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Research Article

Comparison between Practical and Theoretical Investigations of Laser Drilling

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Abstract

This paper presents a comparison between the behavior of two different laser drilling processes, The first is a practical drilling application of the alumina ceramic with thickness (2.2 mm) using Nd:YAG laser whereas the other is a simulation of the transient heat transfer using COMSOL Multiphysics 3.5a for drilling PMMA substrate of thicknesses of (2.5 mm). For the practical work, Effects of the laser peak power, pulse duration and repetition rate, have been determined using optical images taken from the inlet and outlet of the samples. Different laser beam parameters have been used for the laser drilling process of alumina ceramic such as various peak powers increased consecutively by 2 kW from 2-6 kW, various pulse durations increased from 1-5 ms with 1ms increments and various repetition rates increased from 5-25 Hz with 5 Hz increments. Concerning the simulation, the beam parameters used for this study are selected to simulate drilling process using CW Diode laser of 1064nm wavelength. It has been used various output powers (0.96 W, 1.82 W, 2.45 W and 3 W) and various exposure times (2 s, 3 s, 4 s and 5 s) and a spot size with a 0.5mm beam radius. Effects of laser output power and exposure time have been carried out via the studying of the temperature distribution on the cross section of the substrate to determine the optimum conditions obtained from the combination of parameters that improves hole quality. It has been indicated that the results behavior of the practical and simulation of this work are in good agreement when compared to each other.

Keywords: *Simulation of drilling, Laser Drilling, Alumina ceramic, PMMA, Modeling using COMSOL.*

1. Introduction

Combination of the desirable properties of alumina ceramics such as high electrical resistance (volume resistivity > 10^{14} Ω cm), high thermal conductivity (~28 Wm^{-1}/K), high dielectric strength (~10 kV/mm), and excellent thermal stability makes it convenient for wide range of areas of usage in semiconductor, electronics, medical, automotive, instrumentation and communications (Wang X.C. *et al*, 2010; Triantafyllidis D. *et al*, 2002).

On the other hand, due to the unique properties of PMMA poly (methyl methacrylate), it has become the most commonly used among polymers. PMMA has high mechanical strength, high Young′s modulus and low elongation at break. It does not shatter on rupture. It is one of the hardest thermoplastics and is also highly scratch resistant. It exhibits low moisture and water absorbing capacity, due to which products made have good dimensional stability (Van Krevelen D.W *et al*, 2009).

Besides the special properties of PMMA mentioned above due to it is an economical, versatile general purpose material as well as custom profiles. It has been used in a wide variety of fields and applications, including Optics: Dust covers for hi-fi equipment, sunglasses, watch glasses, lenses, magnifying glasses; Vehicles: Rear lights, indicators, tachometer covers, warning triangles; Electrical engineering: Lamp covers, switch parts, dials, control buttons; Medicine: Packaging for tablets, capsules, urine containers; Others: Leaflet dispensers, shatter resistant glazing, shower cubicles, transparent pipelines, toys (Charles A. Harper, 2003; Crawford R. J., 1998).

Laser hole drilling has rapidly become good alternative to conventional hole drilling methods because it is inexpensive and controllable. In materials such as polyimide, ceramic, copper, nickel, brass, aluminum, borosilicate glass, quartz, rubber and composite materials, Laser hole drilling offer high accuracy, repeatability and reproducibility for the medical device industry, nanotechnology support systems and semiconductor manufacturing (M.M. Hanon *et al*, 2012).

Laser drilling is a thermal, contact-free process based on the absorption of the laser energy by the workpiece material and the conversion of the photon energy into thermal energy. When the temperature exceeds that of the melting and/or vaporization, the workpiece material changes phase and the hole geometry is formed. If the laser irradiance is kept below a certain threshold (typically ca. 10^6 W/cm^2 for steels) the workpiece material is melted and not vaporized. In that case, the hole is formed due to ejection of the melted material with the use of an assisting gas jet. For laser irradiance values beyond the threshold value, the material is removed mainly due to vaporization (Tom A. Eppes *et al*, 2012; Salonitis K. *et al*, 2007).

