Study of Hole Properties in Percussion Regime with a New Analysis Method

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To drill sub-millimeter holes, laser percussion drilling has been a well-established industrial process for tens years. However, inherent factors due to laser source, material properties and dynamic of the reaction are still making physical approach very difficult. Moreover conceptions on drilling are often confused with other laser applications like cutting. This paper deals with the study of the properties of holes drilled by an innovative source from Trumpf firm which ensures top hat distribution in focal plane for any laser parameters. Results are based on several post-mortem metallographic analysis.
First a new and very fast hole analysis method (called DODO for **D**irect **O**bservation of **D**rilled h**O**le) is described and compared to the X-ray radiography and metallographic cutting. DODO solves most of the problems of the previous methods, notably to ensure the merging the analysis plane to the drilling axe. Secondly, with the help of the DODO method we describe two drilling regimes separated by a threshold. The hole morphology (diameter, depth, profile) and the recast layer thickness are compared in each regime. We investigate this threshold as a function of pulse duration.
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1. Introduction

Laser drilling in percussion regime is used extensively in aeronautical industries. This process consists in irradiating a metallic target with a laser tuned in the MW.cm^{-2} range (pulse duration in µs-ms range). The laser energy is absorbed by the surface for the heating, the melting and the vaporization of the target. This vapor spreads out and pushes the melt pool. In this case, the drilling is dominated by melt ejection induced by the pressure gradient between the irradiated area and the hole surroundings, see [1, 2].

Translating these physical processes into equations, requires to solve the transport equations (Navier-Stokes and heat transfer) with the laser dump as boundary conditions. Up to now, it is impossible to solve this system without introducing some approximations, then compromising the accuracy of the final solution. This is why parametric and qualitative studies are essential to achieve the miscorrelation between each components and their own modifications. This allows to bring out the main parameters, which induce changes in the hole.

In the first part, we present the HL201P Trumpf laser characteristics used for experiments. In second one, we present a new hole analysis (called DODO for Direct Observation of Drilled hOle) which is faster, cheaper than the others. DODO is compared to traditional hole analysis : X-ray radiography and metallographic cutting. Finally we present and discuss some results with this method. Hole profile allows to identify two drilling shapes separated by a threshold. Below the latter holes are conical and above they are more cylindrical.

2. Laser source characterization

In previous papers [3], we have already presented the HL201P laser from Trumpf.

The laser ranges are reminded on Table 1.

Table 1 : HL201P parameters.

Incident intensity	1 to 22 MW.cm^{-2}
Average power	201 W
Pulse duration	0.08 to 1 ms
Frequency	<1 kHz
Energy dispersion	< 1%
Temporal dispersion	< 3%
Diameter in focal plane	330 µm

Table 2 shows the distribution of intensity in the focal plane, measured with beam analyzer. The intensity distribution is a circular top-hat in the focal plane. The position of the focal plane is constant whatever the peak power and the pulse duration.

The differences between color codes are due to different optical densities that we had to place in front of the beam analyser to protect it. The spot diameter is constant too and is equal to (330±10)µm for all parameters.

So, the HL201P owns very useful guarantees for a parametric study:

- a circular "top-hat" intensity distribution in the focal plane,
- pulse reproducibility,
- constant focal plane position for any laser parameters.

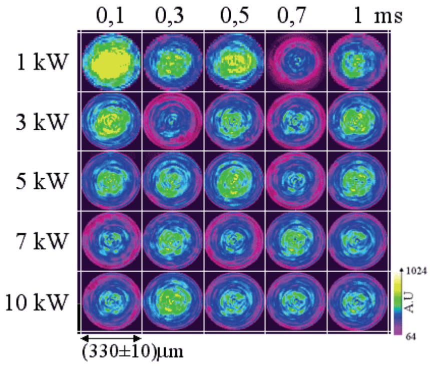


Table 2 : Intensity distribution at a constant focal plane as function of peak power and pulse duration.

