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COMPARISON OF KEYHOLE CHARACTERISTICS OBTAINED BY TWO EXPERIMENTAL METHODS: THE “DIRECT OBSERVATION OF DRILLED HOLE” METHOD AND THE “SANDWICH” METHOD

Paper # 203

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Abstract

The present article is dedicated to the study of the evolution of the keyhole obtained during the drilling of samples of Zinc by YAG laser beam. Two experimental methods are used to observe the shape of the keyhole. The first one is the Direct observation of Drilled hOle, that lets to obtain the shape of the keyhole for different laser powers and different pulse durations. The observations are carried out after drilling. The second one needs to clamp the zinc sheet with a quartz glass. This glass is chosen because of its excellent thermal shock resistance and its high light transmittance. The observation of the keyhole during the drilling shape is then realized through the quartz with a high-speed CCD camera. The evolution of the shapes of the keyhole obtained by both methods lets to highlight the role of the multiple reflections on the shape of the keyhole. When multiple reflections occur, the absorption of the energy by the wall of the keyhole increases and consequently the depth of the keyhole increases. This phenomenon was verified experimentally: in the first method, the multiple reflection of the laser beam on the wall of the keyhole occurs, whereas, for the second experimental set-up, it can be considered that there is only one impact of the laser beam on the keyhole walls. This result was theoretically proved by calculating the absorption for different shapes of the keyhole, in both cases: one reflection and multiple reflections, using the ray tracing method.

Introduction

When a material is irradiated with a high intensity laser beam it can be melted and vaporized. The formation of the keyhole results from the action of the recoil pressure and the ejection of the melted material. It has been identified that keyhole geometry and its stability are key factors in the performance of laser processes. It is also known that

the geometry of the keyhole depends on the spatial distribution of the laser power on the wall of the keyhole. This distribution determines the thermal field, the thickness of the layer of molten metal and the recoil pressure produced by the evaporation of material on the surface, thus the movement of molten metal, which has for consequence to modify the geometry of the keyhole. So there is a very strong coupling between these various phenomena. In order to validate the numerical modelling of drilling or welding processes, experimental data are necessary.

Some attempts have been made in the interest of observing the keyhole during last years. Schneider [1] has carried out an original method for analyzing laser drilled holes called Direct Observation of Drilled hOle (DODO). This method provides instantaneously surface state, geometric shape, as well as recast layer structure, without additional operation. The principle of this technique consists in positioning the drilling axis on the joint plane of a butt configuration. Once the sample is drilled, the two parts are split so that one half of the hole is in each part of the sample.

As it is difficult to directly observe the laser keyhole in the most of engineering materials such as metals, first Arata's [2] group and more recently Xiangzhong Jin et al. [3] used transparent material to observe the keyhole. In their experiments, only Fresnel absorption in the keyhole can be considered, since no plasma was generated. Matsunawa's group [4, 5, 6, 7, 8] and Jouvard et al. [9] carried out other experimental investigations to observe the dynamic keyhole shapes in deep penetration laser welding of metals by X-ray transmission imaging systems with high-speed video cameras. Unfortunately, most of the keyhole shapes were not clear enough to perform the quantitative study.

In this work, two methods have been used in order to observe and to study the evolution of the shape of the keyhole, realized in a target of Zinc, as function of laser power and of time: the first one is the Direct observation of Drilled hOle, that lets to obtain the shape of the keyhole for different laser powers and different pulse durations. The second one, called the Zn/Quartz sandwich method, needs to clamp the Zinc sheet with a Quartz Glass. The Zinc was chosen because of its low boiling point (1180 K) and complete data on its thermophysical properties. Quartz was used for its high softening temperature (1943 K), and its high transmittance: 95 % for the wavelength of YAG laser.

First experimental method: Direct Observation of Drilled Hole

The Direct Observation of Driller hOle method consists in merging the drilling axis on the analysis plane. To do it, one surface of each sample couple is polished. These two planes are assembled.

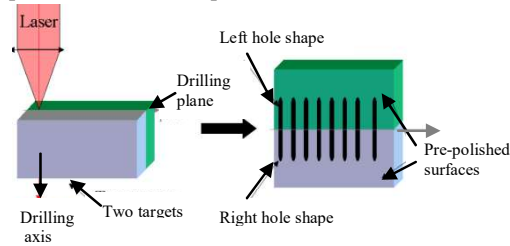


Figure 1 Schematic representation of the DODO method.

