New Experimental Approach to Study Laser Matter Interaction during Drilling in Percussion Regime

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Laser drilling is a well-established process in aerospace industry. However quality and geometry of holes do not get under control in an absolute way. Moreover, drilling understanding is complicated due to the number of parameters and physical phenomena. Laser and matter have some own parameters which are not constant with temperature, and so could not be fitted. In this paper, we describe the mechanism of laser-matter interaction for drilling with single and multi-pulse with a new method (called DODO for Direct Observation of Drilled hOle). We show the existence of a threshold between two drilling shapes called conical and round shape. With geometric optic approach, a simple model estimate the drilling depth corresponding to a drilling with round bottom shape. We show the influence of the peak power in a string of pulse on hole morphology (profile, diameter and quality). The influence of peak power fit in the string pulse to eliminate the recast layer cracking. It comes from a solidification of a melt layer on a previous recast layer. To eliminate it from the hole it is essential to melt the previous recast layer with higher peak power pulse than the previous one.

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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]. In the first part, we show the experimental conditions and a new hole analysis (called DODO for Direct Observation of Drilled hOle). In the second part we show some results for single and multi pulses from this method. We evidence the existence of a threshold between two drilling shapes called conical and round shape. The depth drilled is approximated by a simple model. Thirdly, the recast layer cracking is explained on drillings with two (and more) pulses, and suppressed from the hole. And finally with theses observations we present a simple model to estimate the drilling depth corresponding to an efficient drilling.

2. Experimental Set up and analysis method.

2.1 Laser characterization.

In a previous article [3], we have shown that the HL201P laser from Trumpf owns very useful guarantees for a parametric study:

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

The circular "top-hat" intensity distribution is ensured by an optical principle. The laser beam output is homogenized through a small fiber length. The output of the fiber is imaged in the focal plane by two lenses. Fig 1 shows a beam shape as function of the distance to the focal plane. In the focal plane the laser diameter is 330 µm.

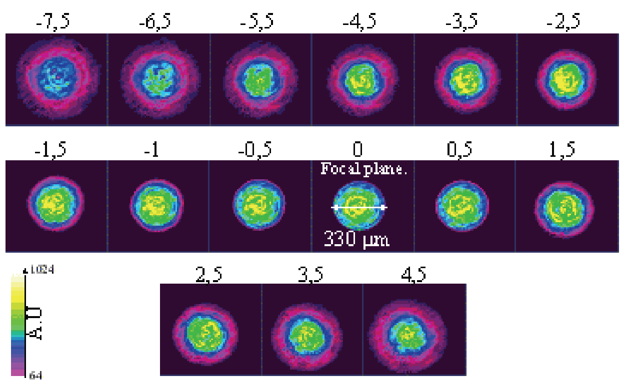


Fig 1 : HL201P beam shape. The distance to the focal plane is in millimeter.

With optic geometric considerations we define :

$$\tan(\alpha)=\frac{R_{L1}-R_{L0}}{f} \qquad (1)$$

with α is the optical aperture, R_{L1} is the laser radius on the focal lens and R_{L0} in the focal plane, see Fig 2.
We assume laser radius is described by:

$$D_{Lz}=D_{L0}+2\times z\times\tan(\alpha) \qquad (2)$$

where D_{Lz} is the laser radius at the distance z from the focal plane.

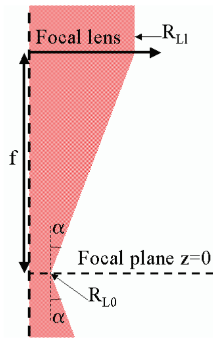


Fig 2 : geometric approach

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

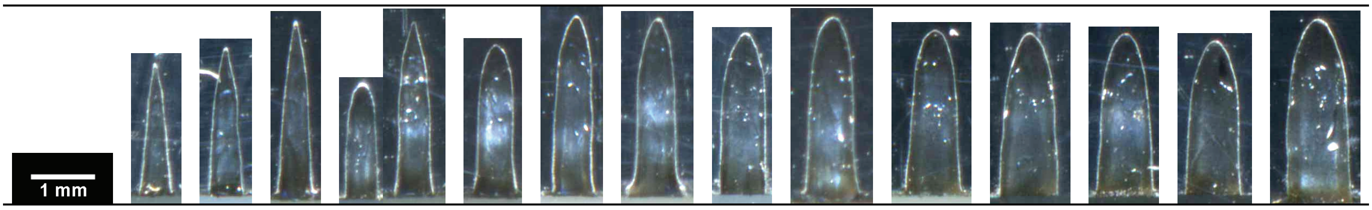
P (kW)	3	4	5	6	7	8	10	12	13	14	15	16	17	18
N	1	1	1	1	1	1	1	1	1	1	1	1	1	1
														