3. Hole analysis method

3.1 X ray radiography

This method is the only one allowing non-destructive analysis. It is based on the shadowscopy principle showed on Fig 1. In practice, the drilled sample is located in front of a radiographic paper. The whole is irradiated with X ray canon. The paper reveals a projection of holes.

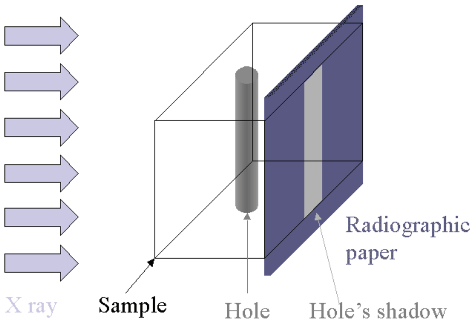


Fig 1 : Schematic representation of X ray radiography method.

Fig 2 shows a typical image of a radiographic paper performed with this method. Four holes appear as shaded columns. From this picture, global shape, depth and conicity can be determined. Typically, top diameter is 500 µm and the depth is 2,5 mm.

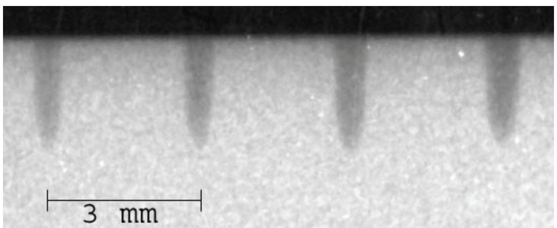


Fig 2 : X ray radiographic image.

Details on images, are not accurate enough to describe precisely hole morphology and recast layer thickness. Moreover the hole bottom is less contrasted than the hole body, (see discussion Table 4)

This method allows a very global analysis.

3.2 Metallographic cutting

This method is destructive one. Indeed, the sample is cut and polished until the cross section is located on the drilling axe. With the help of a chemical reaction it is possible to see metal granularity.

However, it does not ensure the merging of the cross section position and the drilling plane due to the polishing procedure (especially for deep holes). Difficulties concern their parallelism and their location, Fig 3 shows schematic views of these drawbacks. Fig 3.a presents the shift between drilling plane and cross section and on Fig 3.b the double tilt (α and β) between drilling plane and cross section. Besides, resin, used to operate, limits the control of the polishing and allows only a 2 D analysis in the cross section. Consequently, shape measurements (diameters and depths) are not accurate and in some cases not representative

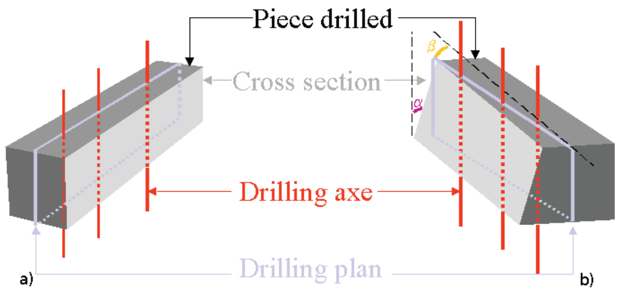


Fig 3 : Schematic representation of metallographic cutting and the different drawbacks

a)Shift between drilling plane and cross section
b)Tilt between drilling plane and cross section

Fig 4 is an image of a cross section done by this method.

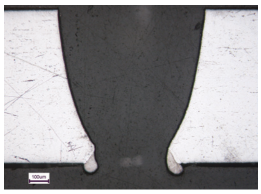


Fig 4 : Microscopy image of metallographic cutting.

This image proves that this method could qualifying, the recast layer thickness and the metal granularity in the cross section. For deep hole analysis it is very difficult to merge the cross section and the drilling plane. This method allows a very local analysis with a high accuracy, typically to determine the granularity and the recast layer thickness.
This method allows a very precise analysis but remains very expensive in time and cost and cannot be used on production site. Typically, only one hole a day can be analized.

