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High-speed manufacturing of HLFC structures by laser micro drilling

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Abstract

To reduce the fuel consumption of large passenger aircrafts the hybrid laminar flow control (HLFC) is a key technology. For drag reduction, several million holes with diameters around 50 µm at the leading edges of the aircraft wings and stabilizers are needed. In this paper, developed laser micro drilling strategies are analysed with respect to quality aspects and machining speed for the perforation of such titanium sheets. Applied methods are the “on-the-fly” single pulse and the percussion drilling technique both using pulsed fibre lasers in single mode operation. Differences can be found of course in the applied pulse length of 200 µs respectively 100 ns by q-switching. The strategies are focused to achieve holes with deviations in diameter of less than 3 µm at machining speeds of more than 300 holes per second, whereas less than 1% of the holes should be blocked by residual melt or particles.

Keywords: Micro processing; drilling; surface functionalization

1. Introduction

Hybrid laminar flow control (HLFC) is an active drag reduction technique. The transition from a laminar to turbulent boundary layer is marked by a sudden increase in the thickness of the boundary layer and a significant change in the local flow behavior. The random variation of velocity and flow direction within the turbulent boundary layer results in an order of magnitude increase in the skin friction compared to that of

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laminar flow as describes by Krishnan et al., 2017. By sucking a small amount of the air in the external flow through the skin surface, the transition of the boundary layer from laminar to turbulent flow mechanisms can be delayed. As skin friction drag accounts for nearly 50% of the total drag of a civil jet aircraft in cruise, technologies that enable laminar flow to be maintained offer the potential for economic and environmental benefit as shown by Schrauf, 2005. The manufacturing to industrial level of micro-perforated large titanium panels represents one of the main challenges for the implementation of the HLFC technique on civil jet aircrafts. Micro-drilled holes can be achieved by different manufacturing drilling technologies like mechanical, Electro Discharge Machining (EDM), Electron Beam (EB) and Laser, partly described by Michel and Biermann, 2018. The two latest technologies are postulated as the most appropriate to carry out the drilling process when a large number of small holes is needed in a short period of time.

The laser beam drilling process offers a flexible and wear-free production method. With this technology it is possible to generate high-quality drillings in an effective way. Up to now several studies e.g. by Meijer et al., 2002 or Jackson and O'Neill, 2003 on laser beam drilling with short-pulse lasers have been performed. Most of the publications deal with the generation of cylindrical holes. The influence of different gases like argon, nitrogen and oxygen at different pressures on ablation productivity and quality has already been studied for pulsed lasers by Walther et al., 2008. Although the use of picosecond and femtosecond lasers could provide better quality holes as shown by Meijer et al., 2002, the drilling time is too long based on currently available commercial laser systems. Li and Achara, 2004 demonstrated a chemically-assisted laser machining technique to minimize recast and heat affected zones while increasing the material removal rate during laser drilling and micromachining. The technique is not yet mature enough for large scale industrial applications. Hybrid laser and mechanical machining were studied by Marimuthu et al., 2017 for drilling high quality shaped cooling holes in turbine air foils to replace the traditional EDM drilling technology. These holes are typically 0.4-0.6 mm in diameter. Therefore, pulsed lasers sources operating in the µs and ns regimes, due to its high beam quality, pulsed repetition rates and high pulse energy, in combination with single pulse and the percussion laser drilling methods, are proposed as the most appropriate for fulfil the requirements for manufacturing HLFC large skin panels as high micro-holes density and precision, high drilling rates, etc.

2. Experimental

2.1. Percussion micro drilling (PMD)

A high-precision multiple-axis gantry machine modified for drilling of flat large panels by a laser beam scanning procedure was used to identify the processing parameters of the PMD technique with respect to a HLFC perforation. The machine has 3 linear axes with a maximum working volume of 2 m x 2 m x 0.3 m, a precision of 10 µm and a maximum speed of 5 m/min. The used laser source is a short pulsed fiber laser from IPG Photonics (IPG YLP-HP-1) with a maximum output power of 200 W and a repetition rate of 200 kHz operating at a pulse length of 120 ns. The laser source is connected to a laser scan head from Scanlab with integrated F-Theta lens for directing the beam to the drilling position on the surface. The focal length of the F-Theta lens is 167 mm using a maximum scan head aperture of 20 mm. The beam was fed by an IPG standard fiber with a core diameter of 20 µm. A clamping device for HLFC structures was developed to enable the drilling of large scale sheets subsequently in smaller bore patterns in a shielding gas environment. The requirements were to clamp a titanium sheet, such that each bore pattern is exactly in the focal position without any misalignment of its lateral position. The tooling is designed to drill one bore pattern of dimension 40 mm x 40 mm at a time followed by the next one after positioning. Therefore, the sheet is fixed and the drilling head moved across the sheet. The clamping device ensures a full shielding gas environment and a constant focal position for each bore pattern region, as it is also mounted on the scan head which can be moved up and down between drilling of different bore patterns on an overall area of 2 m x 1.8 m.

