Lasers in Manufacturing Conference 2015

Highly reproducible laser micro drilling of titanium-based HLFC sections

Hamza Messaoudi[a,*]; Salar Mehrafsun[a]; Geza Schrauf[b]; Frank Vollertsen[c]

[a]*BIAS - Bremer Institut für angewandte Strahltechnik, Klagenfurter Str. 2, 28359 Bremen, Germany*
[b]*AIRBUS OPERATIONS GmbH, Airbus Allee 1, 28199 Bremen, Germany*
[c]*BIAS - Bremer Institut für angewandte Strahltechnik and University of Bremen, Klagenfurter Str. 2, 28359 Bremen, Germany*

Abstract

The reduction of fuel-consumption is an environmentally relevant priority of the aviation industry. One of the key technologies in this field is the hybrid laminar flow control (HLFC), which is based on perforated sections on the leading edge of aircrafts. Up to now the economic efficiency as well as the quality of several micro drilling processes, such as laser drilling, cannot meet the requirements of a high-speed and large-area generation of micro holes with highly reproducible diameter. In this paper, an approach for a highly reproducible laser micro drilling of 0.8 mm thick titanium is presented. The influences of drilling parameters on process stability and bore diameter are discussed. With a commercially viable system technology based on a short pulsed fiber laser and a galvano-scanner, a stable production of micro holes of 35 µm to 90 µm in diameter with a through-going bore density of about 95 % was realized at drilling rates up to 175 holes/s. In terms to improve the inner form and to enlarge the hole diameter, a chemical pickling was carried out. Depending on the required dimension, this results in bores of 50 µm to 130 µm in diameter with deviations less than 10 %.

Keywords: Micro processing; ablation; drilling; system technology

1. Introduction

To realize a reduced fuel consumption of aircrafts, HLFC as an active drag reduction technique is a key technology in aerospace industry. The random variation of flow direction and velocity within the turbulent

* Corresponding author. Tel.: +49-421-218-58045; fax: +49-421-218-58063.
E-mail address: messaoudi@bias.de.

boundary layer results in an increased skin friction compared to that of laminar flow. The transition from a laminar to turbulent boundary layer is marked by a significant change in the local flow behavior.

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 reduced [Schrauf, 2006].

The design and the manufacture of the suction surface represent one of the most significant engineering challenges concerning HLFC. One of the techniques of producing a skin surface, which will allow air to be sucked through it, is discrete holes drilling by electron or laser beam. It is apparent that the parameters of hole size, pitch and skin thickness are not independent of each other and need to be considered together in the design and manufacture of the suction surface [Young et al., 2001].

In laser drilling the combination of duration and pulse peak power significantly influences the material removal mechanism. The micro-hole drilling processing using nanosecond pulses usually produces holes in metal with acceptable quality, but in general, worse than those by an EDM process because of melting [Li et al., 2006]. The material removal rate is usually in the order of 1-10 µm/pulse. Ultra-short pulse lasers operating in the femtosecond or picosecond range exhibit a clean finish because melting is not significant. However, the material removal rate is usually very low, in the range of 10-200 nm/pulse [Tu et al., 2014].

Laser drilling presents three different variants. Firstly, the single-pulse laser drilling process, a very fast process, in which all the material is removed in a single pulse [Ashkenasi et al., 2011]. It is mainly used in low-thickness parts or holes with less than 1:10 aspect ratios. Secondly, the laser trepanning process, which consists in translating the laser beam in circular paths to cut the perimeter of the hole [Schulz et al., 2013]. It is rather a laser cutting process than a laser drilling process. 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 sized holes with diameters ranging between 25 µm and 500 µm [Arrizubieta et al., 2013]. One of the main problems in percussion laser drilling is the low reproducibility of the process with respect to the geometry of the holes due to burr generated around the hole caused by the melt ejection [Ng and Li, 2001].