	a)	b)	c)	d)	e)	f)	g)	h)	i)	j)	k)	l)	m)	n)

Fig 3 experimental beam shape diameter and eq (2).

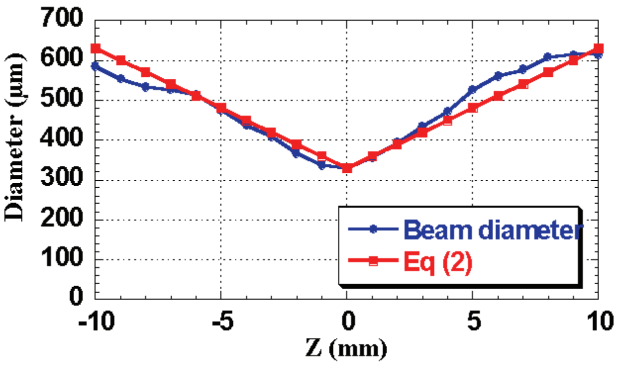


Fig 3 : graphic evolution of beam diameter and optical diameter as function of distance to the focal plane.

There is a very good agreement the two curves. So in the following the author assumes that laser diameter is equal to optical diameter.

2.2 DODO analysis method

To characterize hole produced, we use the DODO method (Direct Observation of Drilled hOle), described in [4]. Traditional hole analysis methods are limited to characterize deep hole. DODO method ensures the merge of the analysis plane and the drilling plane.

DODO:

- allows to characterize the hole morphology (profile, diameter, recast layer thickness, conicity, and depth).
- is a 3D global analysis precise of the hole.
- can be done on production site.
- is the fastest and the cheapest analysis method. Typically thirty holes can be made and analyze in a couple of days.

In following, drillings are made with laser focused on the target surface for a normal incidence. An argon shield gas ($P_{surface}$<1bar) is used to protect optics. Table 2 presents a typical image of the hole from analysis. Pictures are produced from a numerical scanning of samples. The recast layer thickness can be measured with this method. It appears more brightness than the target material original. On images, the front hole is at the bottom of the picture. Holes profiles are selected to obtain a representative profile among a range of thirty holes made with the same parameters.

Table 2: Hole parts.

Hole bottom	
Hole body	

Generally, two geometry parts can be identified in holes. The hole body is the part of the hole where the diameter is constant, and the hole bottom is the complementary part, see Table 2.

3. Hole morphology study with DODO method : single pulse

In this part we show some results obtained with the DODO method. The influence of peak power inside a blind hole is shown.

Table 1 shows hole profile as a function of peak power for a normal incidence.

Holes can be divided into two groups. The first one for low peak power, below 6 kW (Table 1.a to 1.c), where hole shape is completely conical. There is only one part. The second group concerns peak power above 6 kW (Table 1.d to 1.n) for which there are two parts in the hole profile.

<u>Conical hole profile group</u>

We call this drilling profile: conical shape. The hole bottom is very pointed. The diameter evolution is linear, it decreases with the depth and increases with the peak power (600 µm at 8 kW and 800 µm at 17 kW).

Typically, recast layer 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.

<u>Rounded hole profile group</u>

Above 6 kW (Table 1.d to 1.n), two parts start to be separated. In the hole body part, the diameter decreases slower with the depth than it does in the conical hole profile group. At 18kW (Table 1.n) the diameter is constant in the hole body.

On Table 1.d to 1.n, the bottom of the hole becomes rounder and rounder with the peak power. The hole shape is no more conical. The diameter increases with the peak power.

Hole depths are constant whatever the peak power. So above 6 kW, the drilling velocity is constant.