2.2. Single pulse micro drilling (SPMD)

Regarding the experimental set up for single pulse drilling, a three linear motor axis CNC machine with a 1 µm precision, 100 m/min maximum linear speed and travel distance of 650 mm x 850 mm x 400 mm has been used for positioning the laser head over the samples. The processing fiber laser is a single mode quasi continuous wave laser source with a maximum peak power of 1.5 kW. The pulse length set 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 lens that can be adjusted for positioning the beam waist relatively to the sample. The head is provided with nozzle of 1 mm diameter. As assist gas, argon at 18 bar pressure has been applied in order to establish an inert atmosphere and to reduce heat. The SPMD technique requires a constant working distance in order to reproduce the drilling characteristics across the entire area of the sample. Even 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 for micro drilling 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 calibrated Eddy current sensors with measurement accuracies below 10 µm. A closed-loop control ensures that the working distance remains constant with a rapid response at speeds up to 20 m/min.

3. Results

3.1. Percussion micro drilling (PMD)

Main influence on the process window for drilling by the PMD technique has the laser power (resp. pulse repetition rate for fixed pulse energy) with respect to the diameter and the applied energy per hole (resp. drilling time or number of pulses) to drill completely though the material. Fig. 1 shows the relationship of the exit micro hole diameter generated using different processing parameters, on titanium grade 2 and grade 5 specimens, as a function of the laser power as well as Fig. 2 the thereby needed energy per volume.

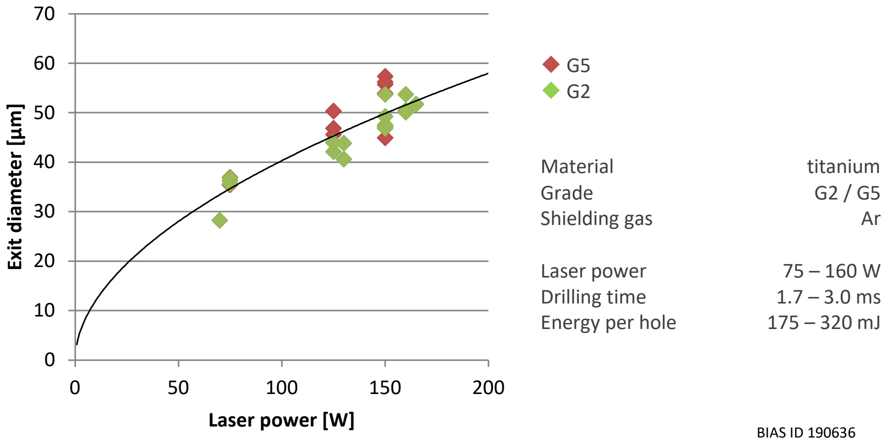

Fig. 1. Process window with respect to the exit diameter of the micro-drilled holes as a function of the laser power

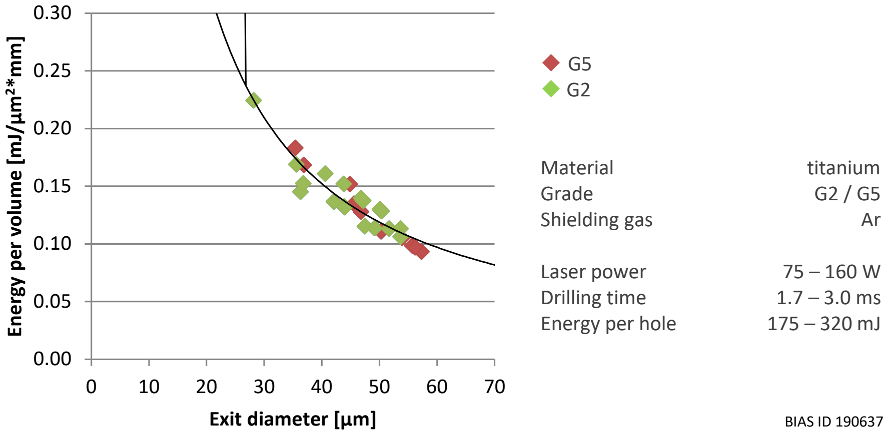

Fig. 2. Energy per volume needed to achieve a defined exit diameter of the micro-drilled holes

