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Monitoring micro-drilling of large Ti plates using single laser pulses for HLFC applications

Roberto Ocaña[a,*], Carlos Soriano[a], Jose I. Esmoris[a] and Rafael Sánchez[b]

[a]*Advanced Manufacturing Technologies Unit, IK4-Tekniker, 20600 Eibar (Spain)*
[b]*Technological Development Department, Aerometallic, 50500 Tarazona (Spain)*

Abstract

The laser single pulse drilling (SPD) is a very promising technique for the construction of hybrid laminar flow control (HLFC) structures for the aerospace industry. However there are numerous issues that have to be addressed before this technique can be applied in industrial production. The requested characteristics of the micro-holes in a Ti panel for a HFLC structure are quite demanding. A typical panel with size 2 x 5 m containing more than 24 million of micro-holes must fulfill a standard deviation for the diameters less than 10 µm at the beam entrance and 5 µm at the exit. Here we have studied the main aspects that govern the laser process at a stable production rate of 300 holes per second. For this, not only in situ monitoring techniques but also off-line measurement systems have been developed. The results provide a feedback for the laser process in order to fabricate large Ti panels.

Keywords: laser drilling; single pulse drilling; HLFC; micro-holes; monitoring micro-drilling;

1. Introduction

Nowadays, pulsed lasers are the most appropriate fabrications tools to fulfill the requirements of the manufacturing of large skin Ti panels for hybrid laminar flow control (HFLC) in the aerospace industry (S. Williams, 2004). The HFLC is a technique that prevents the formation of a turbulent boundary layer in the leading edges of the aircraft wings by sucking a small amount of the air of the external flow through the skin surface. With this procedure the transition of the boundary layer from laminar to turbulent flow mechanisms can be delayed and hence skin friction reduced (Trevor Young et al., 2003). Since skin friction drag accounts

* Corresponding author. Tel.: +34-943-206-744; fax: +34-943-202-757.
E-mail address: roberto.ocana@tekniker.es .

for nearly 50% of the total drag of a civil jet transport aircraft in cruise, technologies that enable laminar flow to be maintained offer the potential for enormous economic and environmental benefit (Schrauf G. 2005).

There are basically two laser techniques that fulfill the requirements for the fabrication of micro-perforated Ti plates for HLFC applications: the percussion micro-drilling (PMD, A. Stephen et al. 2014) and the single pulse micro-drilling (SPMD) techniques (H. Uchtmann, 2017). In this latter technique, a laser that provides pulses in the order of hundreds of microseconds is focused on the Ti plate and a hole is produced with one single laser pulse. By applying a continuous movement to the laser head and setting a pulse repetition rate, a line of micro-holes is made. An X-Y gantry then makes a matrix of holes by drilling several lines. The pitch (hole separation) 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, it 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. In case of deviations, the holes produced are not identical and hence do not comply with the requirements in tolerances of only a few micrometers (usually standard deviations < 5 µm are requested for the diameter of the micro-holes in a Ti plate) for HFLC. 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. Here we use an Eddy current sensor measuring in advance of the nozzle together with an electronic control with data buffer at high sample rate for applying corrections to local deviations of the separation between the nozzle and the sample at the working point. Furthermore, we also present a monitoring system with photodiodes and a bundle of fiber optic 4:1 with a narrow filter that capture the scattered light of the laser at the hole entrance and exit. This system detects local deviations of the expected performance and allows to save the signal characteristics of all the micro-holes performed in a Ti panel. In order to obtain measurements of the hole diameters an automatic software tool has been developed. Thus, a correlation with the overall quality of the micro-drilled panel can be established.

