Lasers in Manufacturing Conference 2023

High-rate micro-drilling in large surfaces by means of a high-power femtosecond laser and multibeam delivery

Roberto Ocaña[a,*], Emeric Biver[b], Alexandre Vendramini[c], and Julien Pouysegur[d]

[a]Tekniker, Basque Research & Technology Alliance, C. Iñaki Goenaga 5, 20600 Gipuzkoa, Spain
[b]Multitel Innovation Centre, Rue Pierre et Marie Curie 2, 7000 Mons, Belgium
[c]Lasea S.A., Rue Louis Plescia 31, 4102 Seraing, Belgium
[d]Amplitude, Cité de la Photonique, 11 Av. de Canteranne, 33600 Pessac, France

Abstract

We report on the development of a prototype for micro-drilling large Ti sheets used in the technology HLFC for reduction of friction in the leading edges of aircrafts. The system uses a custom kW femtosecond laser, an optical path compensator to account for the large surface processing requirement, and a two-stage multibeam generator based on polarization and diffraction beam splitting. The multibeam is then introduced into custom laser heads that exploit different ways to drill the workpiece and to apply the inert local gas protection environment necessary to avoid oxidation of the sample and the formation of unwanted metallographic phases. Preliminary results show an improvement of the overall quality with production rates in the order of magnitude of other conventional technologies using longer laser pulses.

Keywords: USP laser; high-power; micro-drilling; beam-splitting; DOE; hybrid laminar flow control; multibeam;

1. Introduction

The advancement of ultra-short pulse (UPS) lasers is continuously pushing the boundaries of power and unlocking a realm of new possibilities. These cutting-edge lasers are becoming increasingly powerful, holding great potential to revolutionize the realm of machining speed. Enhancing machining speed contributes to increase productivity and cost-effectiveness. Manufacturing processes can be streamlined, reducing production timelines and minimizing resource consumption. This not only saves valuable time but also optimizes operational efficiency, making UPS lasers a game-changer in industrial settings.

In general, femtosecond pulsed laser technology with over 1 kW of power is already available through custom systems, prototypes, and some products offered by conventional suppliers [1,2]. However, the efficient utilization of these systems not only requires specific experimentation but also calls for the development of customized delivery systems in order to minimize heat transfer to the workpiece and maximize the ablation process [3]. Several strategies have been employed to achieve this goal, including high-speed scanning technology with fast polygon mirrors for rapid beam displacement across the workpiece [4-5], as well as process parallelization by splitting a single powerful laser beam into multiple beamlets using either a spatial light modulator (SLM) [5-6] or a diffractive optical element (DOE) [4,7-9].

Liquid crystal based SLMs are a highly intriguing option as they allow for dynamic changes in diffractive patterns at typical frequencies of 50-100 Hz. However, they do have limitations when it comes to the maximum fluence they can withstand, which translates to a maximum laser power of around 100-150 W for real-world applications. On the other hand, DOEs are less flexible but possess the ability to withstand significantly higher power levels [10]. In this article, we use DOEs to generate a multi-beam from a custom high-power laser developed to meet the needs of high-productivity micro-drilling for Hybrid Laminar Flow Control (HLFC) panels.

HLFC serves as a drag reduction technique employed to mitigate turbulent airflow on aircraft wings, thereby reducing fuel consumption. This technique involves applying suction near the wing's leading edge, thereby promoting laminar flow [11]. To achieve this, thousands of micro-holes, need to be precisely drilled into Ti sheets. The drilling process necessitates several crucial requirements, including short processing times, precise hole positioning, and minimal thermal distortion [12]. Currently, laser drilling is the preferred method. There are mainly two techniques: single pulse drilling, which involves pulses lasting tens to hundreds of microseconds, or percussion drilling with pulses in the nanosecond range [13]. Each approach possesses its own advantages and disadvantages, but both methods require post-processing to eliminate burrs that may form during the drilling process. Moreover, it is imperative to subject the micro-holes to statistical analysis to ensure adherence to the required tolerances and to measure the percentage of blocked holes. This analysis is vital in maintaining the overall quality and performance of the HLFC panels. Accurate measurement and control of the hole diameters guarantee optimal aerodynamic performance, while assessing the percentage of blocked holes helps identify any potential issues that may impede the desired laminar flow.