In polymers, the mechanism of UV laser/material interaction can be explained as follows: the absorbed UV

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photons directly break the chemical bonds in a so called photo-chemical reaction. Thermal ablation, which also can be used in case of some thermoplastics, is the other possible mechanism (O. Yalukova *et al*, 2006).

In the present work, the practical interested to study the effects of varying laser beam parameters on the ceramic substrate. Moreover, it has proposed to model the process of laser drilling of PMMA, in the COMSOL Multiphysics environment. Developing an accurate theoretical model for the laser drilling process is a daunting challenge. The model developed here with using all the precision factors of the process like laser beam parameters, material properties, boundary conditions and the equations that governing the process of transient heat transfer which is time dependent. it has been accomplished this by simulating the vaporization of the material with taking into consideration the absorption coefficient to simulate the boundary condition of the incident laser energy boring through the material. The studying of the hole dimensions versus various laser peak powers, pulse durations and repetition rates (in the experimental) and versus various laser beam powers and exposure time (in the theoretical) has been taken in to account.

2. Experimental

The pulsed Nd:YAG laser-robot system employed for the benefit of this article is constructed from the following components;

1) Class four pulsed Nd:YAG 1.064 μm wavelength laser apparatus PB80, maximum output power of 80 W, peak power of 8 kW, and a single pulse capability up to 70J/10ms. The pulse duration is variable between 0.1 to 50ms, and the repetition rate is 1-100 Hz. The pulsed Nd:YAG laser has adjustable pulse shapes which offers high flexibility in optimizing the weld parameters to achieve defect free joints. That means the waveform can be divided into fourteen segments. This apparatus is equipped with a class 2 CW He:Ne laser of 0.5mW maximum output power for alignment purposes.

2) A manipulator model Motoman-HP6, type YR-HP6-A00, controlled axis 6 vertically articulated, 6 Kg Payload, and 1378 mm maximum reach.

3) For a flexible maneuvering transmission of the laser beam from the laser apparatus to the manipulator an optical fiber of 0.4 mm in diameter and 10 m long is coupled to the laser output at one end and to the beam focusing head mounted on the manipulator at the other end. Figure 1 shows the employed Nd:YAG laser-robot system.

For the benefit of this task a 99% purity alumina sheets of thickness of (2.2 mm) were selected. The laser beam is focused on ceramic plates. The radius of the laser spot at the surface is (400 μm) and (0) focal position (the minimum spot size at the surface). Several rows of holes were drilled in each workpiece. For each row of holes one of the laser beam parameters was varied and the rest were kept constant e.g. for the first row of holes different values of the laser output peak power were chosen and the rest laser parameters (pulse duration, repetition rate, and focal plane position) were fixed e.g. Finally, all holes were examined by an optical microscope for obtaining the most acceptable and accurate hole in this row. Hole dimensions and shape are the most reliable factors that were intended for determining the best hole. The optimum peak power that was examined in the first row is fixed for the next row while varying another laser beam parameter, and so on. This was carried until reaching the most optimum working parameters. An optical microscope with a magnification of 40X was used for the determination of the final dimensions of the drilled holes. Table 1 shows the range of each studied laser beam parameter that was varied within.

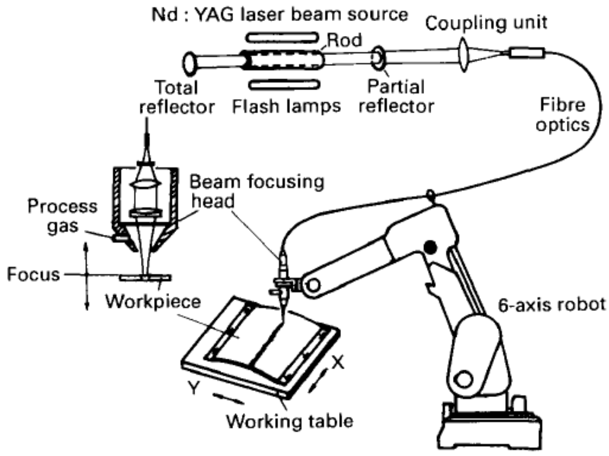


Fig.1 Nd:YAG laser-robot system used for the drilling of alumina ceramic.