2. Experimental and Methods

2.1. Laser drilling system

To ensure the economical use, the developed system technology consists of commercially viable components (see Fig. 1.(a)). The system is based on a pulsed fiber laser (IPG model: YLP-HP-1) operating at a wavelength of 1065 nm in its fundamental Gaussian mode and delivering a maximum output power of 200 W. It operates at repetitions rates up to 1 MHz and has switchable pulse durations between 30 ns and 240 ns.

The collimated laser beam is first expanded and then coupled into a programmable galvanometer scanner (HurriScan 14 from ScanLab), which allows process speeds up to 3 m/s with a lateral resolution of 1 µm. The orthogonal arrangement of the scanner mirrors directs the beam down towards the work piece over the length and width of the scan field. Field distortion is compensated with an F-Theta lens (170 mm focal length) after the two-mirror system. This enables both a large scan field (100 mm x 100 mm) and a small spot size (about 25 µm) at perpendicular incidence of the laser beam. The scan head is mounted on a z-axis to adjust the focal plane with respect to the work piece.

In contrast to common drilling systems, the work piece is fixed in this arrangement. Instead, the z-axis used for the height adjustment of the scan head is mounted on an x-axis with a travel range of 2200 mm. This enables to perforate long panels (up to lengths of 2000 mm) by consecutively adding up scan fields. A pneumatic clamping device is firmly mounted onto the z -axis, allowing a fixation of the processed panel area in a defined distance to the scan head, see Fig. 1.(b) This allows the perforation of 100 mm x 40 mm fields and reduces the thermal distortion during the processing.

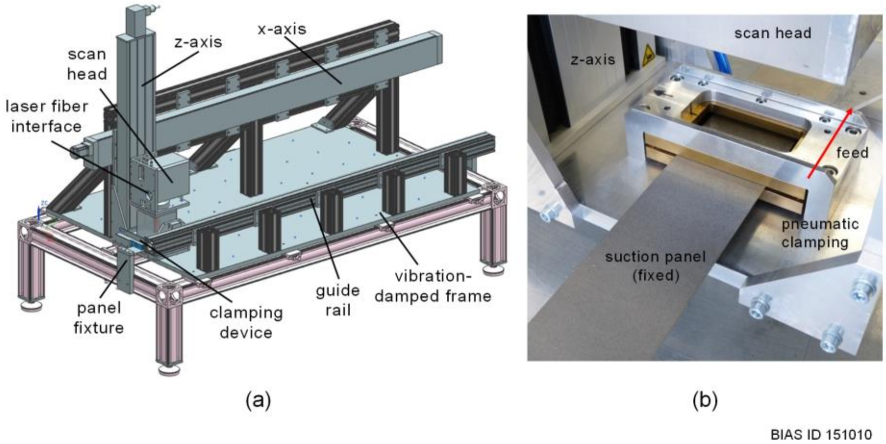

Fig. 1. (a) Laser beam drilling system; (b) pneumatic clamping device

2.2. Material

In this work pure titanium of 0.8 mm of thickness (WL 3.7024.1) was chosen as the material to be processed. It is certified for aerospace applications and distinguished by its excellent toughness, corrosion resistance and great formability at the same time.

Titanium is highly reactive to air atmosphere, especially at high temperatures. From other applications such as laser welding and laser cutting, it is known, that a shielding gas atmosphere is almost necessary for stable processing. Thereby, shielding gas improves the coupling efficiency of laser energy, has a cooling effect of formed plasmas and prevents the surface from oxidations. In addition, shielding gas at the back surface avoids the formation of heat tinting [Bergmann, 2003]. Therefore, a semi-opened shielding gas chamber was adapted to the clamping system. The inert gas used in this work was argon (Ar). In the back surface the air atmosphere is first driven out, and then smoothly flooded with argon. These flow rates are low and can be neglected. At the surface of interaction the flow rates were varied between 0 l/min and 40 l/min, in terms to investigate the shielding gas influence.

