INTERNAL CHARACTERIZATION AND HOLE FORMATION MECHANISM IN THE LASER PERCUSSION DRILLING PROCESS

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Figures included in body text for easier review

ABSTRACT

Laser percussion drilling is increasing its relevance in many industrial applications, being used particularly in the aircraft industry in performing the micro-holes in nickel based alloys turbine blades for cooling, or stainless steel medical components drilling, which require small holes size and quality. Laser percussion drilling process presents extremely high speed for high aspect ratio holes. Moreover, the quality and accuracy of the holes can be excellent if the optimal parameters are set.

The laser percussion drilling process is usually performed with specific equipment, including lasers that achieve high peak powers of picoseconds duration. These systems are usually dedicated exclusively to laser drilling operation. It is also very common to perform this process using the parameters suggested by the manufacturer of the equipment and without any consideration about the mechanism of formation of the hole. On the other hand, laser percussion drilling is performed by a sequence of pulses on the part surface. Each pulse removes a certain amount of material. The energy and duration of pulses set the amount of removed material by each one.

This work discusses the mechanisms of formation of the holes in the laser percussion drilling process of an AISI 304 plate, evaluating the removed material volume in each laser pulse and obtaining the evolution of the hole geometry for the complete pulse sequence. In addition, this experimental analysis has been apply also for the development of a numerical model that can simulate the resulting hole geometry for different pulse sequences.

Keywords: Laser percussion drilling, micro-drilling, process modelling.

1. INTRODUCTION

Laser drilling process has become an industrial solution for massive micro or small hole drilling, ranging hole diameters from 5 microns to 1 mm, high aspect ratios (up to 1:200) and a wide range of workpiece materials. The main advantage of this process is the high productivity in comparison with mechanical drilling or USM, being able to reach hundreds of holes per second in certain conditions. This operation is usually performed by applying a single pulse or a sequence of relatively short pulses (typically from 0.01-100ms) and peak powers up to 50kW. However, laser pulses up to 100J can be achieved and pulses from femtoseconds to milliseconds can be applied [1, 2]. The combination of the pulse peak power and duration significantly influences on the material removal mechanism. For ultrashort pulses (less than 100fs) and high energy density (more than 10^{16} W/cm^2), material is removed by cold ablation mechanism, since the material interacts with the energy of the laser and there is virtually no melted material. On the other hand, for longer pulses (more than 100µs) and lower energy density (less than 10^7 W/cm^2), the material is removed by melt expulsion mechanism, combining material vaporization and melting. The latter is the most common case for conventional laser sources such as disc or fiber lasers [1].

An analysis of the recent research work about laser drilling reveal that there is high interest on the process and the mechanism of hole formation. The main aim of these works is to improve the laser drilling process, considering the different laser drilling process types. Laser drilling presents three different variants. First, the laser trepanning process, which consists in translating the laser beam in circular paths to cut the perimeter of the hole [3, 4]. It is a laser cutting process, rather than a laser drilling process. Secondly, the laser single pulse laser drilling process is a very fast process, in which all the material is removed in a single pulse [1]. It is mainly used in low- thickness parts or holes with less than 1:10 aspect ratios. Finally, the laser percussion drilling is based on removing material by a sequence of pulses. Each pulse removes a certain volume of material so that the entire sequence of pulses can achieve deep hole sizes with diameters ranging between 25 and 500 microns.

The laser percussion drilling is widely used in the industry and different research works, focused on the evaluation of the process can be found. Thus, Dubey [5, 6] review some works about process analysis, focused on a better understanding of the physical phenomena involved in the drilling process and hole formation mechanism. Similarly, research conducted around the laser percussion drilling can be separated into two groups. On one side, the experimental studies that evaluate the influence of process parameters and analyses the geometry of the resulting holes, while on the other side are those where the goal is to model the process.