Fig 4 shows a graphical evolution of hole diameter as function of peak power. The diameter increases linearly with the peak power. At 0 kW hole diameter equals to the focal plane laser diameter (D_{L0}). So hole diameter can be calculated by:

$$D_H = A \times P + D_{L0} \qquad (3)$$

P is the peak power and D_H is the hole diameter. A is a constant in $m.W^{-1}$.

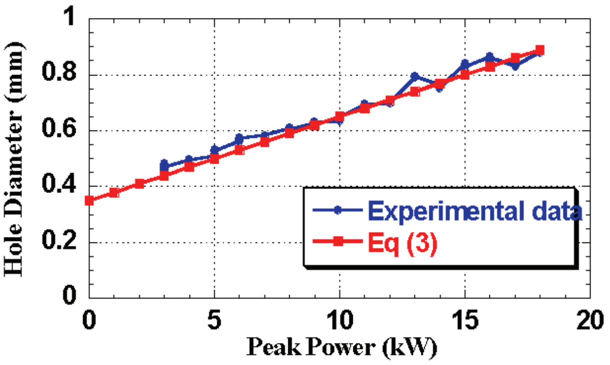


Fig 4 : Diameter as function of peak power. (A=0.03 $mm.kW^{-1}$, D_{L0}=0.35 mm)

4. Hole morphology study with DODO method: multi-pulses

In this part, we present the influence of pulse number. Table 3 shows hole profile for 13 and 18 kW peak power. N is the number of pulse.Fig 5 gives the correspondence between pulse number and depth for 13kW (in red), 18kW (in blue) and for a formula obtained with a simple model (in green).

For 13 kW peak power holes bottom are rounded until 4 pulses (Table 3.d). Between 5 and 7 pulses, (Table 3.e and 3.g) hole diameter is conserved in hole body but holes bottom are pointed. Above 7 pulses, hole shape is conical.

The recast layer thickness is below 10 microns until 7 pulses.

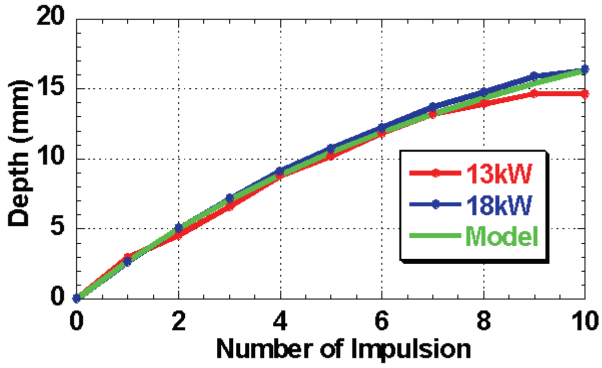


Fig 5 : Graphic evolution of depth as function of pulses number for 13 and 18 kW**.** The Model curve is given by expression (5).

Table 3: Hole profile evolution as function of number of pulse for 13 & 18 kW peak power.

P (kW)	13	13	13	13	13	13	13	13	13	13	18	18	18	18	18	18	18	18	18	18
N	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
	a)	b)	c)	d)	e)	f)	g)	h)	i)	j)	k)	l)	m)	n)	o)	p)	q)	r)	s)	t)