It can be observed that the exit diameter increases approximately root shaped with increasing laser power and the needed energy per volume for drilling reciprocally decreases with increasing diameter due to thermal scaling effects. The relationship between the entrance and exit diameter is in the range of 1.8 for the applied processing parameters. The number of blocked holes is below 1%, assuming proper adjusted and undisturbed processing conditions, and can reach less than 0.1% in case of titanium grade 2. Additionally, to avoid blocked holes also the position of the focusing lens is one of the most sensitive parameters of the drilling process when using the PMD technique. Thereby, the focal position should not be on the surface to drill through as well as to avoid burr formation on the exit side.

The PMD technique permits creating micro-holes at high processing speeds more than 300 holes/s. Several laser pulses of only some ns but low energy allow generating a single hole with a fixed laser beam position. The drilling process is carried out by a scanner synchronizing activation and positioning of the laser beam. To achieve high production rates (holes/s), it is necessary to drill very shortly at high pulse repetition rates and to position the laser beam in between very fast. Fig. 3(a) shows an achieved drilling result regarding quality and geometrical aspects generated with the selected parameters of Table 1 in titanium grade 2 specimens. The mean diameter of the holes is 50.2 ± 3.3 µm. Without post processing the exit side of the surface is free of burrs or debris. Fig. 3(b) shows a large titanium panel which was perforated under these conditions leading to the generation of more than 5 million with a machining time of more than one million holes per hour.

Table 1. Selected PMD process parameters

Parameter	Value	Unit
Average power	150	W
Drilling time per hole	2.0	ms
Number of pulses per hole	300	#
Power density per pulse	1792	MW/cm^2
Rate of productivity	305	holes/s

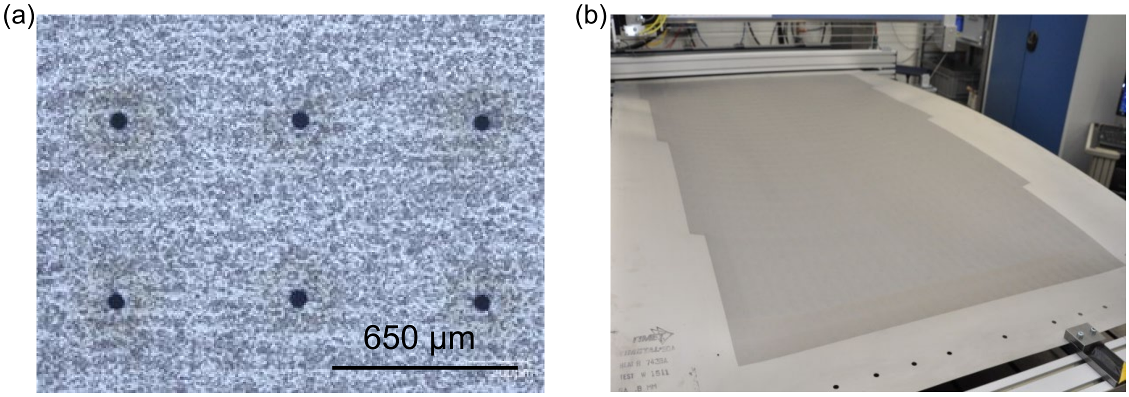

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Fig. 3. (a) Microscopic image of the drilling result with respect to the HLFC requirements for titanium grade 2; (b) Micro perforated large titanium panel for the production of HLFC structures at the leading edges of civil jet aircrafts

3.2. Single pulse micro drilling (SPMD)

In the SPMD technique there are several key parameters that determine the geometry of the hole. With respect to the parameters of the laser, these are e.g. the peak power of the pulse and the length of the pulse. The time of the pulse is fundamental when establishing the circular geometry of the hole: if it is long the hole will be elliptical or it can even become a slot (for very long times). If it is too short, then the laser beam will not pierce the Ti plate. The best strategy is to choose a peak power for the pulse that is the highest that the laser source can provide (in this case 1.5 KW) and minimize the pulse length. Following this way of proceeding, a pulse length of 110 µs that allows moving the head at speeds of up to 12 m/min maintaining the circular geometry of the holes was chosen. The second step to perform with this technique has to do with choosing an appropriate working distance for the focusing lens and the nozzle. The adjustment of the position of the lens allows positioning the beam waist relative to the surface of the Ti plate. The adjustment of distance between nozzle and surface allows a slight modification of the Ar flow on the surface and prevents plugging of the nozzle by ejected material during drilling. To make the use of gas more effective, it is desirable to minimize the nozzle distance. However to avoid clogging the nozzle, it is desirable to maximize that distance. The experiments indicate that the most optimal distance is around 0.9 to 1.2 mm. In the results shown a separation between nozzle and sample of 1 mm was chosen.