In this regard, the utilization of USP lasers in the picosecond and femtosecond range for drilling purposes has shown great potential in enhancing hole quality while offering the possibility of minimizing or eliminating post-processing steps [14]. However, the previous limitation of low drilling rates hindered their applicability in some industrial processes. Fortunately, advancements in technology have paved the way for higher power USP lasers, coupled with parallelization techniques, which hold the key to making them compatible with industrial requirements.

This paper presents the results of the approach undertaken as part of the MULTIPOINT European project. The primary objective was to design and implement a parallel processing station utilizing a kilowatt (kW) femtosecond laser. The aim was to demonstrate the drilling of high-quality holes at rates that align with the demands of the industry.

2. Laser Development

The developed laser system is based on a master oscillator power amplifier (MOPA) architecture. This configuration consists of a master laser, also known as a seeder, and an optical amplifier to enhance the output power. The seeder is a fiber-based laser that emits ultrashort pulses with low average power. These pulses are directed into a stretcher, which elongates the pulse duration and reduces the peak intensity. This step is crucial in minimizing nonlinear effects during subsequent amplification stages. The laser beam then passes through three bulk amplification stages, each designed in a slab-shaped configuration. This amplification process significantly boosts the power of the laser beam. Subsequently, the output beam from the amplifier undergoes conditioning in downstream modules or building blocks. These modules include pulse compression, which reduces the pulse duration to achieve ultrafast laser pulses, modulation of the output pulse train, and isolation against back reflections originating from the workpiece.

This comprehensive laser system architecture, utilizing the MOPA configuration, ensures the generation of high-power, ultrashort laser pulses while maintaining optimal beam quality. The conditioning modules further refine the output beam for precise and efficient laser processing applications.

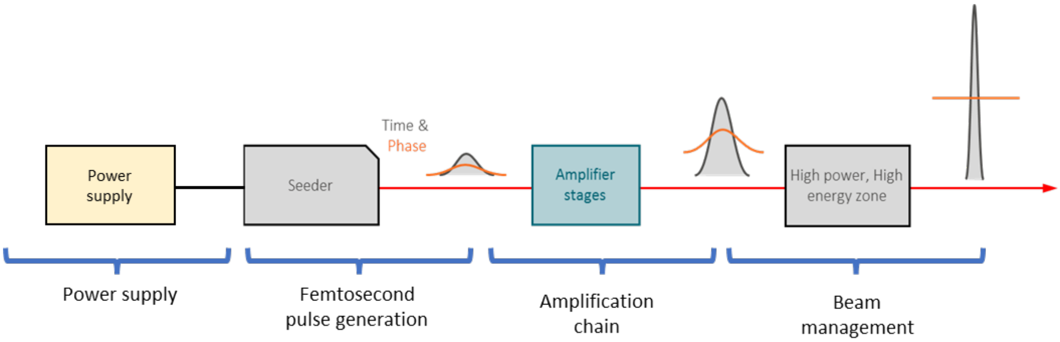

Fig. 1. Upper part: Amplification strategy. Bottom: Laser design

A block diagram representing the architecture of the laser is shown in fig.1. To address the issue of beam pointing deviation between amplifiers, a relay imaging system is employed. This system ensures that the output of each amplifier stage is imaged onto the input of the subsequent stage, thus maintaining stable laser amplification even in the presence of thermomechanical stress. Additionally, an active beam stabilization module has been integrated to mitigate pointing drifts at the output of each amplifier. The active beam stabilization module consists of two active mirrors, which are controlled by a Proportional-Integral-Derivative (PID) control loop mechanism. This mechanism utilizes feedback from two position-sensitive photodiodes to accurately monitor and correct any deviations in the beam's pointing.

Fig. 2. Final laser prototype with enclosure. Dimensions are 2714 x1409 x 634 mm

Fig. 2 shows an image of the prototype housed within its enclosure. The laser system delivers an average output power of 680 W, which corresponds to a pulse energy of nearly 1mJ at a repetition rate of 700 kHz. It is worth noting that the system is capable of operating at a maximum pulse energy of 2.27mJ, corresponding to a lower repetition rate of 330kHz, while maintaining the same average power output. To assess the quality of the laser beam at the output, measurements were conducted, yielding M^2 values of 1.42x1.73. This indicates a relatively good beam quality with well-defined spatial characteristics.

