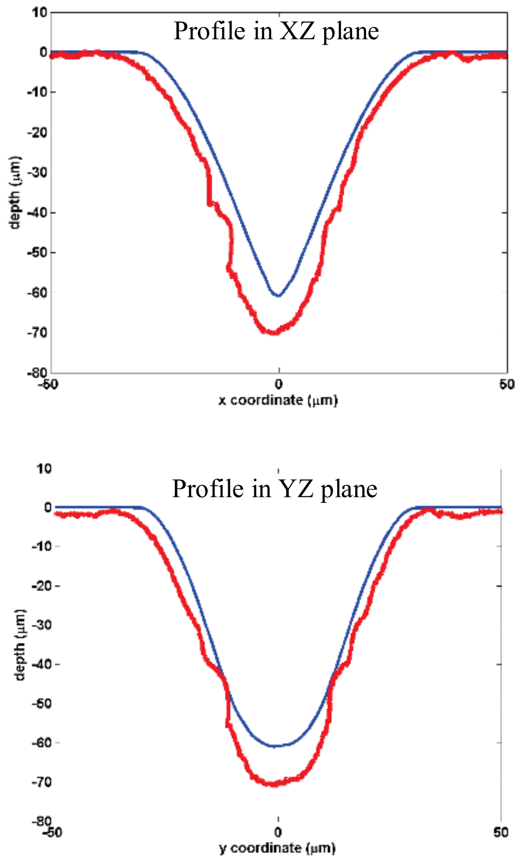
(b) Laser drilled hole with two pulses



(c) Laser drilled hole with three pulses



(d) Laser drilled hole with four pulses



(e) Laser drilled hole with five pulses

Figure 4: Comparison of profiles of the holes along XZ and YZ planes; blue curves are from simulations while red curves are from experiments

The simulations do predict depth, volume and shape of hole well for a single pulse case. As the number of the pulses increases, the discrepancy between predicted and measured values of depths /volume of material removed increases. It can be seen from Fig. 4 that the holes drilled with more than one pulse have ripple-like shapes on the walls and bottom of the holes are flatter. These profiles also show bumps adjacent to the hole. The main reason for these discrepancies between model and experiments could be attributed to the lack of wave – hole interaction in the model. The bumps adjacent to holes could not be predicted as melt displacement due to recoil pressure is not included.

4. Conclusions

An experimental and theoretical investigation has been carried out to understand the CO_2 laser silica interaction by hole-drilling method. In-situ measurements were performed to accurately measure the laser parameters for drilled holes. The experimental results were validated against the predictions of a developed numerical model. The model predicted the hole depth and volume accurately and the discrepancy between the model and experiments were observed to be less than 10% for the case of single pulse drilling.

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