Beginning with the experimental studies, the analysis of the influence of process parameters on the final geometry of the holes shows the most relevant parameters are the peak power and pulse duration, being the most uniform results as peak power is higher and the pulse is shorter [2, 7, 8]. One of the main problems in percussion laser drilling is the low repeatability of the process, an aspect that has been analyzed from the point of view of the final geometry of the holes [2, 9], and measuring the burr generated around the hole because of the melt ejection. Low evaluate also this problem, concluding that spatter formation is the main cause of the poor repeatability of the process [10]. In all these works, the measured values were the inlet and outlet diameters as well as the taper of the holes. The measurement of these parameters was performed by different methods (microscopy, measurement based on artificial vision, etc.) and the taper value was commonly obtained by the ratio of the diameters difference and the part thickness. Moreover, these works agree that two mechanisms of hole formation coexists: melted material expulsion by gas pressure and vaporization of material. Although the removal of melted material is more efficient, since there is no need to provide the latent heat, this mechanism result in lower quality holes. Therefore, the parameters of laser percussion drilling should set the vaporization mechanism as the dominant one, in order to obtain high quality holes, with less HAZ and recast layer. For example, Sezer et al [11], studied the influence of the laser beam incidence angle relative to the workpiece in order to minimize the HAZ and the recast layer of Nickel based alloys for thermal barrier coatings.

Regarding to the characterization of the internal geometry of the hole and the removed material volume in each pulse, there are relative few references and more limited data. Thus, Low [12] presents a study on the quality of arrays of very close laser drilled holes. As one of the presented results, some sections showing the internal shape of the holes are presented. Meanwhile, Li [13] also has some sections of the obtained holes, but this work also presents the final shape of the hole and does not analyze the formation mechanism of the hole. Döring [14] discusses the formation of a micro-drilling by measuring different sections of the holes drilled with an ultrashort pulsed laser with a beam size of 30 microns. The study was focused on the analysis of plasma expansion for each pulse, concluding that the expansion can cause abrasion of the hole sidewalls and the shape of the hole can be modified by this effect.

On the other hand, modeling of laser drilling process has been considered by different authors who have used different approaches to solve it. The evolution of the numeric models, from the first one-dimensional models, has been toward more complex and realistic models including 3D models considering non-linear effects such as phase transformation, variable material properties, etc. [15], [16]. Other relevant approaches, carried out by Mishra and Yadava, include the estimation of the drill profile considering temperature-dependent thermal properties, optical properties and phase change phenomena of the sheet materials. These works present different approaches such as FEM modeling [17], [18] and the use of ANN models [19]. 2D axisymmetric models have been also developed, considering in this case the effect of the reflections of the laser beam with the walls of the hole during percussion drilling process [20, 21]. In any case, these models include assumptions that help reduce the number of variables to consider and reduce the calculation time. The most common simplifying assumptions are not considering the effect of the plasma and its possible generation, the assumption of the absence of melted material displacement due to thermal gradients and the assumption that the melt phase instantly solidifies after the laser pulse, maintaining the same geometry of the hole.

In most of the analyzed works, an empirical study or numerical problem is solved, but separately and decoupled. Furthermore, most of the works focus on the final results of the drilling process, such as inlet and outlet diameters of the holes, without analyzing the shape of the hole or the mechanism of the process. Thus, this paper analyzes the geometry of the holes made by a fiber laser with a maximum power of 1 kW on a 1mm thick sheet of AISI 304 stainless steel.

2. EXPERIMENTAL PROCEDURE

The tests have been carried out using a fiber laser Rofin-Sinar FL010 with a 1 kW maximum power. The laser has been guided using a 100µm fiber and positioned by a Hurryscan 25 scanner head, focusing the beam onto the part upper surface. The focal point has been maintained constant for all the tests so, rigorously, the density energy of the beam is not uniform as the hole becomes deeper. An air nozzle has also been installed for the complete evacuation of the material. The nozzle guides a 5 bar pressure air stream and has been set at a distance of 4 mm from the upper surface of the sheet and forms an angle of 20° measured from the surface normal. Finally, both the scanner and the air nozzle were fixed to a conventional 3 axis CNC machine center. Therefore, the complete programming of the experiments has been carried out using conventional CNC programming. Figure 1 shows the experimental set-up for the drilling process.

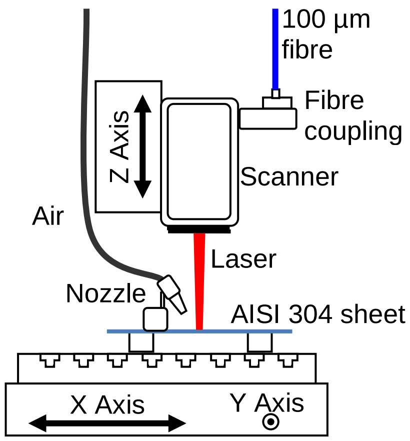


Figure 1. Experimental laser system scheme

The drilling tests have been carried out in a AISI 304 stainless steel 1mm thickness sheet, and the distance between drills has been set to 2 mm, ensuring that each test do not affect the surrounding ones. The composition of AISI 304 is basically 66%-74% of Iron, 0.08% maximum of Carbon, 18%-20% Chromium and 8%-10.5% Nickel, presenting other elements as Manganese or Silicon. The AISI 304 is an austenitic Cr-Ni stainless steel that presents high corrosion resistance, high ductility and excellent formability properties. This stainless steel is mainly used in food and chemical industry. The tests of this work have been carried out on cold formed sheets without any coating and treatment.