3.3 Direct Observation of Drilled hOle

DODO solves most of the problems of the previous methods. Fig 5 shows schematic views of the method. It 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. Holes are drilled in such manner their axes are in the interface plane of samples like on Fig 5.a.

After drilling, two samples are split and reveal half hole shape on each one, as shown on Fig 5.b Consequently, DODO ensures the observation analysis plane and so measurements associated to morphology analysis (depth, conicity).

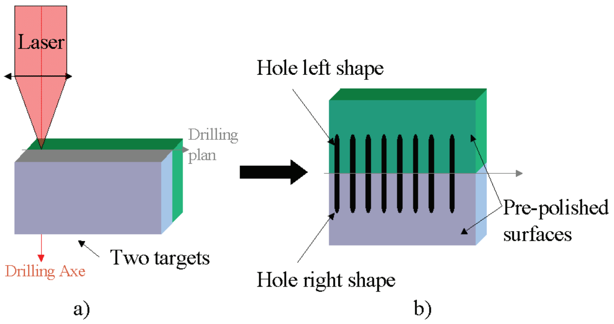


Fig 5 : Schematic representation of new analysis method.

Fig 6 : Hole shape SEM image.

Fig 6 shows SEM images of a half hole provided by DODO method. Pictures prove clearly the morphology and the recast layer thickness. Moreover, because resin is not used like with traditional metallographic cutting, the surface state of the wall and the 3D shape of the hole can be observed and evaluated.

To produce a good quality image we need a depth of field deeper than the radius of the hole, which is in the range of 500 microns. So we use here a SEM but for direct observation an optical microscope is enough.

Besides, this method allows some auto-control ways. Firstly if the two targets are not well merged: the melt metal injected during drilling will be detected after splitting. Secondly, direct observation can show if the drilling axe is not in the cross section.

4. Hole morphology study with DODO method

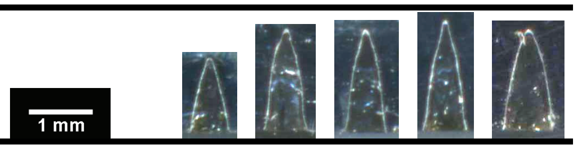
In this part we present some results obtained with the DODO method. We show the influence of peak power and pulse duration inside a blind hole.

4.1 Hole drilled with 0.5 ms pulse duration.

Table 3 shows hole profile as a function of peak power for a normal incidence. The pulse duration is 0.5 ms. The focal plane is located on the surface the pressure shield gas is below 1 Bar on the surface target ($P_{surface}$<1 Bar). On pictures the front hole is at the bottom of the picture. The holes profiles are selected to obtain a representative profile among a range of thirty holes made with the same parameters. The pictures are produced from a numerical scanning of samples.

Table 3 : Hole profile evolution as a function of peak power for a 0.5 ms pulse duration.

Peak power (kW)	5	6	7	8	12
pulse duration (ms)	0.5	0.5	0.5	0.5	0.5
	a)	b)	c)	d)	e)



Generally, two parts can be identified in holes for discussions. The hole body is the part of the hole where the radius is constant, and the hole bottom is the complementary part, see Table 4.

Table 4 : Parts of a hole drilled with 8 kW and 1 ms.

Hole bottom	
Hole body	

The holes on Table 3 can be divided into two groups. The first one for low peak power, below 6 kW, where hole profile is more conical. Drilling velocity is in function of peak power, see Fig 7. The second group concerns peak power above 6 kW for where drilling velocity is constant with the peak power. By comparison with 1 ms drilled hole, these groups are called Conical shape and Round bottom shape hole.