Fig. 1 shows a schematic view of the DODO method. The holes are drilled in such manner that their axes are in the interface plane of the joint, as shown at Fig. 1.a.

After drilling, the joint is split and reveals half-hole shape on each side, as shown at Fig 1.b. Consequently, DODO ensures the observation of analysis plane and so the measurements associated to morphology analysis (depth, conicity).

To carry out the drilling a Nd:YAG laser TRUMPF (model 304 P) was used, with a maximum peak power of 6 kW, and pulsation durations range from 0.5 to 20 ms. The spot diameter at the surface of the sample is fixed at 450 μm . The experiments were carried out for laser powers: 1, 2, 3, 4 and 5 kW. Each experiment was repeated four times to quantify the repeatability of the measurements.

Fig. 2 shows some micrographics obtained for laser power 1kW and different pulse durations.

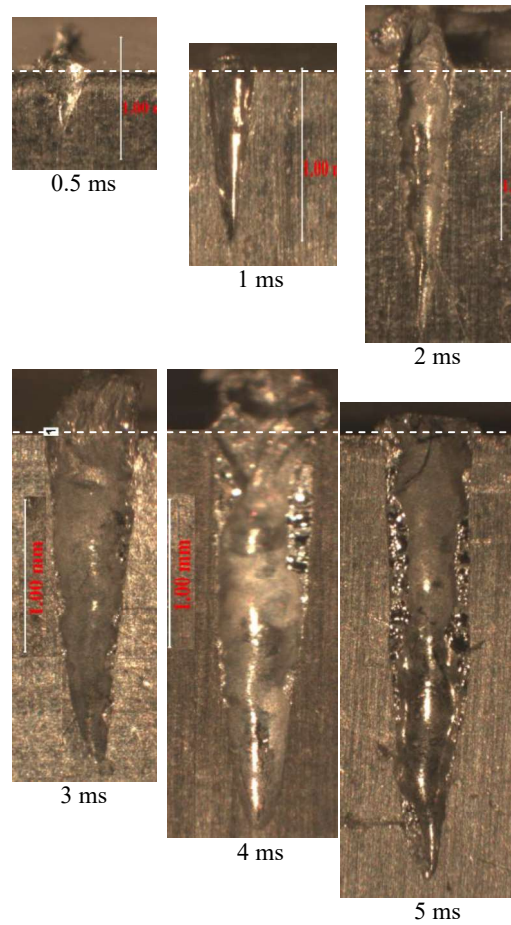


Figure 2 The keyhole profiles for laser power 1kW.

It can be observed that the depth increases with the pulse duration. We can also see the change of keyhole shape: before 3 ms the keyhole is conical, while above 3 ms, this one becomes almost cylindrical with a swelling in the centre and can be approximated by a parabolic function.

Fig. 3 shows the influence of pulse duration on the depth and the shape of the keyhole for laser power 3kW. The figure provides all the four measured values (A, B, C, and D). The fitting are made for mean values labelled "E". The two phases clearly appear: one before 3 ms, and another one after 3 ms. In the first phase, the drilling speed is estimated to be $0.71 \text{ m}\cdot\text{s}^{-1}$ and in the second phase $-0.21 \text{ m}\cdot\text{s}^{-1}$. This change in drilling mode can be explained by the temporal variation of absorption factor [9, 11].

Before 0.5 ms, measurement was impossible. So, maybe, a beginning phase exists before the minimum pulse time of our measurements.

Same observations were obtained for the other laser powers: 2, 3, 4 and 5 kW: a change of drilling velocity is obtained for pulse duration around 3 ms.

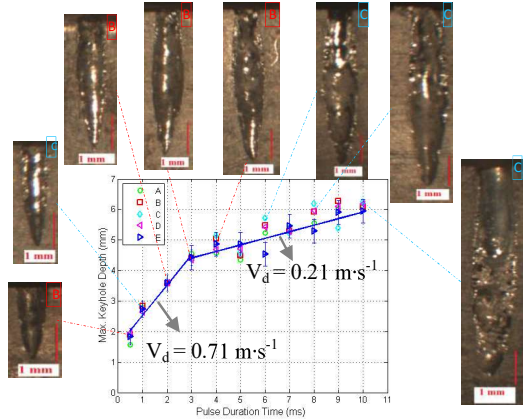


Figure 3 The keyhole profiles for laser power 3kW.

