Fiber Laser Based Single Pulse Drilling for Production of Perforated Titanium Sheets for HLFC Structures

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In the last years, a new generation of developed laser systems with optic fiber as the active medium, the so-called fiber lasers, have made possible that laser technologies whose precision and quality were not so relevant in the production of micro-perforations now become in high-throughput quality solutions in new fields of application. In this work we present a study of the Single Pulse Micro-Drilling (SPMD) technique for the production of large micro-perforated titanium panels needed in the aerospace industry for developing Hybrid Laminar Flow Control (HLFC) structures at production rates as high as 300 holes per second.
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1. Introduction

In the last years, it has been stablished that the most appropriate fabrication technique to fulfill the requirements of the manufacturing of large skin Ti panels for hybrid laminar flow control (HLFC) in the aerospace industry is mainly the application of pulsed lasers [1, 2]. The HLFC is a technique that prevents the formation of a turbulent boundary layer at the leading edges of the aircraft wings by sucking through the skin surface a small amount of air. With this technology the transition of the boundary layer from laminar to turbulent flow can be delayed and hence skin friction drag reduced [3]. Since skin friction drag accounts for nearly 50% of the total drag of a civil jet transport aircraft in cruise, technologies that enable laminar flow control offer potential for enormous economic and environmental benefit [4].

Nowadays there are two laser techniques that fulfill the high rate production requirements (drilling rates larger than 200 Hz) for the fabrication of micro-perforated Ti sheets for HLFC applications: the percussion micro-drilling (PMD) [5] and the single pulse micro-drilling (SPMD) techniques [6, 7]. Here we focus on the SPMD technique. In this technique, a pulsed laser with pulse width in the order of hundreds of microseconds is focused on a Ti sample. Then, a hole is produced by sending one single laser pulse. By applying a constant speed to the laser head and setting a certain pulse repetition rate for matching the required hole pitch (hole separation), a line of micro-holes is produced. An X-Y gantry then makes a matrix of holes by drilling several lines. The resulting pitch in the line is a convolution of the head speed and the pulse repetition rate.

Although the SPMD technique presents different advantages compared to the PMD as better scalability and hardware simplicity [8], it however requires the focus point of the laser beam to be accurately and repeatably located at the surface of the Ti plate, or at a predetermined distance from the surface. Typical specifications of the micro-hole diameters at the beam entrance and exit are 95-110 µm and 55-70 µm respectively depending on the final HLFC requirements. In case of deviations of the distance between the focus point and sample surface, the holes produced are not identical and hence do not comply with the requested tolerances of only a few micrometers for HLFC (usually standard deviations smaller than 5 µm are required for the diameter of the micro-holes in a Ti plate). Thus, an active control of the height of the laser head over the entire Ti panel during the production of the micro-holes is necessary. It is worth noting that both techniques (PMD and SPMD) meets the requirements of the HLFC applications regarding production rate, requested hole diameters and standard deviations [6]. The main differences have to do with the material removal process and the implications that these characteristics have in the hardware needed as well as the way to manage the suction of the expelled material. In the PMD technique a conventional galvoscanner with a suitable chamber creates an array of holes. Micro-drilling an entire panel is achieved by moving stepwise to a different area. On the contrary, in the SPMD technique the micro-drilling is carried out "on the fly" with a conventional cutting head. Whereas in the PMD the removed material is expelled from the upper side of the sample, in the SPMD technique due to the assist gas for creating a local inert atmosphere, part of the removed material is also expelled from the bottom side once the sample has been perforated. This causes not only burrs at the top but also at the bottom. In the PMD the burrs are located only at the entrance side but because of the larger energies needed for drilling and the larger amount of melted material deposited at the entrance side, more thermal stress is transferred to the Ti panel and hence, more bending of the panel is obtained. In general both techniques need of further mechanical and/or chemical postprocessing for the application of HLFC but whereas the PMD for the HLFC has been investigated by different groups (see for example [3] and [5]), the SPMD using the new generation of high energy pulsed fiber lasers is still far from being sufficiently reported.

Here we present a complete study of the laser SPMD technique with active control of the working distance for obtaining reproducible results. In particular the influence of both the position of the lens focus on the sample and the assist gas pressure have been investigated. In addition, a complete characterization of the drilled holes with automatic measurement is presented.