2.3. Drilling parameters and analysis methods

Throughout this work, different parameters were varied, with the aim to determine their influences. These are illustrated in Table 1. Only the pulse duration was kept constant at 120 ns, which was found to be convenient for drilling of titanium [Stephen et al., 2014].

The drilled holes were evaluated using different methods:

- Transmitted light microscopy using diffuse lighting to analyze the through-going hole density.
- Light microscopy to analyze the surface quality and to measure the bore diameter.
- Cross-section - as destructive testing method – to determine the hole geometries.

In this work, the hole circularity – especially at laser exit side – has not been evaluated. It was already demonstrated, that drilled holes using fiber lasers show in general circularities with values close to 1. This can be explained by the excellent beam quality ($M^2 < 1.2$) [Biffi et al., 2011].

Table 1. Varied parameters of laser micro drilling

Parameters	Unit	Variation
Laser mean power	W	50 – 200
Pulse repetition rate	kHz	75 – 200
Drilling time per hole	ms	2 – 9
Argon flow rate	l/min	0 – 40

3. Influence of Process parameters

3.1. Influence of the shielding gas

As mentioned before, a shielding gas atmosphere in both sides of the work piece is supposed to improve quality and stability during laser processing of titanium. In Fig. 2 a comparison of topographical properties with and without shielding gas atmosphere is presented.

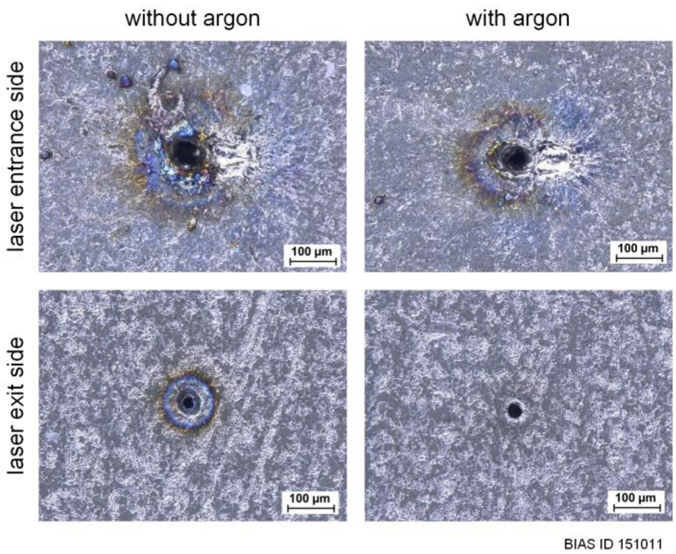

Fig. 2. Views of morphological properties of laser entrance and exit side after laser drilling with (30 l/min) and without argon atmosphere; t_{pulse} = 120 ns; f_{rep} = 75 kHz; P_{mean} = 75 W; t_{drill} = 6,75 ms.

The formation of spatter and droplets was observed in all machined bores at the laser entrance side, which is typical for thermally driven laser-metal-interaction in the short pulse regime. The induced thermal wave can propagate quietly leading by high input energies to the coexistence of all material phases (solid, liquid and vapor). During the vaporization pressure impulses can be created. These drive out not only vaporized but also melted material. The result is the formation of spatter ring, also called “corona”, which describes the formed burr on laser entrance side [Chichkov et al., 1996 and Luft et al., 1996]. Drilling under air atmosphere leads to the formation of an instable corona, which can collapse under throwing out melted material. Here, the heat affected zone is larger, which explains the higher volume of solidified material. On the contrary, the presence of an argon atmosphere (between 5 l/min and 40 l/min) reduces the thermal impact, cools the surface and results in a smaller spatter rings. This effect becomes even evident the higher flow rate is. Furthermore, with flow rates above 30 l/min the through-going hole density was found to be greater than 90 %, so that the following investigations were applied with an argon flow rate of 30 l/min.