Furthermore, the output spectrum and pulse duration were also evaluated. The figure below depicts the output spectrum obtained at a repetition rate of 700kHz, along with the corresponding autocorrelation trace. The measured pulse duration stands at an impressive 650 fs, while the spectrum width spans 1.88 nm centered around 1029.8 nm. These results highlight the laser system's exceptional performance, with high average power, favorable beam quality, and ultrafast pulse characteristics. Such attributes make it suitable for a wide range of demanding applications that require precise and efficient laser processing.

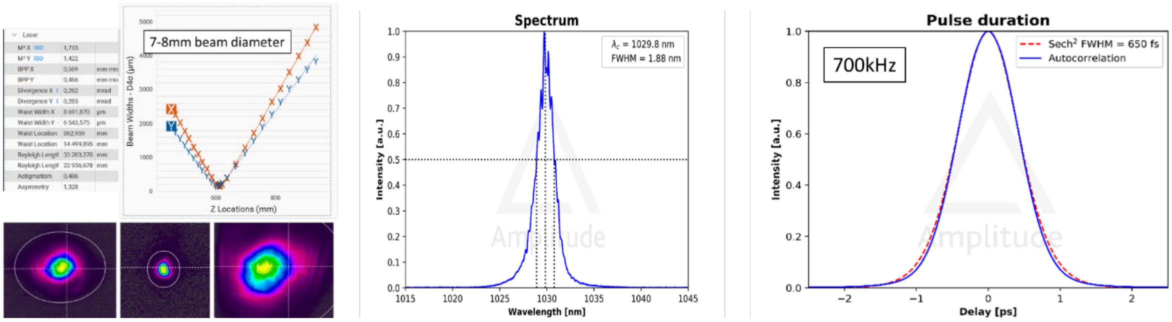

Fig. 3. Left: Beam quality measurement. Center: Spectrum. Right Pulse duration measurement

3. Multibeam Generation

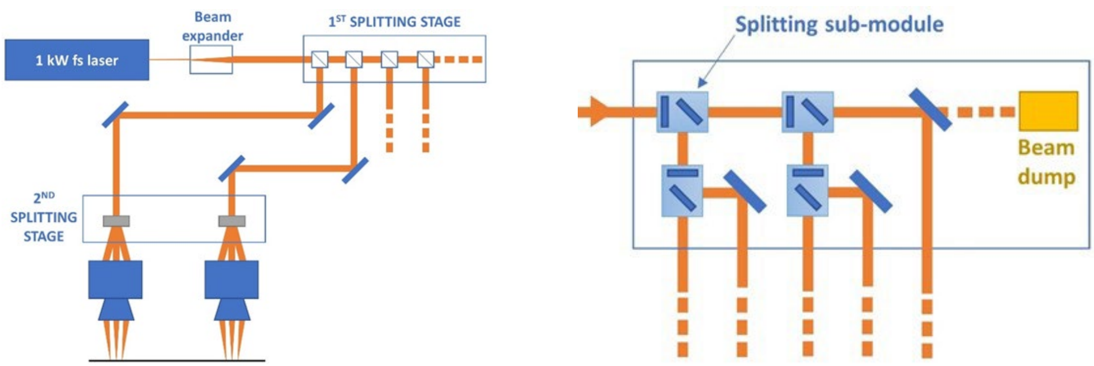

Fig. 4. Left: Overall beam splitting strategy. Right: First splitting stage

The beam-splitting approach employed in this study follows a two-stage strategy, as illustrated in Figure 4. The first stage of splitting involves a single module utilizing polarizing optics. This initial stage offers flexibility in terms of the number of sub-beams generated, enabling the distribution of these sub-beams to multiple scan heads. This parallelization of beams enhances the efficiency of the overall system. Subsequently, the sub-beams, each carrying hundreds of watts of power, progress to the second splitting stage. This stage involves the utilization diffractive optical elements (DOEs) and bulk optics. These components divide the incoming laser beam into several smaller beamlets. The main objectives of this stage are twofold: firstly, to facilitate the controlled transmission of the multibeam to the scan head, thereby avoiding any undesirable clipping of the beamlets, and secondly, to offer a degree of flexibility in achieving the desired pitch between the focal points on the sample. By implementing this two-stage beam-splitting strategy, the system achieves efficient parallelization, controlled beam propagation, and the necessary flexibility for optimal focusing on the sample.