2. Experimental Setup

In order to achieve a fast and precise movement of the laser head on the Titanium sample, a computer numerical control (CNC) machine built in IK4-Tekniker has been used. This machine achieves positioning accuracy of 8 microns at a maximum speed of 100 m/min. The axes have been equipped with linear motors and allow a displacement of 650 x 830 x 360 mm (XYZ). Fig.1 shows a picture of the CNC machine developed.

Fig. 1 Home-made CNC machine used in this work.

Regarding the laser source, a cw fiber laser with emission at 1070 nm has been used. The peak power of this laser is 1.5 kW. Pulses are obtained by modulating the pumping diodes through an external signal provided by the FPGA. The pulses sent to the laser in the modulation signal have 200 µs width. The repetition rates of the pulses determine the drilling rate since in the SPMD technique only one pulse produces a single micro-hole. In this study we present results at 300, 500 and 700 Hz. As laser head, we have used a conventional cutting head with a 100 mm collimator and a 150 mm focusing lens. Fig. 2 shows a picture of the used laser head. To protect the focusing lens and the optical window as well as both to cool down the interaction zone and eject the material removed in the micro-drilling process, assist gas has been provided. We have used Ar at a nominal pressure of 18 bar. In addition, the effect on the diameter of the micro-holes of decreasing pressure have been studied.

Ti grade 2 panels with a thickness of 0.8 mm have been used as a target material in this study. In fact Ti is the most suitable material for the HLFC technology [9] and 0.8 mm is the typical thickness required for the construction of HLFC structures for the leading edges in the aircrafts.

As shown in the results provided in this study, the fabrication of micro-holes requires a constant separation between the sample and the nozzle of the head. Typical deviation in the flatness of Ti samples can be as large as 500 µm and therefore a precise height control is necessary. We have used for this task an Eddy current sensor and a qualitative sensing of the backscattered radiation of the laser by means of photodiodes and optical fiber. These developments allow us to control the height in real time with an accuracy of ±50 µm. In fig.2, the position of the Eddy current sensor as well as the arrangement of optical fiber and photodiodes are shown.

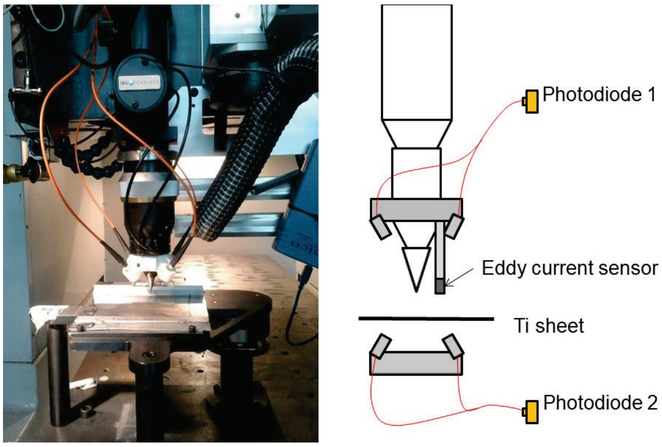

Fig. 2 Left: Laser head. Right: Diagram of the sensors used for controlling the process

3. Experimental results

Below we show the experimental results according to three types of study that have to be carried out in order to give a solution to the requirements of micro-perforation for the development of panels for HLFC: a parameterization of the diameter of the holes with respect to the position of the optical system, with respect to the pressure of the assist gas and finally a complete characterization of the micro-holes.

3.1 Hole diameter vs focus position

In the SPMD technique, the most important parameter to determine the diameter of the holes at the beam entrance and exit in the sample is the position of the focus with respect to the sample. In fig.3, this dependence is shown. In the graph, the zero position has been chosen to match the typical requirements of the hole diameters for the HLFC application, i.e., beam entrance diameter of 105±10 µm and beam exit diameter 60±5 µm. Our focus position measurements indicate that the beam waist is on the surface of the sample at the -0.3 mm position. Hence, the position 0 mm means that the beam waist is 0.3 mm below the sample surface. At lens positions larger than 1 mm, the Ti sheet is not perforated.