At the laser exit side, argon is smoothly flooded and its flow rate can be neglected. In all cases neither spatter nor melt droplets have been observed. In Fig.2 the advantage of argon atmosphere is clearly shown. Due to its cooling effect, both heat affected zones and temper colours, observed under air atmosphere, can be avoided. Furthermore, the variation of flow rates at the entrance side showed no significant influence on the bore diameter at laser exit side. In absence of argon, bore diameters of 26.4 ± 3.7 µm were measured at f_{rep} = 75 kHz, P_{mean} = 75 W; t_{drill} = 6,75 ms. Using argon flow rates between 5 l/min and 40 l/min, the mean diameter was found to 32.9 µm with a standard deviation of 3.2 µm.

3.2. Influence of laser parameters

In Table 1 the laser parameters during these investigations are listed. Expect the pulse duration, which amounts 120 ns, all other parameters were varied.

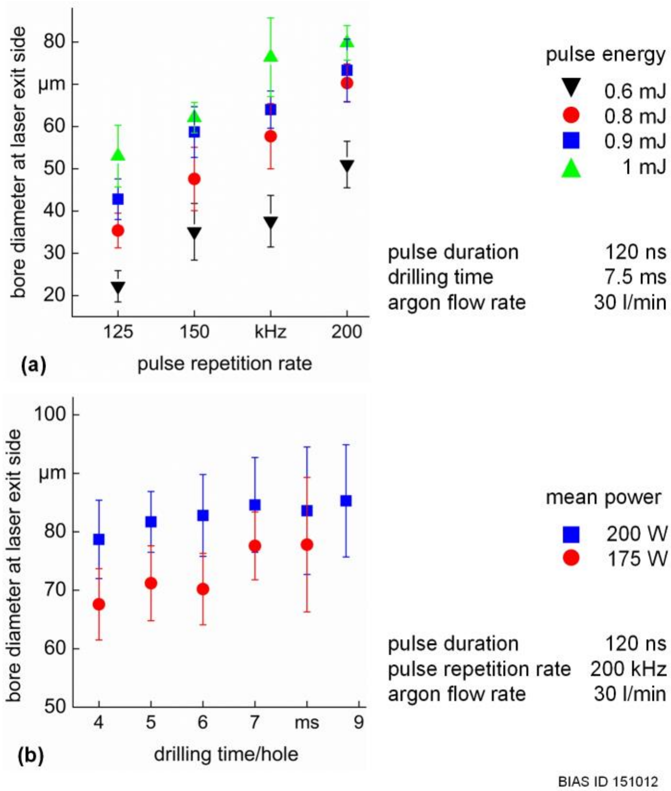

Fig. 3. Influence of (a) pulse repetition rate and pulse energy and of (b) drilling time per hole and mean power on the bore diameter at laser exit side.

Fig. 3. (a) shows the evaluation of the hole diameter at laser exit side in dependence of pulse repetition rate and pulse energy. For pulse repetition rates between 125 kHz and 200 kHz and pulse energies between

0.6 mJ and 1 mJ, the measured bore diameters was found to vary between 20 µm and 85 µm. Referred to single frequencies the hole diameters measured at 1 mJ are in general twice larger than at 0.6 mJ. Similarly, a higher pulse frequency results in increased diameters. The same tendency was observed in other frequency ranges (75 kHz to 100).The average power, which is given by pulse energy and pulse repetition rate, has a direct influence on bore diameter, so that these are enlarged when increasing the energy input.

In Fig. 3. (b) the measured diameters are illustrated in dependence of drilling time per hole for 175 W and 200 W. Here, the pulse repetition rate was kept constant at 200 kHz. Reproducible through-going holes have been first observed at exposure times > 4 ms/hole. Below this time through going densities of less than 50 % was observed.

At an average power of 200 W (corresponds to pulse energy of 1 mJ) the values were ranged between 78 µm and 86 µm and indicate a slight increase with regard to the drilling time. Compared to a mean power of 175 W, the holes were between 7 µm and 10 µm larger in diameter.