The module used in the first stage of beam splitting harnesses the linear polarization of the input beam. As depicted in the right section of fig. 4, this module comprises multiple sub-modules, with each sub-module consisting of a half waveplate and a polarizing beam splitter (PBS) plate. The waveplate serves the purpose of adjusting the polarization ratio between the S and P components of the beam. When the input beam reaches the optimum angle of incidence (AOI) on the PBS plate, the P-polarized portion of the beam is reflected, while the S-polarized portion is transmitted. By employing four sub-modules and a few mirrors, it becomes possible to generate five exit beams and fine-tune the power ratio between each output sub-beam by rotating the respective half waveplates.

The primary technical challenge faced in this stage of beam splitting is handling a laser beam with significant power. To mitigate the power and energy density on the optics, a large beam diameter is utilized, approximately 8 mm at $1/e^2$. This necessitates the use of larger optics, such as 2-inch diameter components in our specific case, to minimize any potential beam clipping and associated issues.

Every sub-beam that emerges from the first splitting stage propagates to a carriage affixed to a motorized stage. There, the second splitting stage takes place. Each carriage is equipped with a module specifically tailored to divide the incoming sub-beam into a cluster of smaller beamlets, which are subsequently directed towards the laser head. The module also governs the pitch between the focused spots by manipulating the angle between the individual beamlets, as well as their ultimate position within the system [15]. In the devised design, a beam-splitting diffractive optical element (DOE) in conjunction with relay optics, employing a 4F system, is used. The primary objective behind this configuration is to ensure optimal overlap of the beamlets in a position between laser head's scanner mirrors, thereby minimizing clipping. This approach effectively mitigates concerns related to excessive energy density on the mirrors and the introduction of distortions caused by the F-theta focusing lens. The system is shown in fig. 5.

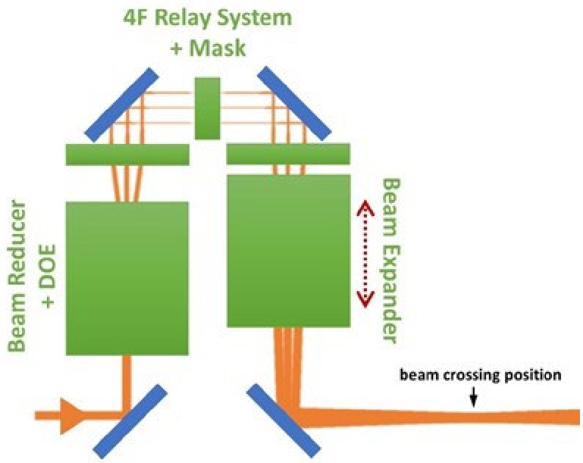

Fig. 5. Second splitting stage

It consists of the following elements:

- Beam reducer and DOE: it reduces the size of the beam to avoid air ionization in the subsequent 4F system and splits the beam and creates the multibeam.
- 4F relay system: it inverts the bundle so that the beamlets converge towards each other and allows to set a mask to spatially filter the higher, unwanted orders from the DOE.
- Beam expander: it expands the beamlets back to the same size than the original input beam and controls the distance at which the beamlets cross, by adjusting its position compared to the 4F.

This design provides us with great flexibility when it comes to testing different DOEs with various diffraction patterns. Within the scope of this work, two linear arrays of beams with two and five spots, as well as a rectangular array with four beams, have been tested to explore different configurations for micro-drilling purposes.

4. Prototype

The dimensions of the laser, in conjunction with the two splitting stages and the demands of processing large surfaces, have presented additional challenges not only from a mechanical design perspective but also from an optical standpoint. To address the substantial travel distance of the laser heads and the resulting significant difference in optical path between the extreme positions, an optical path compensator (OPC) has been integrated into the design. This module ensures a constant optical path for the beam from the laser output to the heads, regardless of their position. By maintaining a constant beam diameter at the head's entrance, it effectively preserves the focal point's position and size.

Moreover, given the considerable optical path, it is crucial to compensate for any misalignments arising not only from the laser's inherent characteristics concerning pointing stability but also due to variations in ambient temperature. To achieve this, a beam stabilization system has been implemented, featuring two pairs of detectors that are sensitive to the beam's position and two pairs of actuators utilizing mirrors with piezoelectric positioners. Each pair of detectors and actuators is placed along each optical path following the initial splitting stage. While the actuators are positioned in the static segment of the optical path, one detector is situated in the static portion, and the other is located on the carriage alongside the laser head and the second beam splitting module. This configuration, along with a closed-loop control system utilizing PID, enables compensation for misalignments caused by thermal effects within the laser, as well as dynamic misalignments resulting from the head's movement across the sample.