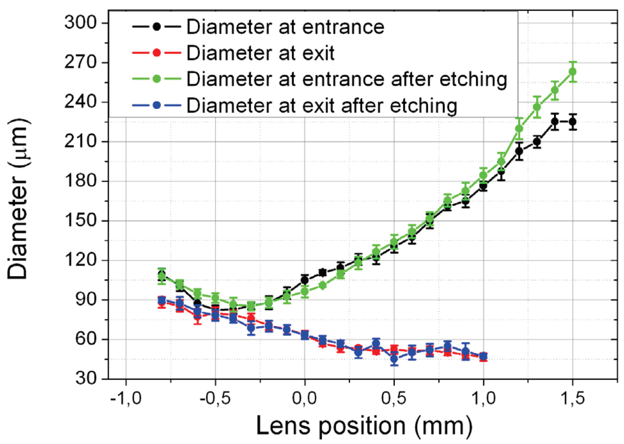

Fig. 3 Diameter of the micro-holes at the beam entrance and exit as function of the lens position. The curves after mechanical and chemical post-processing for removing burrs and debris have been also added

Unlike other laser processes dominated by ablation effects in which shorter pulses are used, in the SPMD process the material is mainly melted. While the drilling process is being carried out, the gas expels the material removed at the upper side of the sample. Once the perforation of the Ti sheet is achieved, the material is pushed through the lower part. This results in burrs and debris at both top and bottom of the sample. While at the upper part the material is spread by the gas assist, at the lower part the material is mostly deposited at the edges of the hole. Therefore mechanical and chemical post-processing of the sample are needed in order to use the micro-perforated panel for the HLFC application. In fig. 4, we show pictures of the sample micro-drilled at lens position 0 mm before and after post-processing (polishing and etching).

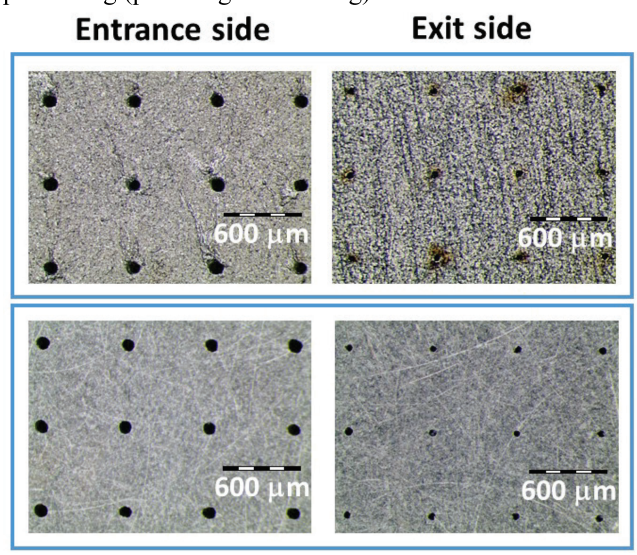

Fig. 4 Pictures of the sample micro-drilled at lens position 0 mm before and after post-processing. Upper row: sample after laser micro-drilling. Lower row: sample after polishing and etching

In fig.3, the curves with the diameters at the beam entrance and exit after a polishing and chemical etching process of 5 µm are also shown. Except at lens positions in which micro-perforation is not achieved, the mechanical and chemical post-processing does not substantially modify the diameter of the holes obtained with the laser process but completely removes all the burr and debris.

3.2 Gas pressure dependence

As mentioned in the previous section, the main role of the assist gas is to remove the material during the process, to cool down the process area and to protect the optical system. That is why it has an influence on the hole diameters that this technique can achieve. The nominal pressure in our experiments has been 18 bar but in order to modify costs in a future industrial process, it is desirable to minimize the gas consumption by decreasing the pressure. In fig.5 we show the diameter of the micro-holes at 0 mm lens position as a function of the gas pressure.

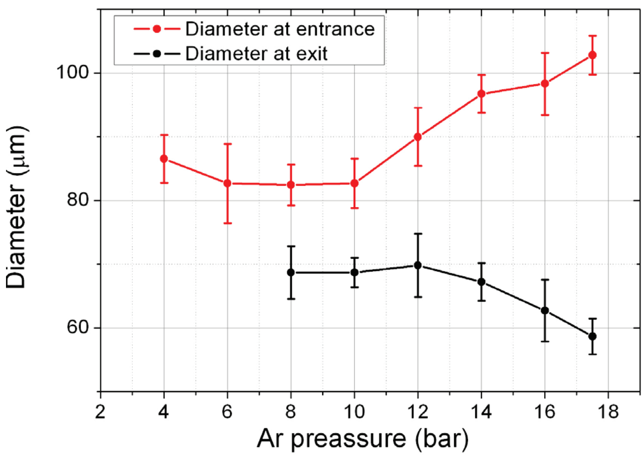

Fig. 5 Diameter of the micro-holes at the beam entrance and exit as function of assist gas pressure.