Table 1 Laser output parameters used in the experiment

Peak Power	Pulse duration	Repetition rate
2-6 kW, 2 kW increment	1-5 ms, 1 ms increment	5-25 Hz, 5 Hz increment

3. COMSOL Modeling and Boundary Conditions

Analysis of this example models the localized transient heating caused typically fixed over the surface of the substrate to produce the desired localized hole as shown in Figure 2. Interaction of a laser beam with a substrate is based on development of a 3-D dimensional model, where the geometry in the present work is a finite rectangular substrate irradiated by laser beam on its surface. The laser beam has a certain wavelength λ, beam spot radius w, and intensity I within the spot.

The beam's penetration depth, which it can be described with an absorption coefficient, depends on the ambient temperature. The model examines the penetration depth and the influence of the laser beam power and exposure time on the transient temperature distribution using 1064 nm continuous (CW) diode laser of 5 W output power. The model simulates the substrate as a 3D object (Figure 1) with the dimensions (2.5) mm in Thickness, (10) mm in length and (5) mm in Width.

It handles the variation of laser intensity with penetration depth using a 1D geometry that represents the substrate's thickness as illustrated in Figure 3.

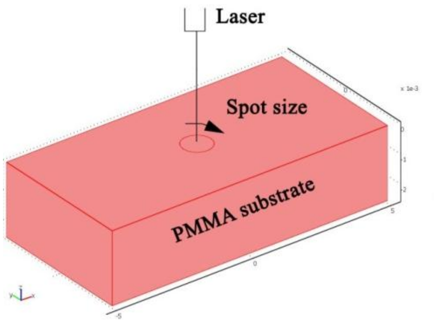


Fig.2 laser beam irradiates a PMMA substrate

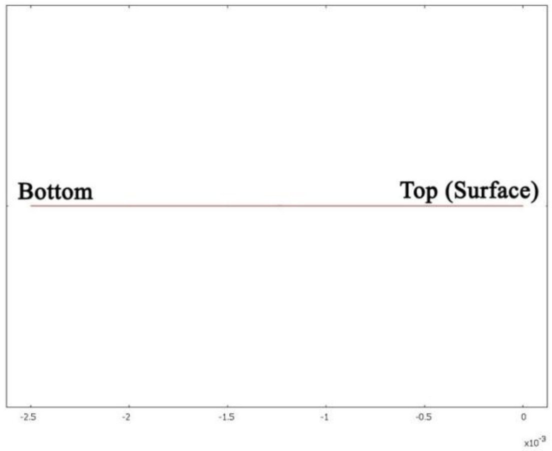


Fig.3 The 1D model geometry

The model makes use of the Conduction application mode to describe the transient heat transfer in the 3D geometry. The transient energy-transport equation for heat conduction is (COMSOL AB, 2008).

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla \mathrm{T}) = Q \qquad (1)$$

Where ρ is the density, C_p is the specific heat capacity, *k* is the thermal conductivity, and Q is the heat source term, which here set to zero.

The material properties are those of PMMA, using an isotropic conductivity of (k*xx*, k*yy*, kzz) = (0.19) in units of W/(m·K), a density of 1.19 g/cm3, and a specific heat capacity of 1470 J/(kg·K) (J.J. Radice *et al*, 2012).

For the model, assume the boundaries are insulating.