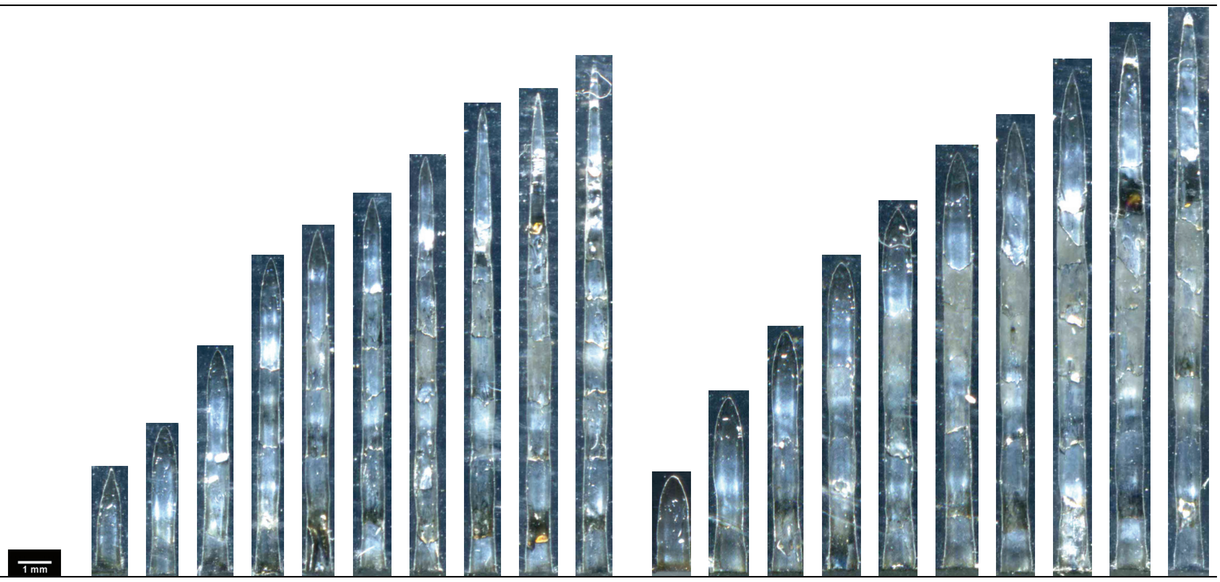
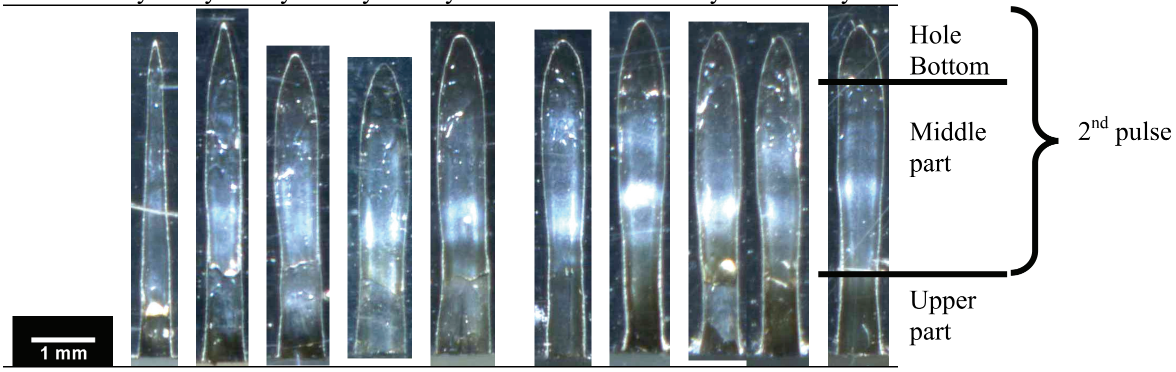


Table 4: Hole profile evolution as function of peak power for two pulses.

P (kW)	5-5	7-7	10-10	13-13	16-16	5-16	7-16	8-16	10-16
N	2	2	2	2	2	2	2	2	2
RLC	yes	yes	yes	yes	yes	no	no	yes- no	yes



	a)	b)	c)	d)	e)	f)	g)	h)	i)

For 18 kW peak power holes bottom are rounded until 6 pulses (Table 3.k to 3.p). Between For 6 and 10 pulses (Table 3.p to 3.t), holes diameters are constant in hole body but holes bottom are pointed. For this peak power holes shape do not become conical until 10 pulses The recast layer thickness is below 10 microns until 10 pulses along the wall of the hole.

So, until 7 pulses for 13kW, drilling has round bottom shape. Above 7 pulses it become conical. For 18kW and until 10 pulses drilling has round bottom shape.