2. Experimental setup

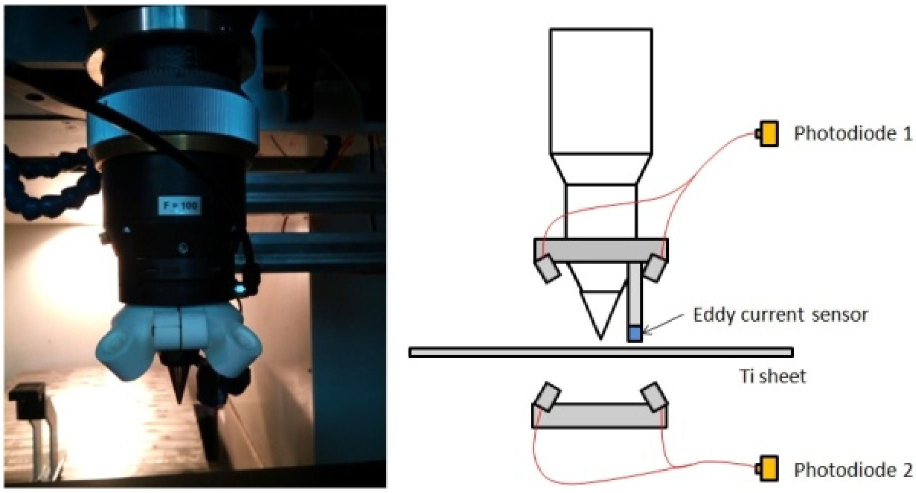

Fig. 1. Laser head for SPMD with attached fiber ports and photodiodes and Eddy current sensor

In fig.1 we show a diagram of the experimental arrangement for measuring the backscattered light of the laser beam at the top and bottom surface of a sample and a picture of the current arrangement in a laser head. The main characteristic that has been taken into account for the design of the tool is to capture symmetrically the scattering light of the process regardless of the movement direction. To that end, a bundle of 4 optic fibers 1:4 has been used. One side of the bundle has 4 fiber outputs that have been symmetrically placed around the laser head nozzle using a custom made adapter. The remaining fiber output of the bundle is attached to a photodiode with an embedded transimpedance amplifier. The photodiode sensor is a Si detector with sensibility in the range from 350 to 1100 nm. A filter placed between the fiber output and the photodiode sensor only permits light at 1070 nm wavelength and 5 nm spectral width to reach the sensor surface. In addition a neutral density filter adjusted to avoid saturation and to enable a clear capture of the voltage signal acquired has been used. A similar arrangement has been made to measure the scattered laser light at the bottom surface by using a second photodiode detector with same spectral filtering characteristics and an adapted neutral density filter to avoid saturation at the intensity levels recorded at the bottom of the surface (see fig. 1).

The processing fiber laser used is a single mode quasi continuous laser source with a maximum peak power of 1.5 KW. The set pulse length was 200 µs. The laser output is collimated with a 100 mm collimating unit and attached to a conventional cutting laser head with a 150 mm focusing unit. A home made three linear motor axis machine with a 1 µm precision and travel distance of 650 x 850 x 400 mm (X, Y, Z) has been used for positioning the laser head over the samples.

The SPMD technique requires a constant working distance in order to reproduce the drilling characteristics across the entire area of the sample. We note that small deviations in the working distance of only 50 µm can produce changes in the micro-hole diameters of around 10%. As the Ti sheets that are going to be micro-drilled are not perfectly flat and deformations of more than 50 µm cannot be ruled out, precise control of the working distance is necessary. This is carried out by means of a home-made Eddy current sensor with measurement accuracies below 10 µm. This sensor has been placed in the structure that holds the fiber outputs symmetrically in the head and senses the distance to the Ti plate in front of the nozzle in the direction of movement of the head (see figure 1. right). A closed-loop control ensures that the working distance remains constant with a rapid response at speeds of up to 20 m/min. The nozzle has 1 mm diameter. Assist Ar gas flow at 18 bar pressure has been also applied.