The tests parameters have been set to obtain energy density values between 10^7 and 10^8 W/cm^2. Results of related works, shows that vaporization mechanism starts to be the dominant one for this range of energy density. Thus, each laser pulse has been set at a power of 800 W and a duration of 0.3 ms, resulting in a series of pulses of an energy density of $1.02 \cdot 10^7$ W/cm^2 and short enough to ensure that the vaporization mechanism is dominant. In order to evaluate the influence of each pulse in the formation of hole, 10 different tests have been performed with the same parameters, changing only the number of pulses applied to each hole. Thus, the first test consists of a single pulse on the sheet surface, whereas in the last test a train of 10 pulses have been applied to the test part. To ensure that the test results are robust and eliminate possible dispersion, all the tests have been repeated 5 times under the same conditions. Each series was done in a line and each hole was separated 2 mm to avoid the possible influence of the surrounding holes. The results are five lines of 10 holes each, which were measured by microscope. Table 1 shows the parameters of the performed tests and Figure 2 show the scheme of the tests.

Table 1. Experimental tests parameters for laser drilling process

Test run	**Power [W]**	**f [Hz]**	**t_{pulse} [ms]**	**Num. pulses**
1	800	500	0.3	1
2				2
3				3
4				4
5				5
6				6
7				7
8				8
9				9
10				10

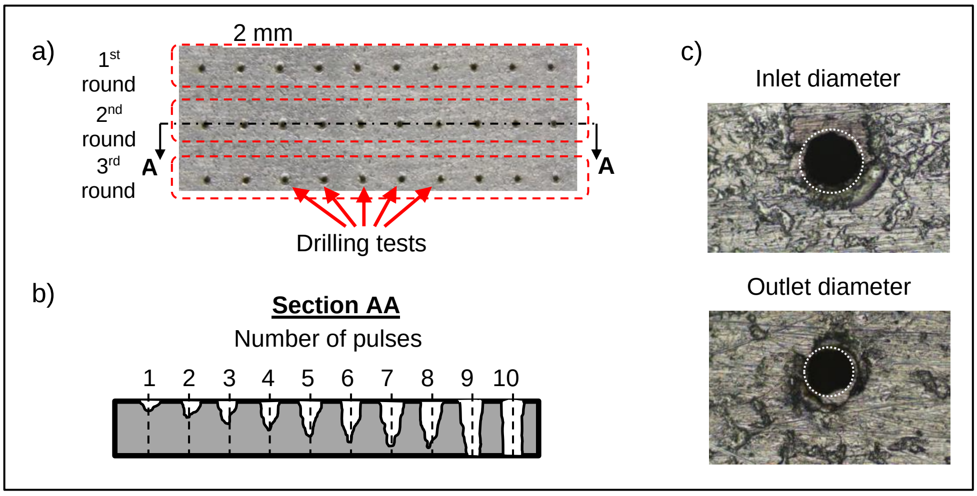


Figure 2. a) Detail of the tests performed on the sheet. b) Section of the holes of one of the rounds. c) Measurement of the inlet and outlet diameter of one of the holes.

Once the tests have been performed, two types of analysis have been carried out. First, the inlet and outlet diameters were measured in order to characterize the holes. Moreover, these measurements have been used also for analyze the dispersion of the results. Second, an analysis of the entire section of the holes was made in order to study its formation. Thus, this analysis has calculated the amount of removed material for each pulse.

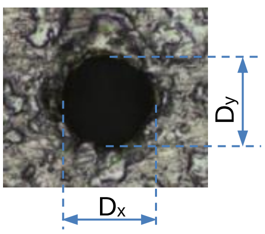
3. TEST RESULTS AND DISCUSSION

3.1 Hole diameter characterization

The measurements of the hole diameters were performed by microscopy. The equipment used was a Leica DCM3D confocal microscope, with an uncertainty of 0,1 microns. Measurement includes both, the inlet and outlet diameters. In order to avoid dispersion, the diameters of the five rounds were measured and the mean value was obtained for each test. The results of the measurements, present very low dispersion, and same range of values of diameters were obtained for all the rounds. In fact, the first 8 tests result in blind holes in all cases, while 9^{th} and 10^{th} tests for the five rounds result in through-holes. Table 2 present the inlet diameters for the first test (corresponding to the single pulse test) for the five repetitions. As it can be observed, the variation of the diameter is below 2.5 % for all rounds. Similar values have been obtained for the rest of the tests. Figure 3 show the inlet diameters of the first 5 tests, corresponding to the tests from a single pulse to a series of five pulses per hole.