Taking into account the standard deviation, the drilling time per hole has a non-significant influence on the bore diameter. In fact, an increase of drilling time results in better hole quality, especially the through going density and the geometry.

In this work, two parameter areas have been identified when keeping the pulse energy constant at 1 mJ. The first applies for pulse repetition rates between 75 kHz and 125 kHz, in which the mean hole diameter at laser exit side is in the range of 20 µm to 50 µm. In the second area the hole diameters are found to have values between 60 µm and 90 µm at pulse repetition rates between 150 kHz and 200 kHz.

4. Large-area perforation

Defining the influences of process parameters on the resulting bore quality, in terms of diameter, heat affected zone (HAZ), roundness and burr formation on both laser entrance and exit side, was the first step following the goal to demonstrate the potential of scanner-based laser drilling for industrial applications. Therefore, panels of 80 mm x 80 mm in 0.8 mm titanium were perforated. Holes of 50 µm and 130 µm in diameter at laser exit side with hole-to-hole distances of 500 µm and 1300 µm, respectively, were targeted. Thereby, the focus rests on determining:

- through-going hole density
- drilling rate
- reproducibility

As additional finishing step to enlarge the bore diameter to the desired values, to improve the inner form and reduce the burr formation at laser entrance side a chemical pickling was carried out.

4.1. Laser drilling

Table 2. Parameter sets of laser micro drilling at pulse energy of 1 mJ

Parameters	Unit	Set 1	Set 2
Laser mean power	W	75	200
Pulse repetition rate	kHz	75	200
Pulse duration	ns	120	120
Drilling time per hole	ms	6.75	7.5
Argon flow rate	l/min	30	30

The drilling of bore holes of different diameters using the same laser source is challenging. The results in chapter 3 show the possibility of drilling holes having diameters between 20 µm and 90 µm. For reason of quality two parameter sets have been chosen (see Table 2.).

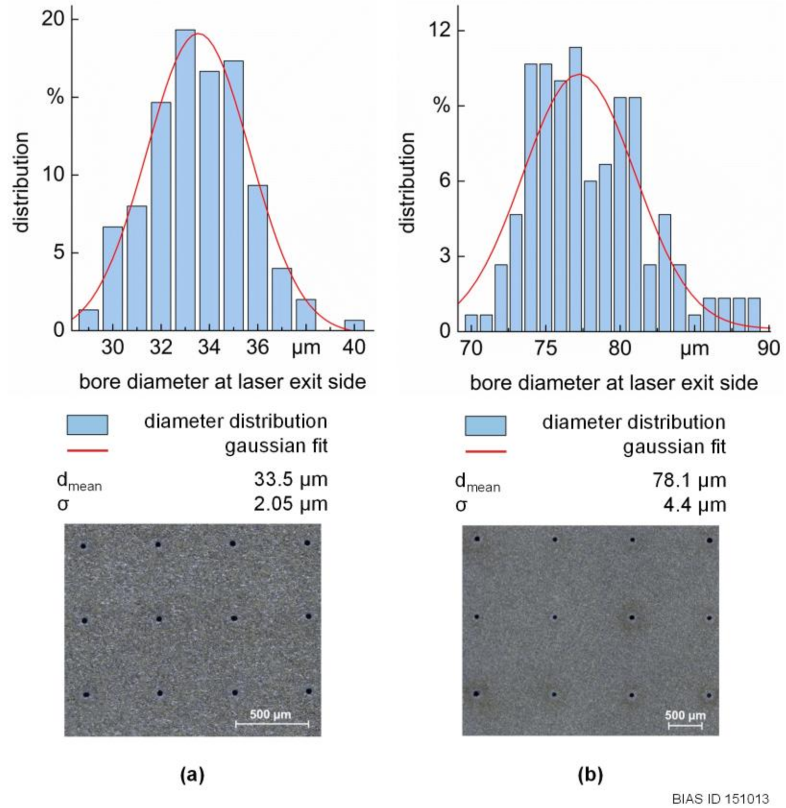

Fig. 4. Relative hole diameter distribution at laser exit side and a view of 4 x 3 hole matrix, drilled with parameter set 1 (a) and set 2 (b).