The Zn/Quartz Sandwich Method

The second experimental method uses two sheets of Zinc and GG17 glass compressed together in a window of steel (Fig. 4). The high speed camera let to obtain 3500 images per second with an exposure time of 256 μm . So, in a range of 10 ms, it is possible to acquire 35 images. We can consider that the obtained quantity of images allows studying the evolution of the keyhole shape during the pulse.

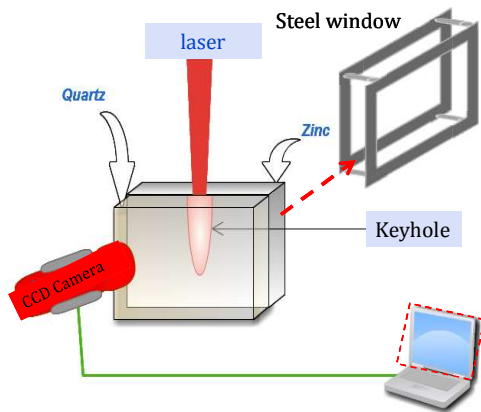
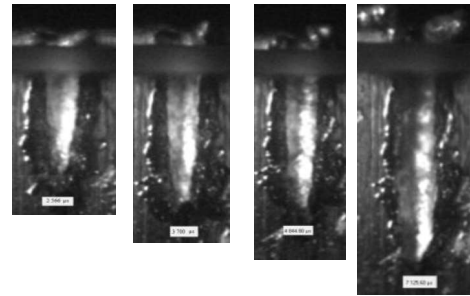


Figure 4 Schematic representation of the sandwich method

The drilling experiments are carried out under normal laboratory conditions, without shielding gas. The beam of a cw Yb:YAG laser (model TruDisk 6002) is operated in the pulsed mode and focused to a spot diameter of 450 μm . The profile of the keyhole is obtained for single pulse duration of 10 ms, and pulse powers of 1, 2, 3, 4, and 5 kW. Laser

beam is perpendicular to the touch-line between Zinc and Quartz sheets as shown in Fig. 4.



Depth (mm)	3.05	3.38	3.75	4.55
Time (ms)	2.5	3.7	4.8	7.1

Figure 5 Keyhole shapes at different times during a pulse of 10 ms for a power laser of 3 kW

Fig. 5 shows the examples of images obtained for a laser power of 3 kW. The depth was measured for each image. Fig. 6 shows the evolution of the keyhole depth during the pulse. From these measurements it is easy to calculate the drilling speed (V_d). It can be observed that in the initial phase of keyhole creation ($t < 3$ ms) the drilling speed is higher ($0.67 \text{ m}\cdot\text{s}^{-1}$) than in the second phase ($0.23 \text{ m}\cdot\text{s}^{-1}$).

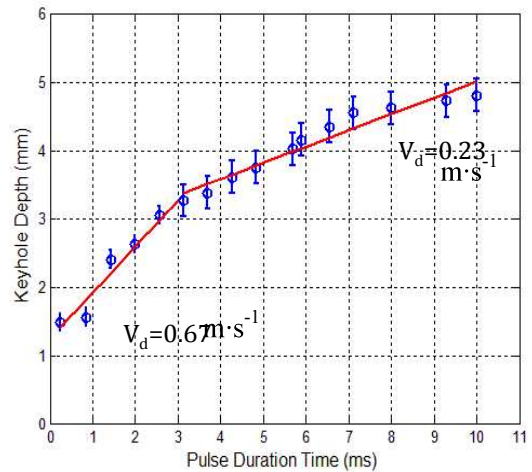


Figure 6 Evolution of the keyhole depth during the pulse (3 kW)

Once again, two phases can be easily observed: the first phase for pulse duration less than 3 ms and the second for pulse duration higher than 3 ms. It shows as well the rapid increase of the depth of the keyhole before 3 ms and the slower increase after. The same observations were obtained for power 1, 2, 4, 5 kW.

Comparison between results obtained by both methods

The depth of the keyhole obtained for 1 kW and 5 kW are plotted in the same graphic (Fig. 7).