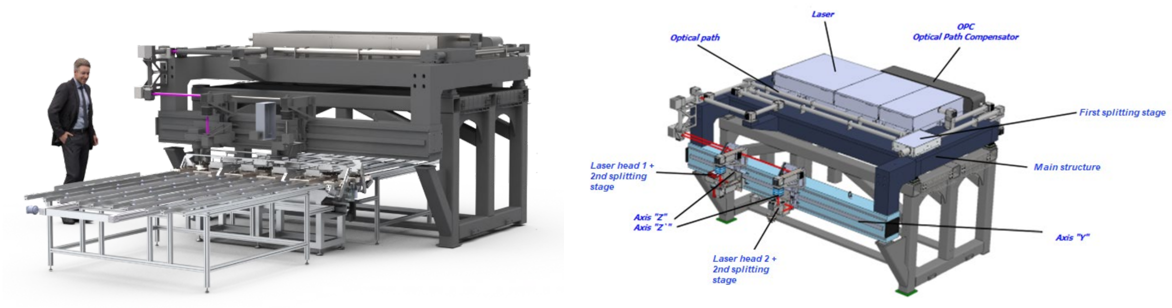

Fig. 6. Experimental prototype (left) and identification of components in the main structure (Right)

In fig. 6, the left side illustrates the prototype design, with the addition of a person in order to provide a visual context for the dimensions of the prototype. The photo reveals that the system is capable of accommodating two heads simultaneously. The utilization of two heads is aimed at maximizing production efficiency. On the right side of the figure, the design of the main structure is depicted, highlighting the identification of the most critical components.

Considering the experimental nature of the prototype and the likelihood of laser tuning tasks and alignment procedures exposing the optics to the surrounding environment, a protective enclosure has been incorporated into the design. This enclosure is equipped with a filtering system specifically designed to prevent the ingress of dust and other contaminants. By implementing this safeguard, the prototype's optical components are shielded from potential damage or degradation caused by external particles, ensuring optimal performance and longevity.

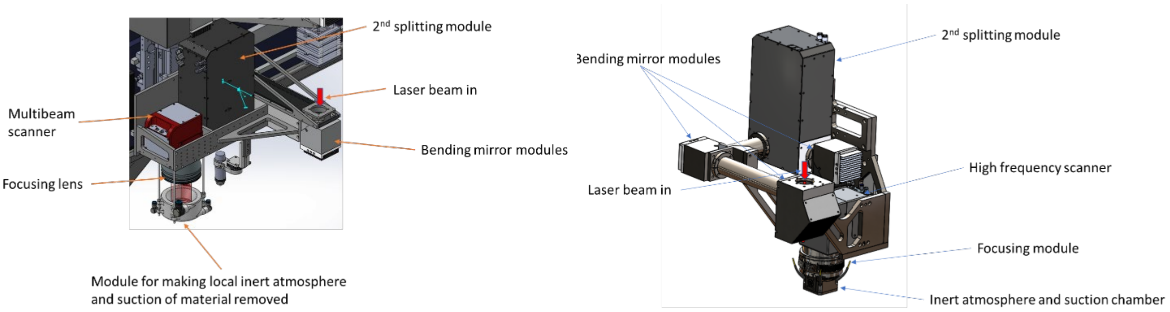

Fig. 7. Multibeam scanner head (left) and dynamic multibeam head (right)

Figure 7 shows the implementation of the two developed laser heads, each designed for specific types of processing. The first laser head, equipped with a multibeam scanner, enables static micro-machining of arrays of structures within the working field of the spindle. Once the machining is completed, the head moves to another position for subsequent operations. On the other hand, the dynamic multibeam head allows for micro-machining with the multibeam in a smaller working field, approximately 2 x 2 mm in size. This dynamic head enables on-the-fly micro-machining, maximizing production efficiency. The laser processing trajectories in this case dynamically accommodate the head's speed, ensuring precise operations.