Fig. 4. (a) shows the normal distribution of hole diameter at laser exit side using the parameter set 1, which is consistent to the calculated Gaussian fit. After evaluating 150 boreholes in different positions over the 80 mm x 80 mm scan area the mean diameter was found to be 33.5 µm with a standard deviation of 2.1 µm. A matrix of 4 x 3 holes, placed below the diagram, gives a proof of the reproducible high-quality. Furthermore, the analysis of the transmitted light microscopy images has identified a through-going hole density > 95%.

Identically, the results of parameter set 2 are shown in Fig. 4. (b). Here, the evaluation of 150 holes reveals a mean diameter of 78.1 µm with a standard deviation of 4.4 µm. The bores at laser exit side are burr-free and do not show any significant heat affected zone. The normal distribution shows, that about 75 % of the holes have a diameter between 74 µm and 81 µm.

Under these conditions, a reproducible high-quality is assured with tolerances below 7 % for both diameters 35.5 µm and 78.1 µm. Thereby the productivities amount 149 holes/s and 133 holes/s, respectively for parameter set 1 and 2.

4.2. Chemical pickling

As shown in 3.1., the short pulsed laser drilling is basically thermally driven. Due to the rejection of melted material during the process, a spatter ring (corona) is formed at the laser entrance side. For that reason an additional step is needed to smooth the surface.

Table 3. Process parameters of the chemical pickling

Parameters	Unit	
Solution type	-	Aqueous sulfuric acid
Process temperature	°C	21
Process duration	min	6 – 25

In this work, a chemical pickling, as a common industrial process to improve the quality of metallic surface, was carried out. During this post-process the surface is chemically etched using in general acidic solutions resulting in the removal of spatter and oxide layers [Demir et al., 2010]. A description of the used parameters during the chemical pickling is illustrated in Table. 3. Each sample was cleaned first with Isopropanol and then immersed in fresh acidic solution for a specified time depending on the targeted diameter.

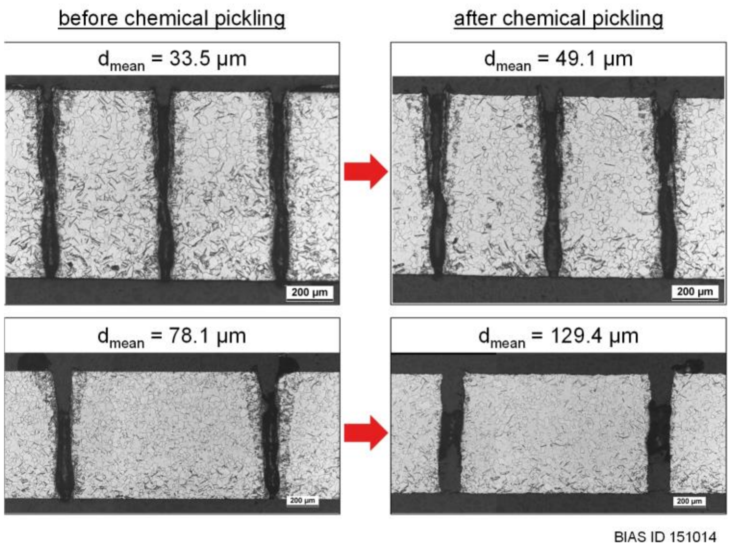

Fig. 5. Cross-sections of hole geometries before and after the chemical pickling.