3. Results

3.1. SPMD process height control with Eddy current sensor

One of the key parameters in the SPMD process that needs to be controlled for micro-drilling a Ti plate with holes of the same dimensions is the height of the head on the sample. On the one hand, working as close as possible to the Ti sheet helps keep the Ar flow focused on the hole while minimizing its consumption, but on the other hand, working very close could result in plugging the nozzle due to the expelled material during micro-drilling. In our experiments we have determined that the most optimal working distances are in the range 0.8 mm to 1.4 mm using a 1 mm diameter nozzle. The distance used in the experiments shown here is 1 mm. Since the Ti plates are not perfectly flat, a method is needed to permanently ensure that the distance between the nozzle and the sample is maintained at 1 mm. For this we have used a current Eddy sensor measuring ahead of the working point along with a control and storage electronics that allows correcting the local deformations of the sheet. In contrast to optical sensors, the Eddy current sensor is not affected by the optical radiation of the process. However, it could be affected by disturbances of local magnetic fields due to the passage of magnetic particles expelled from the process. Being an electromagnetic sensor, it needs to be calibrated for the metallic material whose distance needs to be evaluated. In our case the sample is a grade 2 Ti sheet that has to be micro-perforated. In Figure 2 we show the calibration performed to the sensor.

As shown, there is no influence of ferromagnetic or paramagnetic effects that can cause some hysteresis effect. The results show a linear behavior that can be fitted with a linear regression with R^2 = 0.99912. This, on the one hand, helps to develop a simple PID process as control strategy in order to correct possible deviations from the established height and on the other hand, it allows determination of the working distance in real time. The deformations of a Ti plate of large dimensions (typically 5 x 2 m for HLFC applications) are not locally abrupt but can be extended over several hundred millimeters due to the weight of the sheet itself. Maximum deformations expected are in the order of hundreds of microns. The convolution of the extension of deviations and the working frequency of the control electronics determine the maximum speed at which the micro-drilling process can be carried out. In our experiment, head speeds of up to 25 m/min have been reached with a control degree of less than 20 microns. These characteristics are sufficient for a typical micro-drilling of a large Ti sheet for HFLC application with a hole separation (pitch) of 650 µm at 300 holes/s and at 11.7 m/min speed of the laser head.

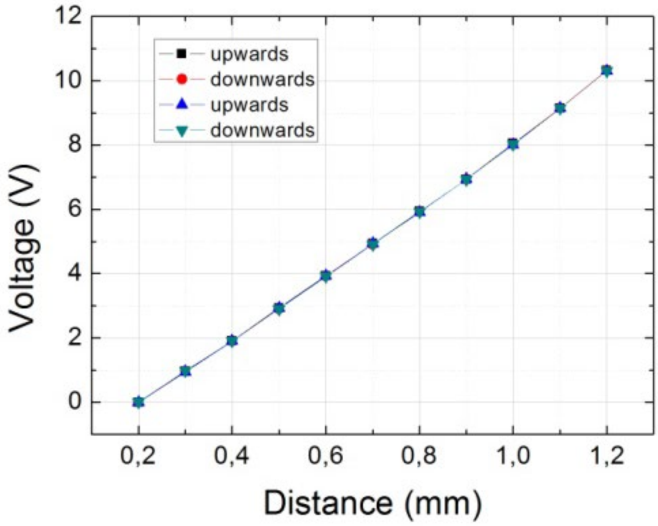

Fig. 2. Calibration of the Eddy current sensor in front o a 0.8 mm Ti sheet. The curves show no hysteresis behavior.

As previously mentioned, the use of Eddy current sensors offers excellent results since the sensor are not influenced by any other electromagnetic effect from the SPMD process. However there are other issues that need to be addressed to ensure reliability when micro-drilling large panels. In fact, during the drilling process part of the material is expelled upwards and then pushed laterally by the assist gas. This causes part of that incandescent material to deposit on the walls of the Eddy current sensor and another part to pass underneath. To prevent deposition of material, a dedicated cross jet has been developed that uses compressed air at 7 bar. On the other hand, it has been proven that the expelled material passing under the sensor has no influence on the distance measurement.