Table 2. Measurements of the inlet diameter of the one pulse test for the 5 rounds.

$$Dm = \frac{Dx + Dy}{2}$$



Round No.	Dx (µm)	Dy (µm)	Dm (µm)	Variation
1	138.5	143.3	140.9	2.19%
2	137.2	138.5	137.8	0.01%
3	132.8	139.8	136.3	-1.09%
4	139.3	139.8	139.6	1.25%
5	133.7	135.5	134.6	-2.34%
	Mean value (µm)		**137.8**	

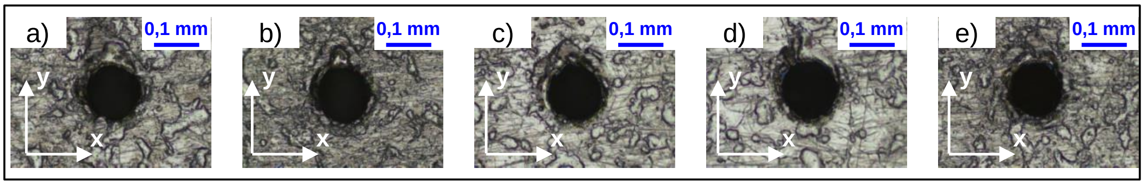


Figure 3. Inlet diameters of a) Single pulse test. b) 2 pulse test. c) 3 pulse test. d) 4 pulse test. e) 5 pulse test.

The mean diameters for each group of holes have been obtained. The results shows that the inlet diameter ranges 150 microns, while the outlet diameter around 115 microns. Results present dispersion below 5% in all cases and the laser drilling process cannot get through the sheet until 9 pulses per hole are used. The mean diameters for all tests are shown on Figure 4, where inlet and outlet diameters are plotted. It can be observed that the inlet diameter is larger than the outlet diameter because of the taper-shape of the holes. This is a typical effect of the laser drilling process due to the material removal mechanism.

Num. Pulses	D_i (µm) Mean value	D_o (µm) Mean value
1	137.8	-
2	144.2	-
3	149.9	-
4	150.1	-
5	147.7	-
6	149.1	-
7	150.9	-
8	145.8	-
9	148.3	113.3
10	145.4	119.3

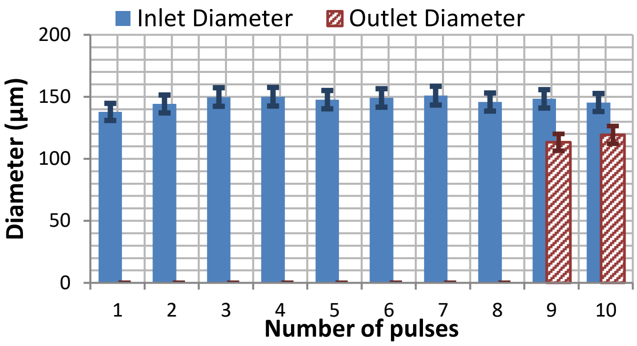


Figure 4. Mean values of inlet and outlet diameters for all the drilling tests.

3.2 Hole internal shape characterization

The internal sections of the holes have been evaluated with the following procedure. First, a WEDM cut has been performed 0.3 mm close to the center of the holes. Then, the cut part has been polished with a 400 grit paper size until the first measuring. Once the sections have been measured, the test part has been polished again with a smoother abrasive (1200 grit size). The reduction of the sample thickness for each polishing operation has been measured with a micrometer. Therefore, the procedure allows the measuring and locating of different longitudinal sections of the holes. Figure 5 shows the scheme of the measuring procedure for each round.