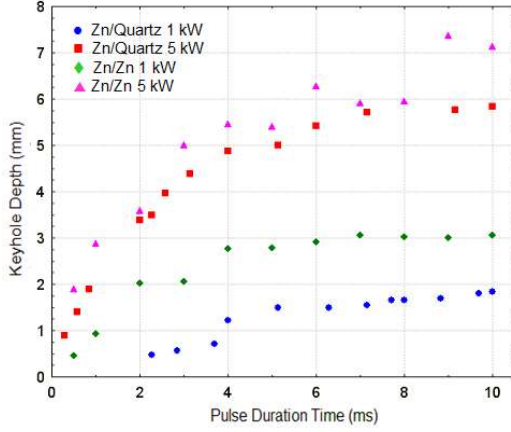


Figure 7 Comparison between both methods (Zn/Zn: DODO method, Zn/Q: sandwich method) (d1: 1 kW, d5: 5 kW)

Fig. 7 shows, first, that the depth obtained for 5 kW is greater than that obtained for 1 kW: the more the incidental energy is raised, the more the keyhole is deep.

This figure shows also that the depth of the keyhole is higher in the case Zn/Zn than for Zn/Quartz, for the same power. This may be explained by the effect of multiple reflections. In fact, this phenomenon increases the absorption of the energy by the keyhole walls, which occurs in the case Zn/Zn and does not occur in the case of Zn/Quartz. So, in the next paragraph, the modelling the multiple reflections is presented.

Modelling of the reflection inside the keyhole

From the obtained observations, we can determine the shape of the keyhole. With the ray tracing method, [10, 11] it is possible to obtain the absorbed intensity on the wall of the keyhole.

The concept of the used method is that a fixed portion of energy of the laser beam is absorbed at the irradiation point on the wall, and the rest is reflected to the opposite wall and acts as a new energy beam. All the segment cells located on the beam path at the keyhole wall are irradiated by the beam.

In the case of the interface Zinc/Quartz, the mechanism of energy deposition is simpler. The reflection factor of an interface vapor-quartz is supposed weak (for a real index of Quartz of 1.459, the reflectivity is of the order of 0.03). So after a reflection of the beam on the surface of the keyhole, this one will travel the quartz (Fig. 8). To model the absorption of the beam by the zinc, it is enough to take into account only the first absorption.

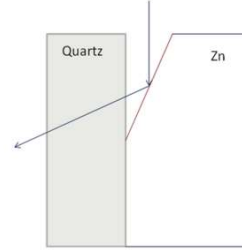


Figure 8 The path of laser beam in the case of the sandwich method

The absorptivity of material depends on the angle of incidence. If we consider that the beam propagates in the air and is reflected on a metal, the absorptivity is calculated from the Fresnel's law by equation (2). However, in the case of unpolarized laser beam and in normal incidence on the metallic surface, we can consider that beams are the superposition of all the states of polarization. In that case, the absorptivity is the sum of two terms corresponding to both polarizations (equations 2 and 3):

$$\alpha_{\text{Fresnel}} = \frac{\epsilon_{\perp} + \epsilon_{\parallel}}{2} \quad (1)$$

$$\epsilon_{\perp} = 1 - \frac{(n_r^2 + \chi^2) \cos^2 \theta_i - 2n_r \cos \theta_i + 1}{(n_r^2 + \chi^2) \cos^2 \theta_i + 2n_r \cos \theta_i + 1} \quad (2)$$

$$\epsilon_{\parallel} = 1 - \frac{(n_r^2 + \chi^2) - 2n_r \cos \theta_i + \cos^2 \theta_i}{(n_r^2 + \chi^2) + 2n_r \cos \theta_i + \cos^2 \theta_i} \quad (3)$$

The modeling is constructed using the Matlab software in 2D axisymmetric for different keyhole geometries (conic, parabolic) and the algorithm presented in Fig. 9.

We carried out the calculation of the absorbed heat flux for the case of only one reflection and multiple reflections for different keyhole geometries: conic and parabolic.