The sensor is located outside the working point of the laser but in front of the direction of movement of the head as shown in fig. 1. This has the disadvantage that the measurement cannot be carried out simultaneously at the point in which the laser is micro-drilling. However, control electronics with a buffer that takes into account the distortions of the sheet at the processing point, is sufficient to ensure constant distance between the nozzle and the sample. A lowpass filter with cutoff at 1 Khz has also been implemented to rule out mechanical vibrations of the system due to the accelerations and decelerations in the displacement of the laser head.

3.2. Monitoring SPMD process with photodiodes

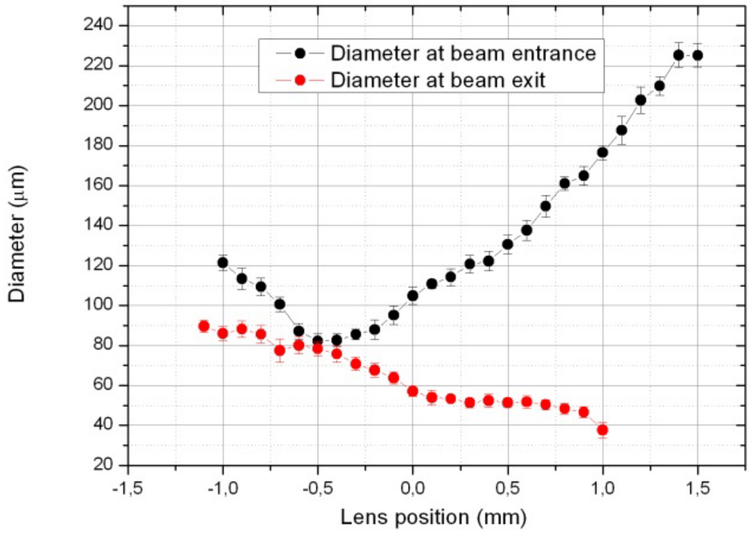

Fig. 3. Diameter at the beam entrance and exit as a function of the lens position.

As mentioned in the previous section, the SPMD process is very sensitive to changes in the distance between the optical system and the sample. This not only affects the distance between the nozzle and the sample (i.e., the distance between the head and its optical system with the sample) that is controlled by the Eddy current sensor but also the relative position of the beam waist after the focusing lens with respect to the sample. In our system, the latter is controlled by a ring that allows an adjustment of the focusing lens. In Fig. 3 the adjustment effect of the lens position on the diameters of the micro-holes is shown. The 0 mm position means that the beam waist has been placed on the surface of the Ti plate. By adjusting the position of the lens and keeping the separation between the nozzle and the sample constant, we can change the diameter of the holes following the curves of the fig. 3. A similar effect on the diameter of the holes occurs by modifying the gap between nozzle and sample. The manufacture of micro-drilled panels for HLFC requires of specific diameters for the set of the holes of the panel with tolerances smaller than 5 microns. This requirement implies that all the control and monitoring strategies have to be carried out on each of the manufactured holes and not only statistically for all the manufactured holes. Monitoring with photodiodes provides a solution for the control of all holes manufactured.

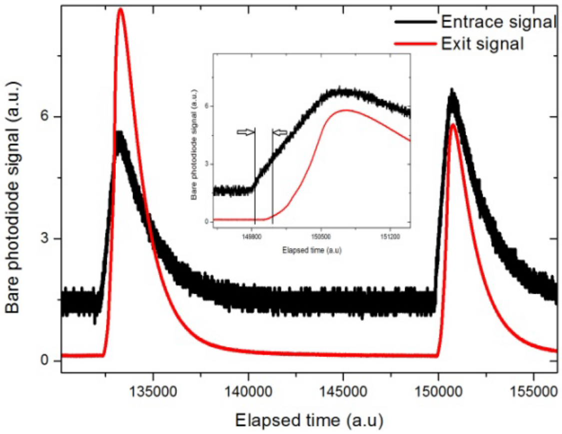

Fig. 4. Bare photodiode signal as function of the elapsed time. In the inset a zoom of the second peak has been performed in order to show the delay between the signals at the beam entrance and exit