In the 1D geometry, this model uses the Weak Form. The weak form in COMSOL Multiphysics is a particular way of specifying a model; it makes it possible to enter certain equations which can be derived from an energy principle in a very compact and convenient form (COMSOL AB, November 2008). So the Weak Form is used in this work as Subdomain application mode to model the laser penetration. In the equation describing the penetration

$$\frac{\partial I}{\partial x'} = k_{abs}\, I \qquad (2)$$

I represents the relative laser intensity (the variable in the Weak Form, Subdomain application mode), *x*' represents the 1D coordinate, and k_{abs} is the absorption coefficient. The absorption coefficient can depend on the temperature, and the expression used in this model is (COMSOL AB, 2008).

$$k_{abs} = 8 \cdot 10^3 \mathrm{m}^{-1} - 10\ (\mathrm{m} \cdot \mathrm{K})^{-1} (T - 300\ \mathrm{K}) \qquad (3)$$

The volumetric heat source term, Q, in the 3D geometry is then

$$Q = P_{\mathrm{in}} k_{abs}\, I \qquad (4)$$

Where Pin is the total power of the incoming laser beam.
Both of these equations are included in the Weak Form, Subdomain application mode, where they become one equation:

$$\mathrm{I\_test} * (\mathrm{Ix} - \mathrm{k\_abs} * \mathrm{I}) + \mathrm{k\_abs} * \mathrm{I} * \mathrm{P\_in} * \mathrm{T\_test} \qquad (5)$$

The first part of this expression describes the penetration equation, and the second part comes from the heat-source term in the 3D Heat Transfer application mode.

At the left boundary, apply a homogeneous Neumann condition, and at the right boundary set the relative intensity, I, to unity.

The model implements the heat source when coupling the 3D temperature variable, T, to the 1D equation. It does so with a subdomain extrusion coupling variable using a general transformation. A time-dependent transformation expression results in a heat source. This case describes a vertical laser beam without moving using the transformation expressions

x= 0, y= 0, z=x'

Where x, y, and z correspond to the 3D coordinates, and x' represents the 1D coordinate.

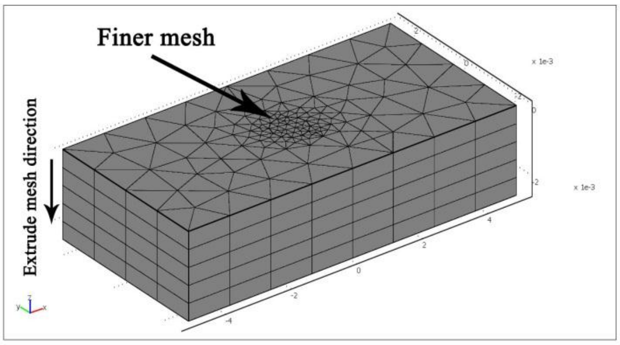


Fig.4 The 3D mesh produced by extruding a 2D triangular mesh, refined along the laser spot size.

This method "using a separate geometry and equation to model the source term" is very useful because it provides that term directly at the test-function level.

The 3D model makes use of an extruded triangular mesh, which has a fine resolution close to the laser incident line and is coarse elsewhere (See Figure 4). This results in a high-resolution solution with minimum computation requirements.

Figure 5 depicts the temperature distribution at the laser-beam incident surface.

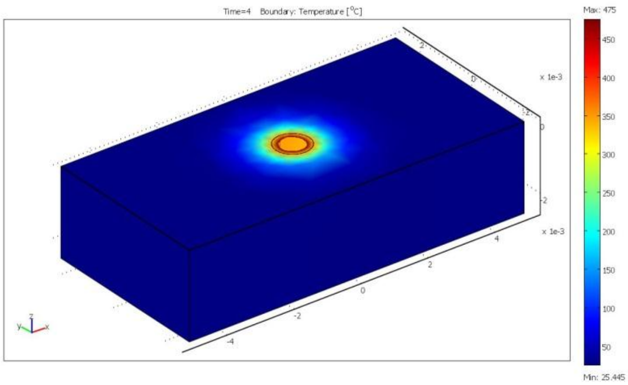


Fig.5 Temperature distribution after 4 s of laser drilling

The Figure 6 clearly shows a hot spot (vaporized material) where the focal plane position (*fpp*) is considered zero when it is set on the substrate surface. Furthermore, the results show the warm side and the cold side next to the vertical line of the laser beam. The warm side represents the heat affected zone (HAZ) as a result of high temperature next to the ejected material.