The parametrization of the lens position is shown in Fig. 4(a). The position of the lens at 0 mm means that the beam waist is on the surface of the Ti plate. By varying the position of the lens relative to the surface of the sheet, a range of diameters at the beam entrance and exit can easily obtained. For the application of HLFC, the most relevant diameters are located around the 0 mm position but holes with an almost cylindrical geometry can also be obtained at lens positions around -0.5 mm. At lens positions above 1 and below -1 mm no perforation of the sheet is achieved. Fig. 4(a) indicates that changes of only 100 µm of distance in the optical system cause changes in the diameter of the holes. This means that in applications with strict requirements for tolerances of the diameters of holes such as the HLFC, it is necessary to control the distance between the head and the surface of the sample. Especially when dealing with large panels, deformations of sheets larger than 100 µm are expected. In this experiments Eddy current sensors together with a control loop to keep the distance between the head and the sample surface constant were used. This method allows fast responses of the head to variations of the distance between the nozzle and the sample at processing speeds of the head up to 15 m/min.

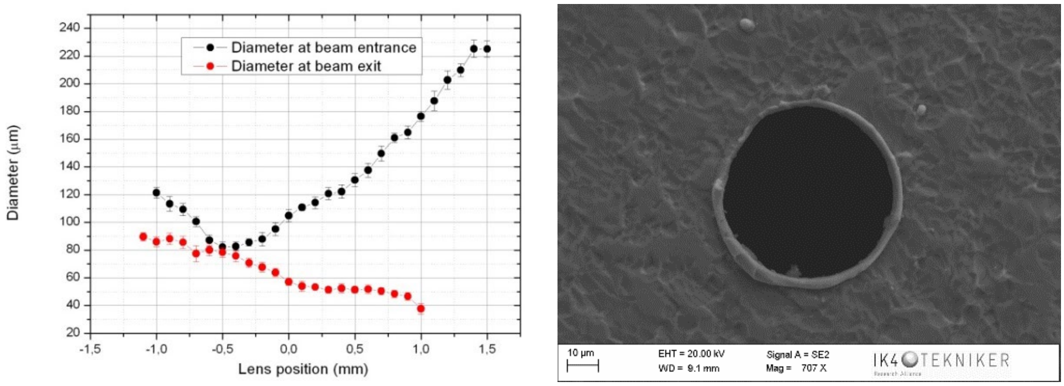

Fig. 4. (a) Diameter at the beam entrance and exit as a function of the lens position; (b) SEM micrograph of the beam exit side with the SPMD technique for titanium grade 2 at a lens position of 0 mm

Unlike the PMD technique, in the SPMD technique part of the material is expelled from the bottom of the sheet at the moment in which the perforation is achieved. This produces burrs at the edges of the holes that need to be removed by mechanical and/or chemical procedures. On the other hand, since it is a very fast process and does not use a large average power (approx. 50 W is the real average power of 1500 W peak power 110 us pulses at 300 Hz), the distortion of the micro-drilled panels due to the thermal and internal stress is minimized. In Fig. 4(b) a SEM micrograph of a drilled hole in a Ti panel is shown. The hole in this micrograph has been made at a rate of 300 holes per second. The average diameter measured on 100 holes of a sample made of Ti of 200 mm x 200 mm is 59.6 ± 3.1 µm at the beam exit and 109.5 ± 3.0 µm at the beam entrance. In Table 2 the most relevant parameter of the micro drilling of Ti panels with the SPMD technique are summarized.

Table 2. Selected SPMD process parameters

Parameter	Value	Unit
Average power	50	W
Peak power	1.5	kW
Pulse length	110	µs
Head speed	11.7	m/min
Drilling time per hole	50	µs
Rate of productivity	300	holes/s

4. Conclusion

The laser drilling techniques SPMD and PMD are both shown to be suitable for manufacturing to industrial level HLFC structures in titanium sheets with more than 300 holes/s which are 50 µm in diameter with deviations less than 3 µm.

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