Author assumes that the decreasing of drilling depth between consecutive pulses is linear at first order and comes from the evolution of the laser distribution along the optical axis. The increasing of irradiated laser surface approximates this evolution. So for the nth and the (n+1)th pulses :

$$\frac{z_{n+1}}{z_n}=\frac{S_{Lzn}}{S_{Lzn+1}} \qquad (4)$$

with z_n are respectively the depth drilled by the nth pulse and S_{Lzn} is the irradiated laser surface corresponding to the depth, z_n

So, the depth of drilling (z_n) is equal the sum of the depth of each pulse, and with laser geometric approach we define:

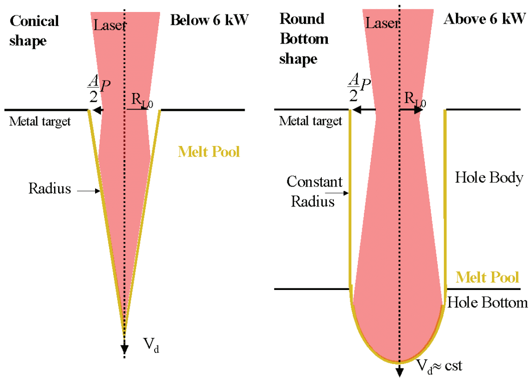
$$\frac{z_n}{z_1}=\sum_{i=1}^{n-1}\frac{S_{L0}}{S_{Lz}}=\sum_{i=1}^{n-1}\left(\frac{R_{L0}}{R_{Lz}}\right)^2=\sum_{i=1}^{n-1}\left(1+\frac{z_i}{R_{L0}}\times\tan(\alpha)\right)^{-2} \qquad (5)$$

with $z_1=2.7\ mm$ is the depth after the first pulse. N is the number of pulse, z_i is the position at the beginning of the nth pulse.

On Fig 5, the 18 kW curve equals to the model curve for all number of pulse, whereas the 13 kW curve is moved away from the fit curve from the 7th pulse. So the fit curve described the drilling depth above the threshold as function of pulse count.

Table 5 shows a brief recapitulative of drilling shape with a string pulse. For the first pulses above the threshold, the drilling has round bottom shape. At the nth pulse (7th for 13 kW) the intensity is below the threshold the hole shape is conical. And the drilling velocity decreases at each additional pulse.

Table 5 : Schematic representation of drilling shapes for 1 ms pulse duration with multi pulses.



5. Hole morphology study with DODO method : two pulses

In this part, we show the influence of peak power for two pulses on recast layer cracking. Table 4 shows hole drilled with two pulses. Holes are drilled with twin pulses in the left part (Table 4.a to 4.e) and with different first pulses peak power in the right part (Table 4.f to 4.i). The second pulses have a constant 16 kW peak power.

<u>The left part (Table 4.a to 4.e) : twin pulses.</u>
The first hole (Table 4.a) is produced with two pulses at 5 kW. Its shape is conical.
The others have round bottom shape. Diameter is constant in the hole body and hole bottom start pointed to become curved when the peak power increases, as seen previously.
All hole produced by twin pulses show a recast layer cracking (see Table 6).

Table 6: Recast layer cracking.

Recast layer cracking

The right part (Table 4.f to 4.i) : pulse train.

In this part hole are produced with a first pulse of which the peak power is lower than the second one. To the right the first pulse peak power increases. The peak power of the second pulse is constant and equal to 16 kW.

Three parts constitute holes. The upper is drilled by the first pulse with the lowest peak power of both pulse. The middle part which is the hole body of the second pulse at 16 kW. And the last part which the bottom hole of the second pulse. The diameter increases between the upper and the middle part. The hole bottom is curved.

Recast layer cracking is missing for the holes Table 4.f and 4.g when the peak power of the first pulse is below 8 kW.

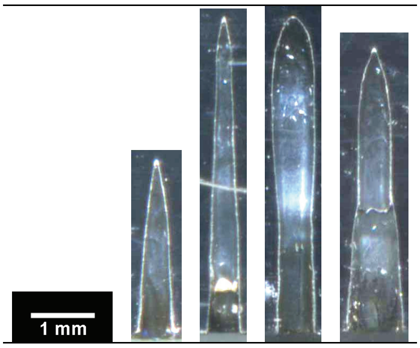
For hole Table 4.h with a 8 kW first pulse peak power, hole has recast layer cracking. And for higher first pulse peak power, every holes have recast layer cracking.

6.Discussions

Table 7 shows hole produced with 5 kW peak power for first or second pulse. It resumes holes shapes observed previously.

Table 7: Hole profile evolution for 5 kW peak power.