Below 8 bar, perforation of the Ti sheet is not achieved. This pressure establishes a limit for the mimimum pressure in order to micro-drill a Ti sheet with reduction of the Ar consumption. As shown, while the diameter at the beam entrance decreases by reducing the gas pressure, the diameter at the beam exit increases. This might be explained in terms of a lower force to eject the material removed at the top of the sample and a lower cooling effect for the solidification of the melted material at the bottom. In any case, for the correct manufacture of panels for HLFC we note that the pressure has to be maintained constant to obtain reproducible results across a panel with millions of holes.

3.3 Micro-hole characterization

The requirements demanded by the aeronautical industry for the manufacture of micro-perforated Ti panels are very challenging. Typically, tolerances of less than 5 µm are required for the diameters of all the holes in panels as large as 5 x 2 m. It is for this reason that parallel to the development of the laser process, it is necessary to develop an automatic measuring system that allows a characterization of all the holes. A measure of the obtained diameters also constitutes a feedback for the development of the laser process. In addition, regarding processing Ti, the formation of fragile phase alpha-case is not allowed at all, so an additional characterization that ensures the absence of oxygen during laser processing is necessary. Fig. 6 shows a cross-section of a group of micro-holes. Metallographic studies have ruled out the formation of an alpha-case layer in the walls of the holes. The picture also reveals that the micro holes are not perfectly conical. A trumpet shape appears close to the hole edges. This means that one has to take this effect into account to match the result of the laser process with the most optimal diameters as specified by theoretical models for the HLFC application. Since the pressure drop tests for validating the panel for the HLFC application are mostly sensible to other issues as deviations of the diameters in the sample and percentage of blocked holes, the trumpet shape obtained do not play any relevant role for these tests.

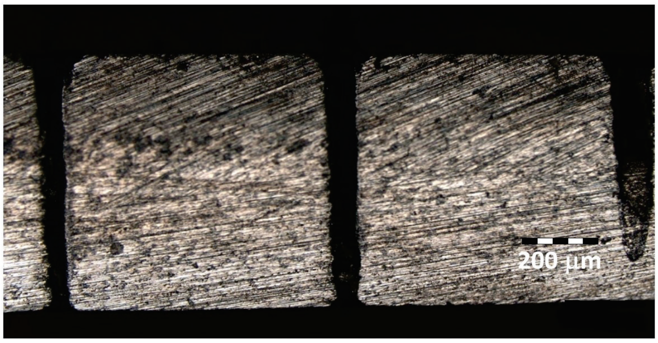

Fig. 6 Cross-section of a group of micro-holes. No alpha-case layer formation has been detected in the hole walls.

Fig 7. shows the front panel of a home-made application developed for the automatic measurement of micro-holes. This application is able to measure the diameter of groups of 14-16 holes and obtain the statistical information. A panel of 5 x 2 m contains more than 10^7 micro-holes. Therefore, an automatic measuring tool is necessary. In fig.6, on the left side, our application shows the capture of a micro-drilled area with 14 holes. On the right side, the software shows the holes detected in the image and then, measures the diameters. In this way, it is possible not only to obtain the statistical information in order to compare with the requirements for the HLFC application but also to register the particular diameter for each hole in the Ti panel.

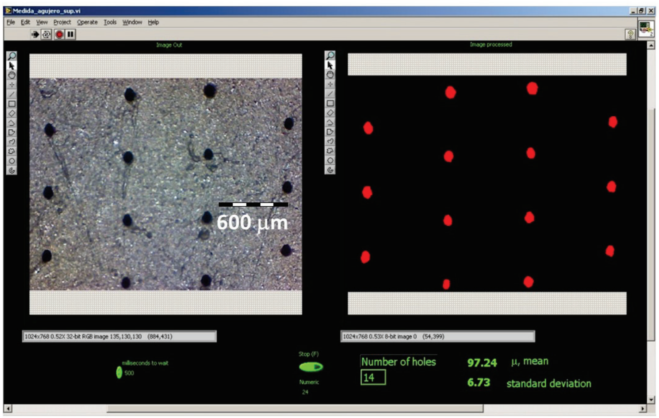

Fig. 7 Front panel of the developed software for measuring the diameters of the holes automatically and obtaining statistical information.