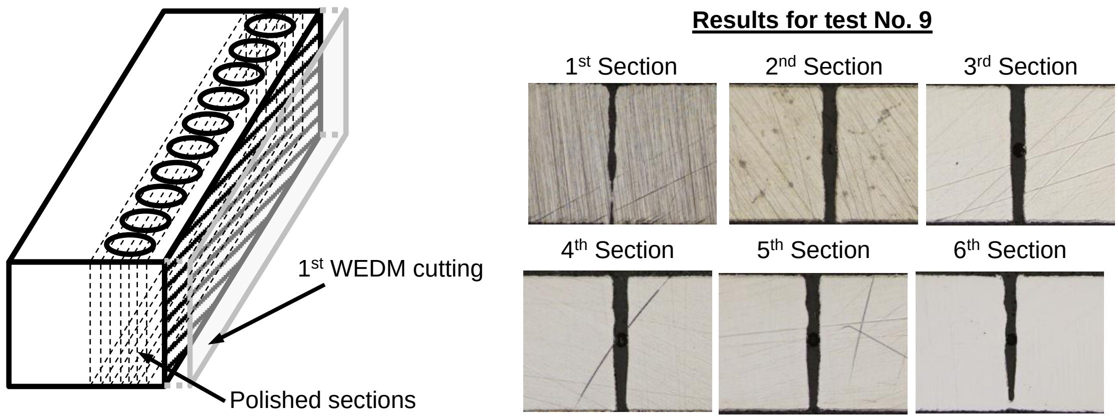


Figure 5. Left) Procedure for the measuring of the internal shape of the holes.
Right) Result of the measurements for a 9 pulse test.

The measurements of the different sections have been used to evaluate the formation of the holes pulse by pulse, evaluating the volume of removed material for each pulse. In order to calculate the volume of each test, the different microscopic photographs of each section have been imported on a 3D CAD software, and the 3D internal shape of the drills have been reconstructed. Figure 6 shows the reconstruction of the test number 9 as an example of the methodology for obtaining the 3D profile of each test.

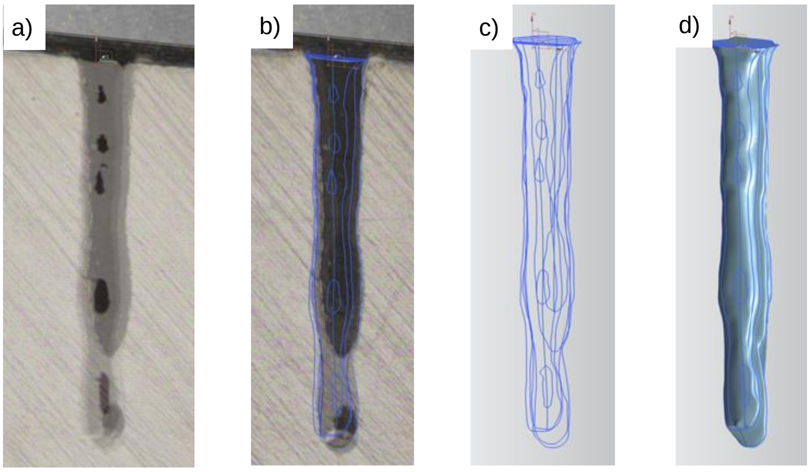


Figure 6. a) Sequence of images of each section. b) Drill profile reconstruction for each section. c) Drill profiles for all sections. d) Reconstruction of the 3D shape of the drill.

More than 100 nodes are taken for the reconstruction of the splines for each section. Therefore, the uncertainty of the reconstruction can be similar to the microscope (0,1 microns). For the complete hole reconstruction, 11 sections are taken for each hole, resulting in a section every 13-14 microns. The exact position of the section has been measured after the polishing of the hole. Thus, the uncertainty between different sections is higher, because of the larger discretization steps. This uncertainty can be only measured on the inlet diameter of the holes and comparing experimental results with reconstructed hole geometries. The errors found in that comparison ranges 1 µm.

Once the 3D geometry of the drills is obtained, the volume of removed material in each test can be evaluated. Figure 7 show the evolution of the removed material per pulse and the accumulated volume for the sequence of 10 pulses. The removed material volume for each pulse has been designated as ∆V, while the accumulated removed volume of material for the sequence of the pulses has been designated as V. The measurement show that the drilling rate decreases as the hole formation goes deeper into the part. The maximum removed volume of material is obtained in the first pulse, where a hole initiation is achieved. The measurement show that the drilling rate decreases as the hole formation goes deeper into the part, due to the difficulty of material evacuation and laser defocusing effect because of the thickness of the part.

Figure 7 show also that the volume of removed material per pulse becomes relatively constant after the 2nd pulse. There is a variation of these rate in the 5th pulse, due to a full vaporization of the material, and internal material resolidified after 4th pulse has been completely removed, increasing the drilling rate.