5. Performance

While the developed prototype possesses the capability to undertake diverse micromachining tasks using the fundamental wavelength of the laser on large surfaces, its primary application focuses on high-productivity micro-drilling for the HLFC application. Current micro-drilling techniques employed for this application utilize lasers with longer pulse durations, ranging from microseconds to nanoseconds [13]. Although these techniques achieve high productivity, reaching up to 300 holes per second on relatively thick metal sheets (0.8 mm), they suffer from the drawback of requiring chemical and mechanical post-processing to eliminate burrs surrounding the drilled holes. These techniques rely on melting processes to remove the material from the holes, hence necessitating additional steps to ensure a clean outcome. Consequently, alternative processes that prioritize ablation as the dominant material removal mechanism rather than melting have become highly desirable. In this regard, femtosecond laser micro-drilling presents an ideal solution to test these hypotheses.

By utilizing femtosecond laser pulses, the process focuses on ablation, resulting in cleaner hole formations without the need for extensive post-processing.

However, the ablation process utilizing femtosecond pulses presents challenges due to the material ejected in the direction of the laser beam. This material ejection can potentially create a shielding effect, transferring the energy of the pulses as heat to the sample, leading to thermal accumulation and ultimately melting. Hence, depending on the specific process employed, it is necessary to consider that a portion of the energy transferred to the sample through the laser beam will be converted into heat and result in melting. The key challenge lies in minimizing this effect and achieving a process that predominantly removes material from the sample through ablative mechanisms.

Percussion drilling, despite its productivity benefits, poses a challenge as the stationary laser beam encounters interference from the ejected material, leading to a notable rise in the probability of thermal accumulation [3]. To overcome this issue, our drilling process utilizes a different approach based on trepanning with alternate jumps to other areas. This strategy aims to minimize thermal accumulation. With this method, we were able to successfully drill holes in Ti 0.8 mm at a rate of 150 holes per second. It is worth noting that the drilled holes exhibit a tapered shape, with some residual burr near the beam entrance due to the presence of melting phenomena. Nevertheless, this burr is considerably smaller compared to laser micro-drilling processes utilizing longer pulses, as reported in previous studies [12]. On the beam exit face of the drilled holes, there is no burr observed. This outcome was expected, as in ablative processes, the predominant ejection of material occurs perpendicular to the surface hit by the laser pulses. Additionally, the reduced contribution of melting processes positively influences the reproducibility of hole creation, achieving 100% non-clogged drilled holes.

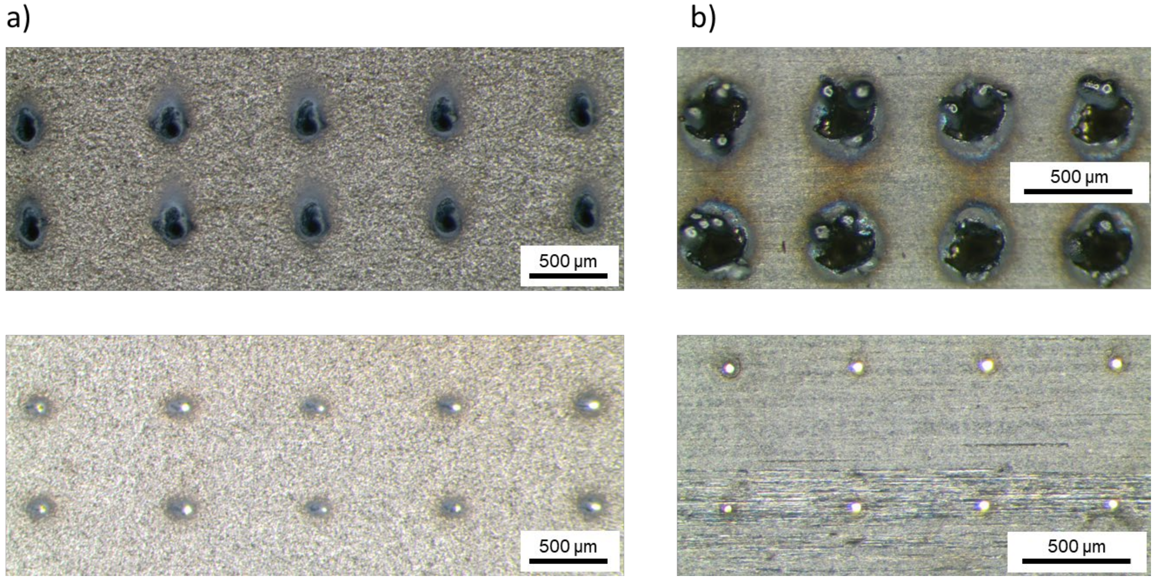

Fig. 8. a) Array of holes made with a multibeam of 5-beamlets. Top: beam entrance. Bottom: Beam exit. b) Array of holes made with 2-beam multibeam. Top: beam entrance. Bottom: Beam exit. Sample in both cases is Ti, 0.8 mm thickness. Pictures taken from the beam exit have been done with retro illumination to illustrate that the holes are not clogged.