In fig. 8 we show pictures of the micro-holes made at rates of 300, 500 and 700 holes/s, where D is the diameter at the beam entrance and d the diameter at the beam exit. Higher production rates are achieved by increasing the pulse repetition rate of the laser and enhancing the speed of the laser head in order to match the requested hole pitch. However, we note that when using an "on the fly" strategy, the shape of the hole strongly depends on the relative movement of the laser head during the laser pulse duration and hence, when this movement is in the same order of magnitude as the diameter of the hole, no longer a circular shape can be expected. Only shortening the laser pulse while maintaining the pulse energy would allow to increase the drilling rate. As shown, with our laser source at rates greater than 300 holes/s the shape of the hole at the beam entrance is no longer circular but elliptical. Dx denotes the diameter of the major axis and Dy that of the minor axis. At the beam exit, however, we were unable to resolve an elliptical shape for the hole within the measurement error. We can conclude that whenever a circular shape is not required for the beam entrance (which in the application of HLFC is not really important since it is located on the side of the suction chambers) production rates up to 700 holes/s are possible with the laser SPMD technique. Otherwise the highest production rate should be established at 300 holes/s.

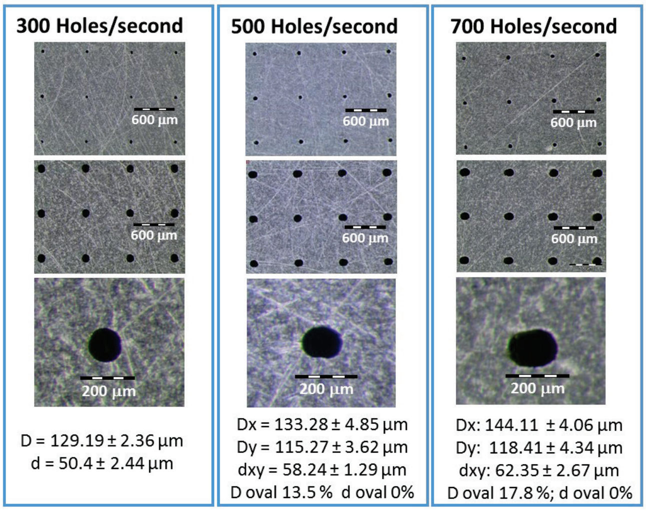

Fig. 8 Measurements of micro-holes produced at rates of 300, 500 and 700 holes/s. Pictures at the top row: Exit side. Pictures at the central row: Entrance side. Pictures at the bottom row: detailed view of a hole at the entrance side

This characteristic is maybe the most remarkable feature of the SPMD technique versus the PMD technique. The PMD technique been demonstrated up to a maximum rate of 300 holes/s with similar quality characteristics [5]. In fact, in the PMD technique, the performance of the machine axis for microdrilling a panel stepwise with arrays of microholes has to be taken into account for calculating the real micro-drilling rate whereas since the SPMD technique uses an "on the fly" strategy, the real micro-drilling rate is set by the pulse repetition rate of the laser. This represents an advantage for scaling the process in a real industrial environment with panels as large as 5 x 2 m. Also further improvements in the fiber laser source by shortening the laser pulse and maintaining pulse energy should help in achieving higher production rates with circular shape at the beam entrance for the micro-holes.

4. Conclusions

The SPMD laser technique allows fabrication of micro-holes on Ti panels for HLFC structures at rates up to 700 holes/s whenever a circular shape is not required for the beam entrance. The circular shape of the beam entrance is lost at rates larger than 300 holes/s and therefore this rate should be considered as the highest one for obtaining circular micro-holes within a measurement uncertainty of 5 µm. By adjusting the lens focus position, different diameters for the beam entrance and exit can be achieved in order to fulfill the particular requirements of the HLFC application. Here we have presented a parametrization of the diameter at the beam entrance and exit as function of the lens position for the particular optical system used. The gas pressure has an influence on the diameter of the micro-holes. At pressures below 8 bar no perforation of the Ti sheet is obtained and above it a dependence has been measured. Finally, a description of the methods for characterizing the micro-holes has been provided.

Acknowledgments

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