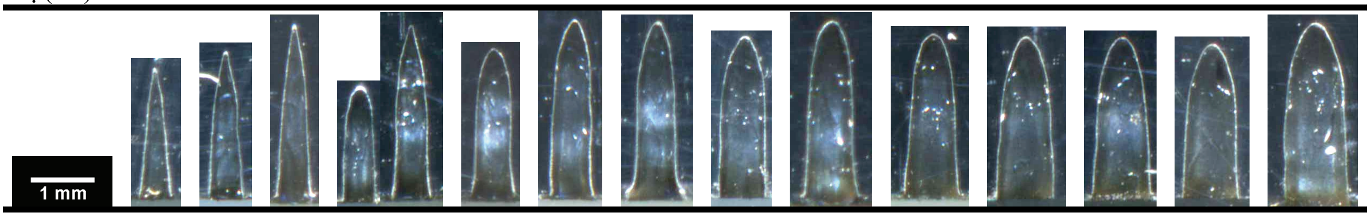
Conical shape hole group

The radius evolution is linear and decreases with the depth and increases with the peak power (300 μm at 8 kW and 800 μm at 17 kW).

The recast layer thickness can be measured with this method. It appears brighter than the original target material. Typically, its thickness is below 10 microns and it is constant along the hole.

In this conical hole morphology group, holes depth, and so the drilling velocity, increase with the peak power. Fig 7 presents hole depth as a function of peak power.

Table 5 : Hole profile evolution as function of peak power for a 1 ms pulse duration.

P (kW)	3	4	5	6	7	8	10	12	13	14	15	16	17	18
τ(ms)	1	1	1	1	1	1	1	1	1	1	1	1	1	1
														
	a)	b)	c)	d)	e)	f)	g)	h)	i)	j)	k)	l)	m)	n)

<u>Round bottom shape hole group</u>

Above 6 kW, the two morphological parts start separating.

In the hole body part, the radius decreases slower with the depth than it does in the conical shape hole group. And the bottom of the hole start rounding. The hole profile is no more totally conical. The radius increases with the peak power.

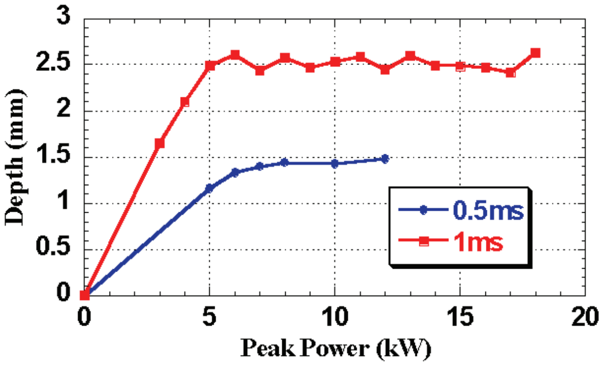


Fig 7 : Depth as a function of peak power with a single pulse.

The holes depth are rather constant when the peak power increases. So, the drilling velocity is constant.

The recast layer thickness is below 10 microns and it is constant along the hole, like in the conical shape hole group.

4.2 Hole drilled with 1 ms pulse duration.

Table 5 shows the holes profile evolution as a function of peak power for a 1 ms pulse duration. Shape evolution in two groups is confirmed, as it is with 0.5 ms pulse duration.

<u>Conical shape hole group</u>

Below 6 kW the holes profile are still conical, have the same characteristics, but they are deeper than with a 0.5 ms pulse duration, see Fig 7.

<u>Round bottom shape hole group</u>

Above 6 kW, the radius is rather constant in the holes body. And the holes bottom is rounder when peak power increases.

Fig 8 shows the radius of the hole body as a function of peak power. Radius increases linearly with the peak power. The radius at 0 kW peak power is close to the laser spot diameter in the focal plane (330 µm).