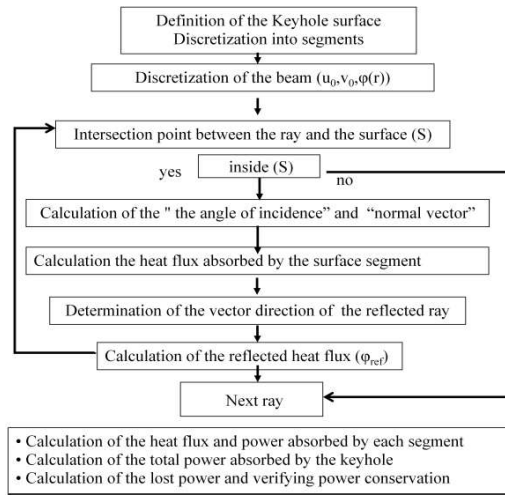


Figure 9 Used algorithm for the ray tracing method

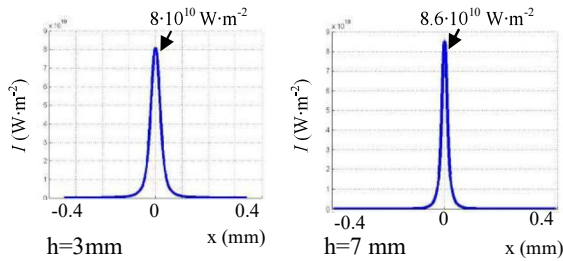


Figure 10 Radial distribution of absorbed flux (conic geometry, laser power 5 kW)

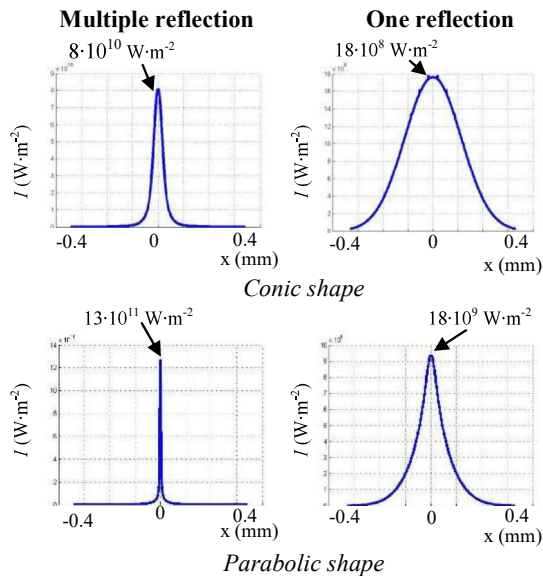


Figure 11 Radial profile of specific heat flux for conic and parabolic shapes of the keyhole with depth of 3 mm, radius of 0.4 mm and laser power of 5 kW.

Fig. 10 presents examples of absorbed heat flux for a laser power of 5kW, conic geometry, and depths 3 mm and 7 mm. It can be noticed that the energy is

concentrated at the bottom of the keyhole in a spot with 0.2 mm diameter.

Fig. 11 shows absorbed energy profiles for conic and parabolic shapes, in the case of one reflection (“sandwich” method) and in the case of multiples reflections (DODO method). When the keyhole profile becomes parabolic, the concentration of the energy is enhanced, which leads to drilling. It can be observed that the maximal specific heat flux increases by around 40 times from one to multiple reflections for the conic shape and 140 for the parabolic one. We can observe also that the absorbed heat flux is localized in the bottom of the keyhole, and particularly in case of multiple reflections.

Conclusion

A quantitative data on morphological evolution of keyhole shapes during the drilling by YAG laser was obtained by two experimental approaches: direct observation of drilled hole method and sandwich method. The obtained results reveal the existence of at least two drilling modes during the development of the keyhole: the conic shape mode during the initiation of the keyhole ($t < 3$ ms) and cylindrical shape mode ($t > 3$ ms). Each of these modes has a proper drilling speed which is found to be close for both methods.

Experimental and numerical results obtained in this study show that the phenomenon of multiple reflections involves an important increase of efficiency of laser/material interaction. The absence of multiple reflections in case of drilling by sandwich method leads to the systematic decrease of keyhole depth comparing to the DODO method. The numerical study based on the method of the ray tracing allows determining the profile of the power density deposited on the keyhole walls and demonstrates the increase of maximal specific heat flux in the bottom of the keyhole generated by multiple reflections.

The next step of this work, undertaken in the thesis of M. Mostafa [12] is to use the calculated intensity absorbed by the walls of the keyhole in a multiphysical 2D transient model in order to obtain the temperature distribution, the recoil pressure, and the shape of the keyhole in function of time.

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