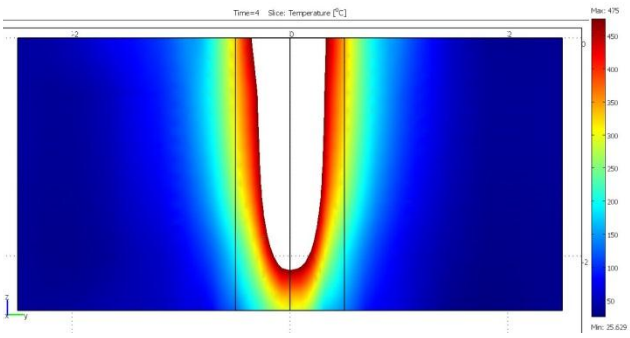
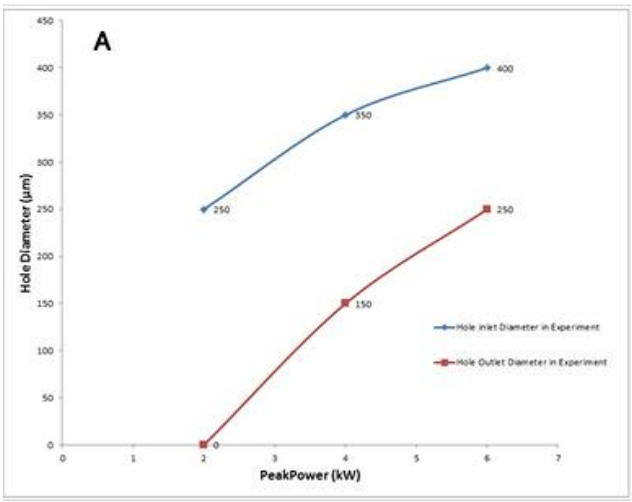


Fig.6 Temperature distribution for the cross section of the hole after 4 s of laser drilling.

4. Results and Discussion

4.1 Experimental Results



Hole quality represented by the hole cylindricality and depth is intended for the evaluation of the laser working parameters effects including peak power, pulse duration and pulse repetition rate. Laser peak power was increased consecutively by 2 kW from 2-6kW at constant pulse duration of 0.5 ms, 10 Hz repetition rate and zero focal plane position, i.e., focusing the laser spot on the workpiece surface. It is noticed that at 2 kW peak power

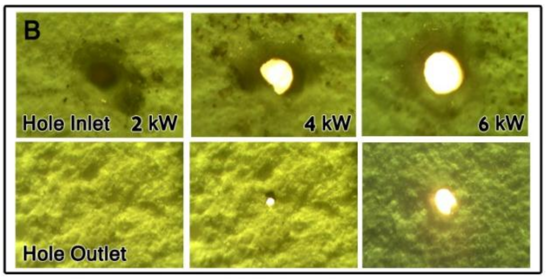
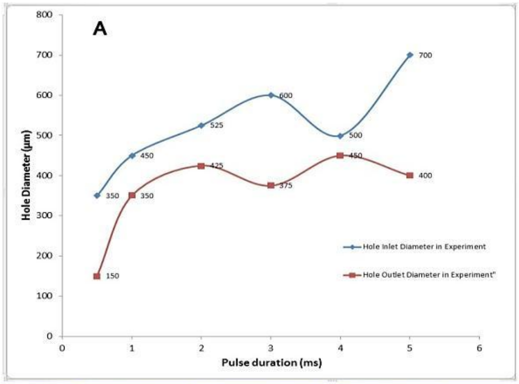


Fig.7 Variation of the hole diameter as a function of peak power at 0.5ms pulse duration and 10 Hz repetition rate (a) The experimental results, (b) Optical images for the holes inlet and outlet