In fig. 4 we show the signals collected for two holes made at a rate of 300 holes per second. The black curve shows the capture made by the bundle of 4 optical fibers at the top of the sample whereas the red curve shows the signal from the bottom. The amplitude of the peaks measured depends on the lens position and the distance between the nozzle and sample but also on local effects that could influence the formation of the hole. As expected, both signals are out of phase by a delay. This delay is due to the formation of a micro-hole. At the pulse beginning, most of the laser radiation is absorbed but a part is diffusely scattered by the Ti sheet and recorded by the upper photodiode. Only when the sheet is fully penetrated by the laser beam, the lower photodiode detects radiation. Hence, the measured delay of the signals might be related to the time needed for the laser beam to drill a hole in the sheet for a certain processing parameters. The inset of fig. 4 shows a zoom of the area in which a laser pulse starts. The arrows show the delay between the start of the signal at the laser entrance and exit.

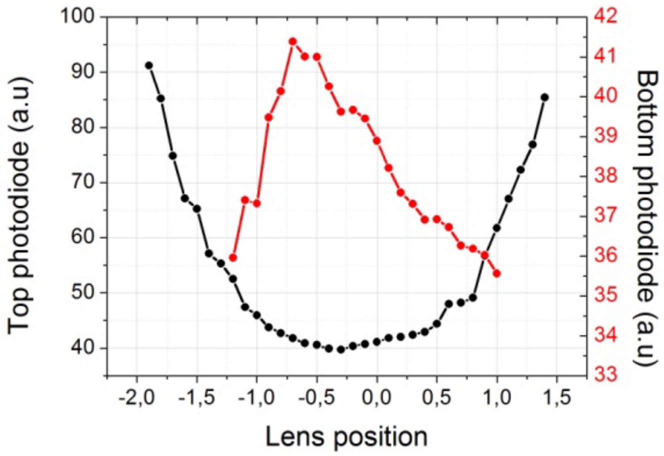

Fig. 5. Photodiode integrated signal as function of the lens position.

The integration of the signals is shown in fig. 5. The red curve contains the signals measured with the lower photodiode, while the black curve represents the signals measured with the top photodiode as function of the focusing lens position. Each point of this graph represents the integration of the signal over ten holes. As shown, the lower photodiode shows a significant sensitivity to changes of the lens position (and therefore to changes in hole diameters) in the range from 1 to -0.7 mm. Below this interval, the behaviour shows a maximum and then the signal drops abruptly down to the position -1.2 mm. Below this position full perforation of the Ti plate is no longer achieved. The upper photodiode shows a smoother behaviour especially in the range from -1.2 to 0.9 mm with a minimum at -0.4mm. In the ranges from -1.9 to -1.2 and from 0.9 to 1.4 mm, the upper photodiode presents larger slopes but complete perforation of the sheet is not achieved.

As discussed, the slope of the curves could be related to the sensitivity of the measurement in the framework of a monitoring strategy. In our case the requested diameters of the entrance and exit holes for the manufacture of micro-drilled Ti panels for HLFC required a lens adjustment around the 0 mm position. In this zone, the absolute value of the slope of the lower photodiode is larger than that of the upper photodiode. This means that it will provide more sensitivity to both uncorrected distortions of the sheet and other effects that may lead to incorrect diameters. This system provides alarm signals in real time during the manufacture of micro-drilled Ti panels if the values are outside a pre-established range and can save the signals for each manufactured hole. Therefore, a subsequent analysis of the characteristics of the fabricated panel is also possible.

3.3. Off-line diameter measurement system

The last aspect for obtaining a complete description of the laser process is to measure all the micro-holes performed. For this, we have developed an automatic machine vision system that is able to measure each hole on the Ti plate. The system consists of a usb-microcospe that is attached to the machine axis. The height control with the Eddy current sensor is now used to maintain the microscope focused on the panel regardless of the deformation of the plate. The camera of the microscope has a LED ring that provides illumination of the front field. However a different adjustment of the camera settings allows to measure the light passing through the holes by placing an additional illumination source behind the panel. In this way not only the diameters are measured but also blocked holes can be detected.