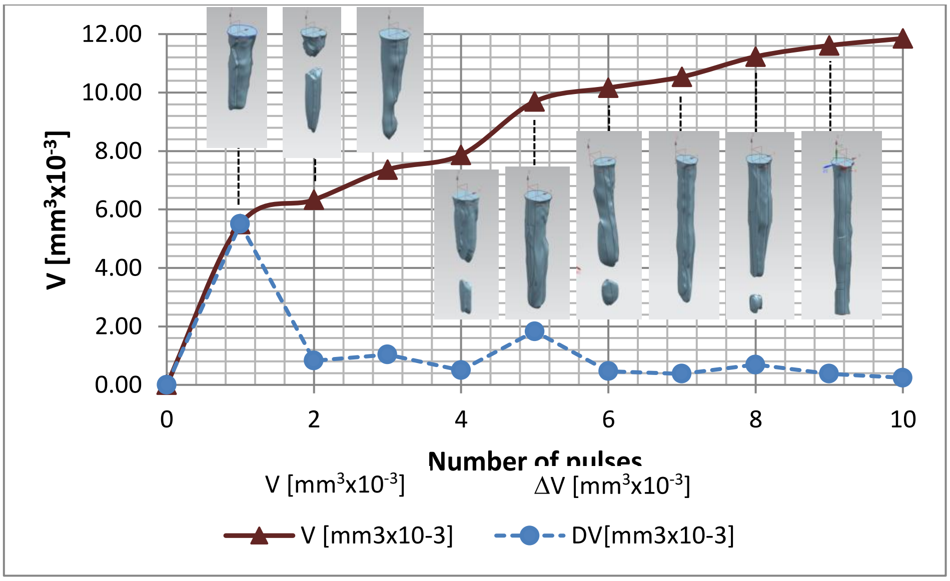


Figure 7. Evolution of the volume of removed material per pulse.

4. NUMERIC MODELLING OF THE LASER PERCUSSION DRILLING PROCESS

With the aim of understanding the process mechanisms and try to explain the experimental results, a numerical model has been developed. This numerical model can predict and explain the experimental results with a reasonable accuracy. The main goal is to predict the final geometry of the holes and set the laser percussion drilling parameters without testing.

The numerical model has been developed as a tool to solve the problem in an approximate way with the minimum number of parameters and computation time. Therefore, it does not take into account the thermo-fluid-dynamic phenomena of molten material into the holes but it considers the thermal problem and that the material is removed by vaporization. This aspect has been verified experimentally. The model presents also some assumptions to simplify the model development and calculation of the removed material:

- The part material is considered continuous, homogeneous and isotropic.
- As it has been mentioned, the mechanism of material removal is vaporization.
- There are no considerations about fluid-dynamic phenomena.
- The thermal model considers the convection and radiation energy within an overall loss coefficient "A".
- The physical properties of the material only depend on temperature.

The numeric model is based on a conventional thermal model, developed and particularized specifically for laser material processing. The complete description of the base model is in [22]. The model is based on the general heat transfer equation (Eq. 1).

$$a \cdot \nabla^2 \theta \pm \frac{(1-A) q_v}{\rho \cdot c_p} = \frac{\partial \theta}{\partial t} \qquad (1)$$

Where a is the thermal diffusivity [m^2/seg], so that $a=\lambda/\rho Cp$, θ is the temperature in [K], q_v the source in [W/m^3], ρ is the density [Kg/m^3], c_p is the specific heat [J/KgK], t time in [s] and A the global looses factor.

The boundary conditions necessary for the differential equation solving are on one hand, the initial temperature condition same as room temperature (Eq.2) and on the other hand, the boundary condition of heat flow in each element (Eq.3).

$$\theta(t=0) = \theta_{room} \qquad (2)$$

$$q_s = q(x_s, y_s, z_s, t) \qquad (3)$$

This thermal model does not take into account the phase transformation from solid-liquid and liquid-vapour. Therefore, in order to incorporate this phenomena and consider the latent heat for the phase transformations, a variable specific heat is considered for the material. Thus, if the temperature of a node is in the phase change range, an extra heat will be needed to increase the temperature of the material. Figure 8 shows the specific heat variation considered for AISI 304 material and the values for some temperatures. This Figure also shows the result of the numeric model application for a percussion drilling operation.