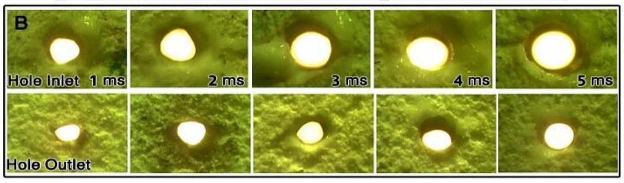
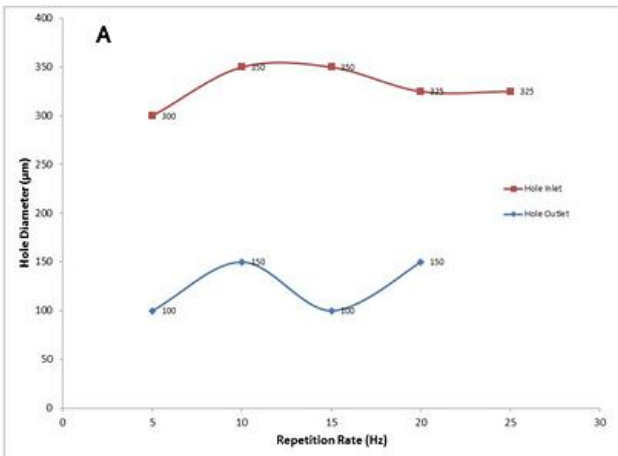


Fig.8 Variation of the hole diameter as a function of pulse duration at 4 kW Peak power and 10 Hz repetition rate (a) The experimental results, (b) Optical images for the holes inlet and outlet



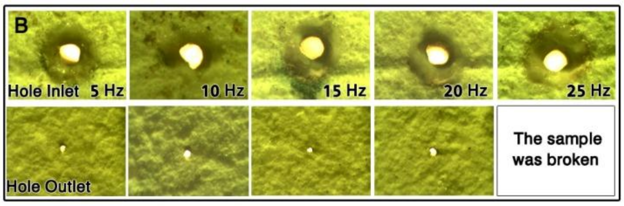


Fig.9 Variation of the hole diameter as a function of pulse repetition rate at 4 kW Peak power and 0.5ms Pulse duration (a) The experimental results, (b) Optical images for the holes inlet and outlet

laser pulses could not reach the back side of the alumina ceramic plate whereas increasing the peak power up 4kW led to a hole diameter enlargement as seen in Fig. 7 (a,b). Laser pulse duration effect is examined by increasing its values using an increment of 1ms from 1-5ms at a fixed peak power of 4 kW. It is noticed that the hole diameter increased as the pulse duration increased except in 4ms decreased as shown in Figure 8(a). It has been observed that spatter area around the hole entrance was larger with up to 3ms pulse duration as seen in Figure 8(b).

Figure 9(a,b) illustrates the varying of laser pulse repetition rate while fixing the other laser parameters. It is noticed that up to 5Hz of repetition rate almost open holes were executed in the tested workpieces. Increasing the repetition rate up to 20Hz withdraw the hole to become smaller.

4.2 Simulation Results

The most important parameters that affect the quality of the laser drilling process using CW laser are laser output power and the exposure time. In order to determine the effect of the laser output power on the dimensions of the hole, the laser beam has been focused onto the surface of the substrate with various powers at constant exposure time of 4 s. When the power of the laser beam increases, hole depths and hole diameters increases as shown in Figure 10.

PMMA was experimentally observed to vaporize from 310°C to 475°C via differential scanning calorimetry (Salonitis K. *et al*, 2007). In the present work it has been adopted the vaporization temperature of PMMA in this range. Fig. 6 shows the temperature distribution on the PMMA substrate after various powers (0.96 W, 1.82 W, 2.45 W and 3 W) and the area which is shown in white color should therefore be removed, since it reached to a temperature more than the vaporization temperature. The dimensions (width and depth) of the hole in relation to the temperature distribution on the specimen can clearly be seen in the same figure. Crater has remained a blind hole when the laser output power used of 0.96 W whereas a full hole has been investigated when the laser output power reached up to 1.82 W.