The results of chemical pickling are illustrated in Fig. 5, in which cross-sections of boreholes before and after the etching are compared. The cross-section of the narrow holes (d_{mean} = 33.5 µm) before the etching shows the typical geometry of laser drilled holes. At the entrance side a wide funnel shape is observed and can be assigned to the spatial intensity distribution of the focused beam. Along the depth the HAZ decreases in width. Furthermore, Process instabilities caused by high fluences (> 50 J/cm²), multi-reflection along the bore wall and pressure recoils, lead to some changes in shape and direction [Luft et al., 1996]. Here, both indents at depths of 485 µm ± 5 µm and of bulges near the laser exit side at depths of 763 µm ± 3 µm can be observed. These, as seen in cross-section after 6 min. of etching, can be partially improved. The hole geometry stills tapered and the inner form becomes larger.

When increasing both, mean power and pulse repetition rate, holes become wider and the shaping along the depth occurs smoother. Nevertheless, a necking (indent) is observed over a range of about 200 µm in the middle of material thickness before bulges can be formed at depths of about 760 µm. After 25 min. of chemical pickling, it can be seen, that the heat affected wall sides are totally removed. This leads to nearly straight hole geometry with diameter ratio close to 1.

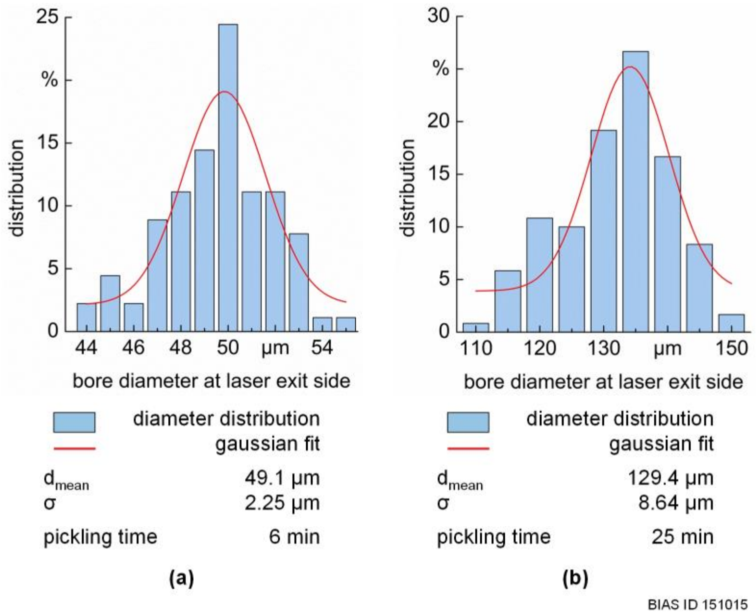

Fig. 6. Relative hole diameter distribution at laser exit side after the chemical pickling, with respect to parameter set 1 (a) and set 2 (b).

Fig. 6 shows the normal distribution of hole diameter at laser exit side after the chemical treatment. The targeted diameters of 50 µm and 130 µm have been successfully achieved. The mean diameter of the small holes was found to be 49.1 µm with a standard deviation of 2.3 µm, which corresponds to a standard deviation of < 5%. For the larger holes the value of mean diameter amounts 129.4 µm with a deviation of 6.7 % (8.64 µm). These results confirmed the findings after the laser drilling and give the proof of the stability of scanner-based drilling.

5. Conclusion

In the present work, the stability and productivity of scanner based laser micro drilling was demonstrated. The perforation of 0.8 mm titanium was performed with drilling rates between 130 and 150 holes/s. Thereby, burr free and circular bore holes with different diameters at laser exit side were produced with tolerances below 7 % and with through-going hole densities above 95 %. In terms of improving the surface quality at laser entrance side and the inner form and geometry of the holes, a chemical pickling was carried out. It confirmed the tolerances of laser drilling and enables a high-quality finishing. This method of manufacturing fulfills all requirements for a high-speed and high-quality perforation of titanium-based HLFC sections and presents an economically competitive technology.

Acknowledgements

The authors gratefully acknowledge the support of the Clean Sky Joint Technology Initiative within the 7th Framework Program of the European Union (GA n°338546).

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