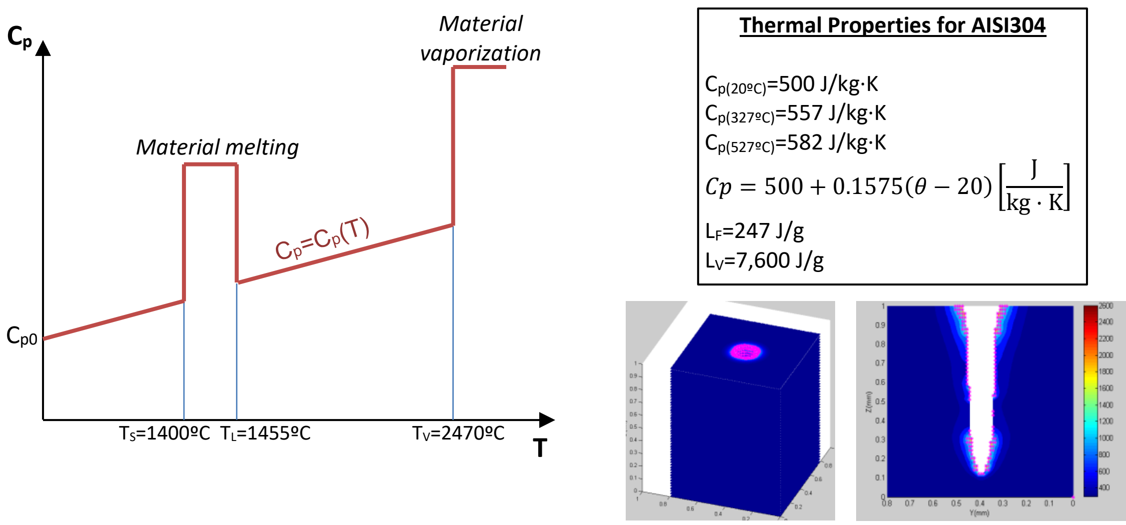


Figure 8. Thermal properties of the AISI304 and variable specific heat for numeric model.

The model has been validated by comparison of two different values. First, the inlet diameter of the hole on the top of the surface and, second, the volume of removed material in each test. The values, showed in Table 3, show a reasonable good agreement, considering that the model neglect any fluid-dynamic phenomena of molten material into the holes. Errors, both in volume or in diameter are always below 10% and the model predicts the hole formation for different pulse sequences. Figure 9 show the section of both, real and simulated tests for different number of pulses. As it can be observed, the results shows that the model can predict the geometry of the holes, including the taper shape of the drills and the number of pulses needed to get a through hole.

Table 3. Model validation: Estimated and measured inlet diameter [µm] and removed material volume [mm^3x10^{-3}].

Num. Pulses	V_{real} [mm^3x10^{-3}]	V_{model} [mm^3x10^{-3}]	Error[%]	Dreal [µm]	Dmodel [µm]	Error[%]
1	5.50	5.95	8.13	137.83	141.15	2.41
2	6.33	5.93	-6.35	144.23	158.23	9.71
3	7.37	6.94	-5.82	149.85	158.23	5.59
4	7.87	7.19	-8.63	150.08	158.23	5.43
5	9.69	10.39	7.15	147.71	158.23	7.12
6	10.16	11.10	9.23	149.09	158.23	6.13
7	10.54	11.70	11.05	150.93	158.23	4.84
8	11.23	12.87	14.56	145.79	158.23	8.53
9	11.61	11.91	2.57	148.34	158.23	6.67
10	11.85	11.63	-1.85	145.43	158.23	8.80