The same tendency has also been obtained in determining the effects of the exposure time on the dimensions of the holes, exposure time has been increased from 2 s to 5 s with 1 s increments at the fixed laser output power of 1.82 W. The effect of exposure time on the hole shapes and the diameters can easily be seen, in Figure 11.

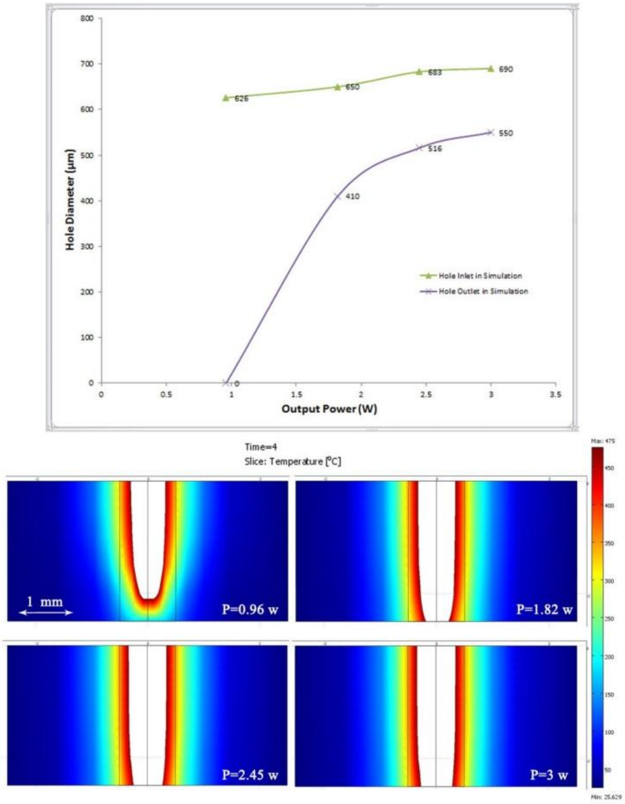


Fig.10 Variation of the hole dimensions as a function of laser output power at 4 s exposure time with zero focal plane position.

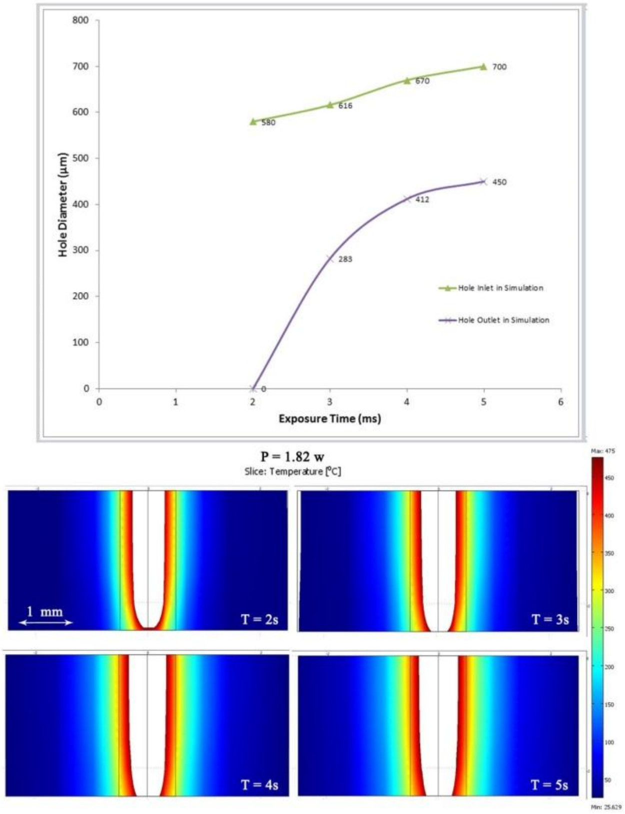


Fig.11 Variation of the hole dimensions as a function of exposure time at 1.82 W laser output power with zero focal plane position.