P (kW)	5-	5-5	5-16	16-5
N	1	2	2	2



	a)	b)	c)	d)

The first and second hole (Table 7.a and 7.b) have a conical shape, they respectively drill with 1 and 2 pulses.

The next hole (Table 7.c) is produced with a first pulse at 16 kW and the second at 5 kW. It is also constituted by three parts. The diameter in the upper part is higher than in the middle one. There is recast layer cracking.

The last hole (Table 7.d) drilled by the second pulse at 5 kW has a round bottom shape. Whereas the hole drilled with twin pulses at 5 kW (Table 7.b) has conical shape. So, for a second pulse at 5 kW the drillings are different if the first hole has a round bottom shape or conical shape. This could be explained by difference of the irradiated surface at the bottom of the first hole. The ration between a cone and a sphere surface is given by :

$$\frac{S^{irradiated}_{cone}}{S^{irradiated}_{sphere}} \approx \sqrt{1+\left(\frac{h}{R}\right)^2} > 1 \text{ and } h>R \qquad (5)$$

where h is the cone high and R is the cone and the sphere radius. The cone surface is always higher than the sphere surface. So the absorbed intensity decreases in consequence.

Concerning Recast layer cracking :

Hole drilled with a first pulse peak power below 8 kW and a second one equal to 16 kW have not any recast layer cracking.

Each pulse forms a recast layers. The recast layer cracking comes, in multi pulse drilling, from the solidification of the melt layer on the previous recast layer.

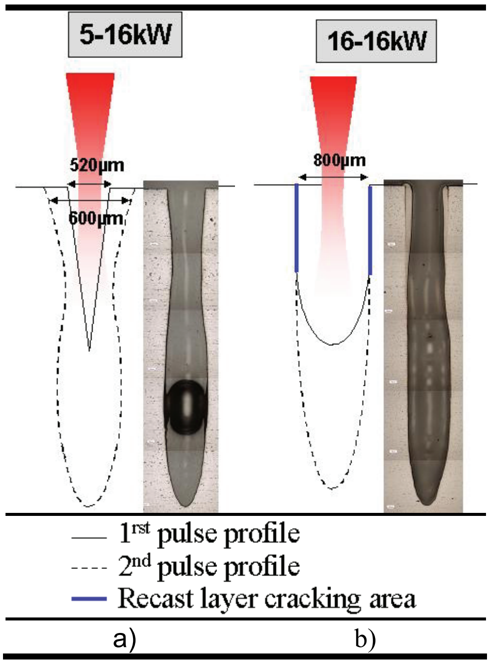
The only recast layer has not any cracking is the one comes from the solidification of the melt layer on the substrate. So if a hole drilled with two, or several pulses, has not recast layer cracking it is the last pulse had melted the previous recast layer.

Table 8 shows two holes diameters averaged among a range of thirty holes made with the same parameters, obtained with the DODO method. The first hole is made with two pulses with 5 and 16 kW and the second with a 16 kW twin pulses.

For the Table 8.a, the hole diameter of the upper part is much higher than for a single pulse. So the second pulse has widened the diameter of the first pulse. So the first recast layer has been melt.

For the hole Table 8.b the diameter equals to the first pulse peak power. So the recast layer has not been melted by the last pulse. And so recast layer cracking is in the hole.

Table 8: Interpretation of two pulses drilling with different peak powers.



5. Conclusion

Concerning drilling process :
The hole diameter increases linearly with the peak power, see Fig 4.

The recast layer thickness is below 10 microns and it is constant along the hole whatever the peak power.

There is a threshold below which :

- the hole is constituted of only a part.
- the diameter decreases linearly with the depth. The hole profile is conical. The conicity is maximum.
- the drilling velocity increases with peak power

And above which :

- the hole is constituted of two parts.
- the diameter is constant in the hole body.
- the hole bottom is rounded, or pointed.
- the drilling velocity is constant at 2.5 $m.s^{-1}$

For multi pulse drilling:
The diameter is conserved with the depth, as the drilling intensity is higher than the threshold.

The recast layer thickness is conserved. The cracking comes from a solidification of a melt layer on a previous recast layer. To eliminate it from the hole it is essential to melt the previous recast layer with higher peak power pulse than the previous one.

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