Fig. 6 shows the front panel of our home-made application. The software is able to measure the diameter of groups of 14-16 holes and obtain the statistical information. 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.

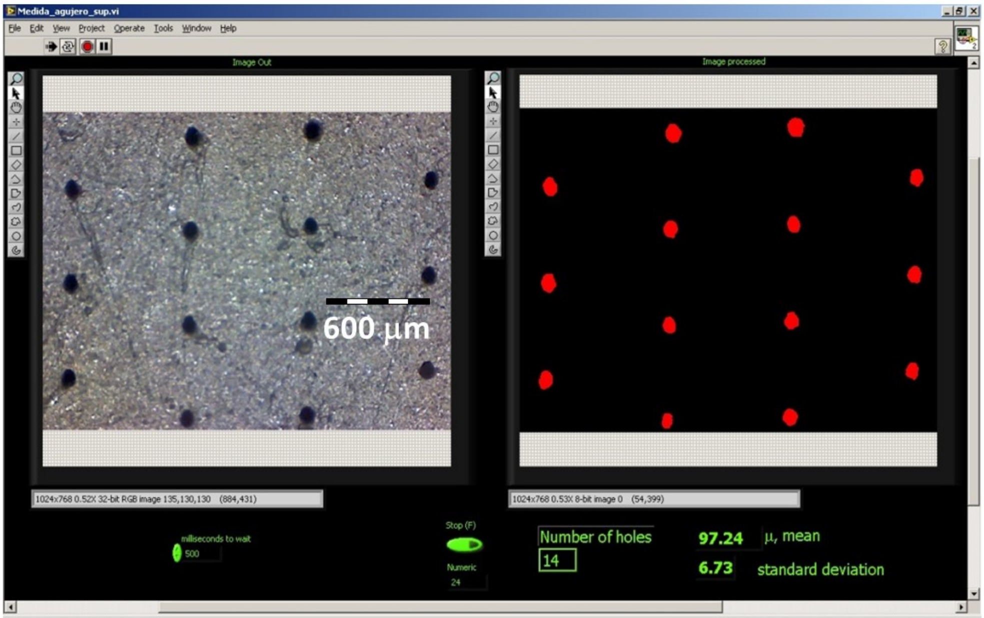

Fig. 6. Front panel of the software developed for automatic measurement of the microholes

In fig. 3, the diameters shown have been measured with this method. Each point in this figure represents the mean and the standard deviation of 800 microholes.

4. Conclusions

The fabrication of large micro-drilled Ti panels for HLFC is not a straightforward process. A typical panel with dimensions of 5 x 2 m contains more than 10^7 micro-holes. The SPMD laser technique fulfills the requirements of the aeronautical industry for the manufacture of these panels at 300 holes/s but due to the sensibility to the working distance, it needs a precise control and monitoring system to manage deviations that may occur during the process. Here we have presented the use of an electromagnetic Eddy current sensor for precise control of the working distance between the nozzle and the sample during the micro-drilling process. The precise control of the working distance enables that the standard deviation of the micro-hole diameters is below 5 µm at the beam entrance and exit. Furthermore a simple system for monitoring the process based on the capture of scattered light from the laser beam at the upper and lower part of the Ti plate has also been shown. This system provides information in real time about both quality and diameters of the produced micro-holes enabling real time decision making in case of deviations during the fabrication of a large Ti panel for HLFC application. In order to assess the performance of both monitoring techniques, an off-line automatic system for measuring the diameters of the microholes has been developed. Monitoring the scattered laser radiation and sensing the working distance with a Eddy current sensor might be also applied to other laser processes that are sensible to both working distance and local deviations from the optimal processing parameters in order to develop real time controls.

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