When the exposure time has been increased, hole depth and the outlet hole diameter have also increased as seen in Fig. 7. At 2 s exposure time it can be clearly seen that the laser beam made a blind hole while at 3 s or above the exposure time is enough to make a full hole. Furthermore, after 3 s exposure time the conical shape of the hole has changed to isosceles trapezoid shapes as seen in Figure 11.

In order to simulate the progression of the hole formation versus the time of the process, 2.45 output beam power has been chosen and the stages of drilling in each 0.4s are illustrated in Figure 12. It shows that until 0.8 s time, laser beam penetrated the PMMA substrate approximately more than 2 mm in depth but the crater still a blind hole. While after 1.8 s the hole has opened from the outlet side and the outlet hole diameter increases with increasing the time of hole progression in the drilling process. And finally at time 4 s the outlet hole diameter became almost near to the inlet hole diameter.

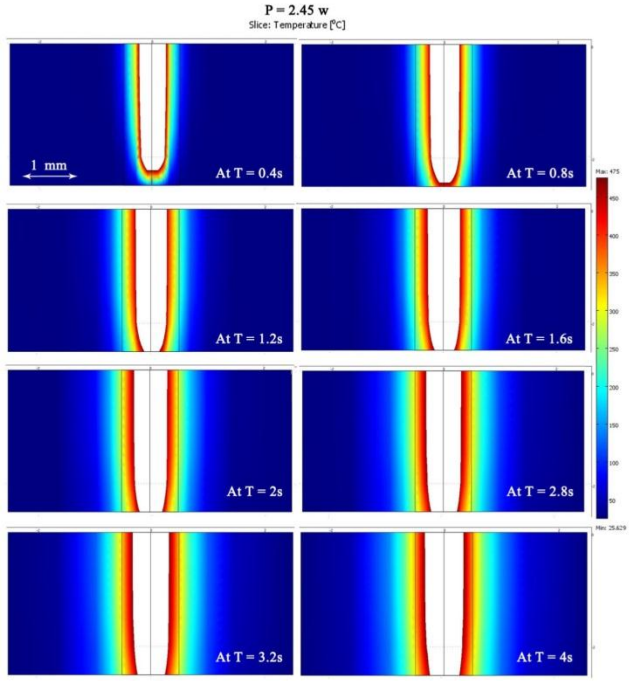


Fig.12 Simulate Hole Progression versus Time at 2.45 W laser output power with zero focal plane position.

Conclusions

Pulsed Nd:YAG laser-robot system used for the task of hole drilling of alumina ceramic substrates of thickness of (2.2mm). On the other hand, COMSOL program employed to simulate the drilling of PMMA for the thicknesses of (2.5 mm) using a CW 1064nm Diode Laser. Both of the mentioned studies (experiment and simulation) have been carried out to determine the effects of laser beam parameters such as laser peak power, pulse duration and repetition rate on the dimensions of the holes.

The results show that the hole diameter and depth can be controlled by varying the laser peak power, pulse duration and repetition rate for the experiment and the laser output power and the exposure time of the laser beam for the simulation. However, the experiment inferred that the diameter and depths of the craters have increased linearly with the laser peak power. The diameters of the holes have also increased when the pulse duration has been increased with observing spatter formation larger around the hole entrance. In contrast, the hole diameter decreased with increasing the repetition rate. Concerning to the simulation, craters have remained a blind hole when the laser output power and the exposure time used 0.96 W and 2 s respectively while full holes have been investigated when the laser beam reached up to 1.82 W output power and 3 s exposure time.

Comparing the behavior of experimental and the computational results of the drilling task shows that both results are almost coincident since both point to an increase in hole dimensions (diameter and depth) as the peak power increases. Moreover, this comparison shows that the hole dimensions increases as the pulse duration increases.

Acknowledgment

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