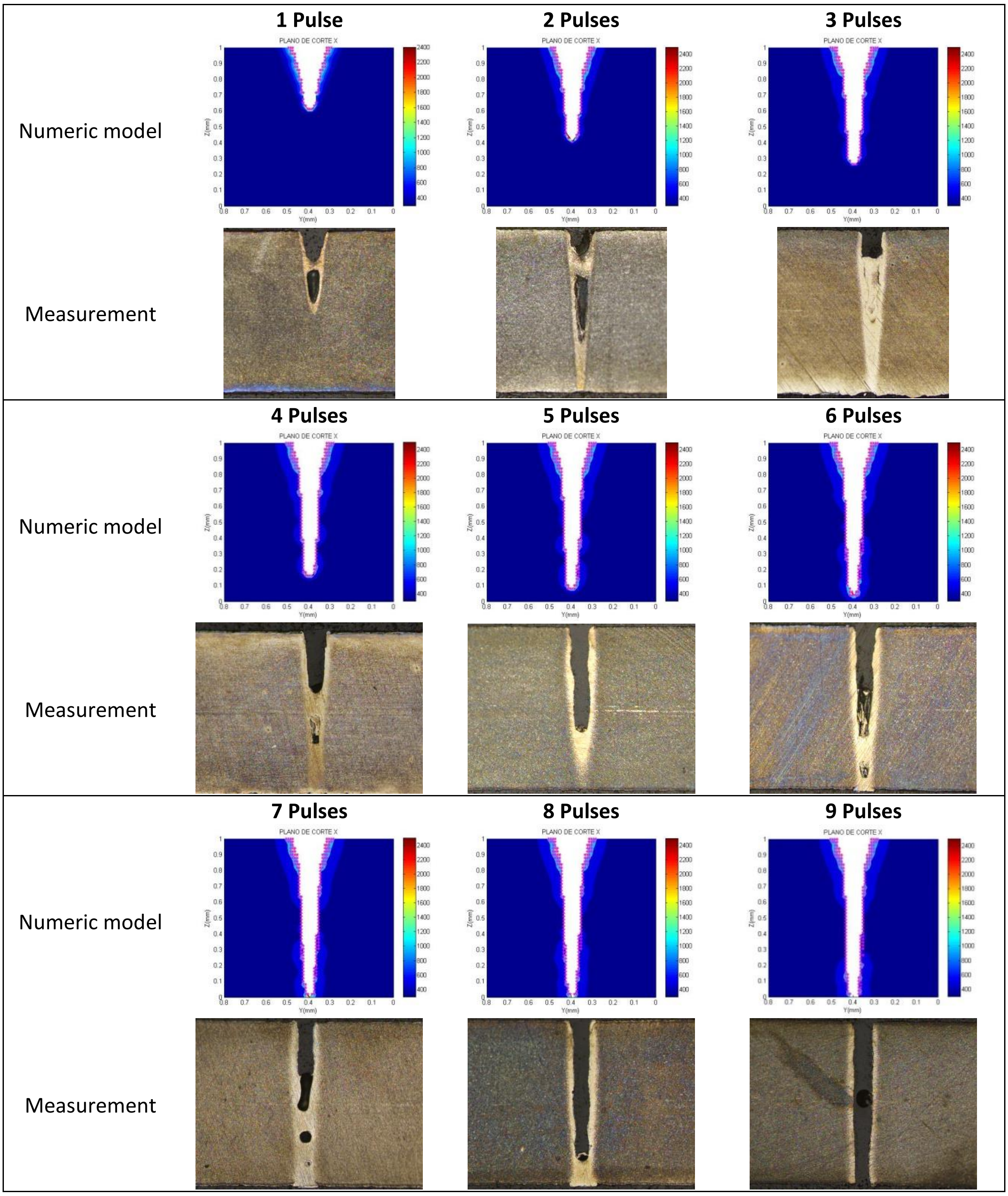


Figure 9. Experimental and predicted sections for different numbers of pulses in laser percussion drilling process

5. CONCLUSSIONS

The present work analyses the hole formation on a fiber laser percussion drilling process. The drilling process has been carried out with a conventional fiber laser on 1 mm thick sheet of stainless steel AISI 304.

In order to evaluate the process, 5 similar rounds of tests have been carried out. 10 drills were performed per round, from a single pulse test up to a sequence of ten pulses. The process has proved highly repetitive, and the obtained holes show excellent circularity both the inlet and the outlet diameters. Despite the optimum focal plane position has been picked out, the drilled holes showed a small taper (2-4º), which is an inherent feature of the laser drilling process. Furthermore, with the aim of analysing the internal geometry of the holes, 3D reconstructions of each test have been carried out by measuring different sections of the drills. These analysis can be used for evaluating the evolution of the hole formation and calculate the removed material volume rate. The internal hole walls showed relatively low roughness and good quality. The presented methodology allows the observation of the resulting internal geometry, including the pulse-by-pulse formation of the holes. It can be observed that some voids due to the drilling process are present before the material break out. The results show that the removed material volume rate decreases for each pulse, because of the laser beam defocusing while the hole becomes deeper. This phenomenon can be very important when determining the maximum drilling depth that a specific laser can reach.

Lastly, a relative simple model has also developed, based on vaporizing of the material, for evaluating the main process parameters. The results of the model show relative good agreement between the real and estimated values of removed material volume and hole diameters, with errors below 10% in all cases. The model also demonstrates that the mechanism of formation of the holes in the laser percussion drilling process is mainly based on the vaporization of the material.

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