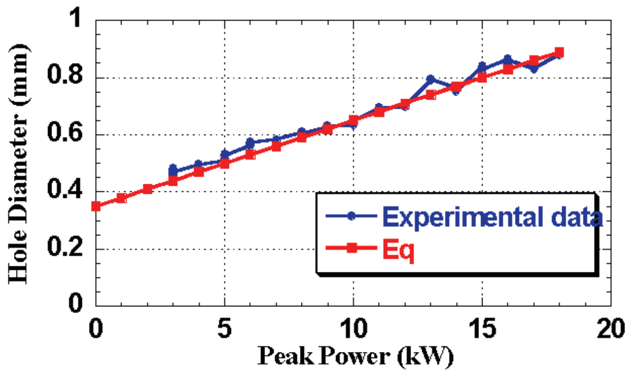


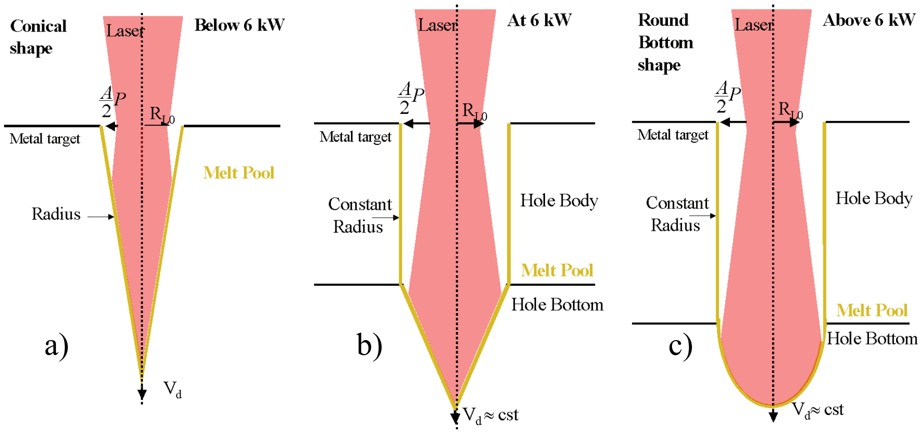
Fig 8 : Diameter as a function of peak power.

Above 6 kW, the depth is also constant for increasing peak power. So drilling velocity is constant too.

The recast layer thickness is always below 10 microns and it is constant along the hole.

In the previous paper [3], we showed that drilling velocity increased with the peak power without any threshold, and the radius evolution was different. But experiments concerned drilling velocity on thin target (0.9 mm). And radius were those of rear and front hole. The rear hole diameter is smaller to the internal hole radius, because when the drilling breaks through the rear hole opens up and its diameter depends on gas parameters, melt layer thickness, and peak power [4].

Table 6 : Schematic representation of drilling regimes for 1 ms pulse duration with single pulses.



5. Conclusion

<u>Concerning DODO :</u>

DODO method ensures the merge of the analyze plane and the drilling plane, and allows a 3D analysis inside the hole.

DODO :
- allows the characterization of the hole morphology (profile, radius, recast layer thickness, conicity, and depth).
- is a 3D analysis global and also precise of the whole hole.
- can be done on production site.
- is the fastest and the cheapest analysis method. Typically thirty holes can be made and analyzed in a couple of days.

<u>Concerning drilling process :</u>

The hole radius increases linearly with the peak power, see Fig 8.
The recast layer thickness is in the range of 10 microns and it is constant along the hole for increasing peak power.

Hole shape can be separated in two parts (hole body ,hole bottom).

There is a threshold below 6 KW ,see Tab 6.a, which :
- the hole is constituted of only a part.
- the radius decreases linearly with the depth. The hole shape is conical. The conicity is maximum.
- the drilling velocity increases with peak power.

Equal or above the threshold see Tab 6.c:
- the hole is constituted of two parts.
- the radius is constant in the hole body.
- the hole bottom shape is rounded, (pointed at the threshold , see Tab 6.b). The conicity is minimum.
- the drilling velocity is constant at 2.5 m.s^{-1}.

The physical reasons of theses changes in hole morphology are discussed in the paper [5],

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