Fig. 8 depicts examples of micro-drilling performed on a 0.8 mm thick Ti sheet using a 5-beam multibeam and a 2-beam configuration. When drilling with the 5-beam multibeam, the laser power is divided among a greater number of beams, resulting in a reduced available power for each hole. To ensure minimal thermal accumulation and maximize quality, the tests were conducted in a static manner, incorporating programmed jumps in the trepanning trajectories between groups of 5 holes. The achieved production rate is approximately 10 holes per second, with average diameters of 150.1 µm at the beam entrance and 29.8 µm at the beam exit. Notably, the holes exhibit slight irregularities in their circularity at the beam entrance due to the asymmetry of the laser beam in terms of M^2.

In the right side of fig. 8, the results of drilling using a two-beam multibeam setup are presented. Similarly, trepanning trajectories with jumps were employed, but the entire process was executed on the fly. In this case, the whole laser power, except for losses in the optical path, is concentrated in only two beams. The beam entrance displays a small burr concentrated around the hole's perimeter. However, overall quality is quite good when compared to conventional processes [13]. Productivity reaches 150 holes per second in this configuration. It is worth noting that, in comparison to case a), the process in case b) exhibits some melting alongside ablation, resulting in a slight degradation in quality. Nevertheless, the influence of beam asymmetry is less pronounced in case b). The photographs presented in fig. 8 highlight that, depending on the desired quality and diameters, it is possible to design highly productive processes using these technologies and strategies. For HLFC applications, particularly when seeking robustness, reproducibility, burr-free at least in one side, and maximum productivity, the strategy shown in case b is the most suitable.

Furthermore, the developed technology has been successfully employed with other materials that could not be properly drilled until now at high production rates such as CRFC and multilayers of Ti and composite materials, achieving productivity rates of up to 100 holes per second in similar thicknesses.

6. Conclusions

In conclusion, a high-power femtosecond laser system prototype capable of micromachining on large surfaces has been developed. To achieve this, a custom-designed laser capable of delivering ultrashort pulses of 650 fs at 680 W has been constructed. Productivity has been maximized through the use of multibeam technology, employing customized DOEs and laser heads capable of operating in both static and on-the-fly modes. As a result, high drilling rates ($>10^2$ holes per second) with acceptable quality for HLFC applications, minimizing the need for post-processing have been achieved. Furthermore, the developed technology opens up possibilities for micro-drilling in non-metallic, composite, and multimaterial sheets while maintaining high productivity rates. Future work in this field should focus on improving the optical properties of the laser beam and developing monitoring techniques to achieve more autonomous and robust processes.

Acknowledgements

This work was funded by the European Union's Horizon 2020 research and innovation program under Grant Agreement no 825567

References

[1] Pouysegur, J., Gruson, V., Godin, A. Denis Ferachou, Loyez, J, Baratange, F, Mottay, E., Hönninger, C., 2021. Kilowatt femtosecond lasers with high energy for high productivity through parallel processing. Proc. SPIE 11664, https://doi.org/10.1117/12.2578889
[2] Eidam, T., Breitkopf, S., Herrfurth, O., Stutzki, F., Kienel, M., Hädrich, S., Gaida, C., Limpert, C.,2021. High-power ultrafast fiber lasers for materials processing. Advanced Optical Technologies 10, p. 277-283, https://doi.org/10.1515/aot-2021-0033
[3] Brinkmeier, D., Holder, D., Loescher, A., et al., 2022. Process limits for percussion drilling of stainless steel with ultrashort laser pulses at high average powers. Appl. Phys. A 128, p. 35. https://doi.org/10.1007/s00339-021-05156-7)

[4] Gillner, A., Finger, J., Gretzki, P., Niessen, M., Bartels, T., Reininghaus, M., 2019. Journal of Laser Micro/Nanoengineering 14, 2.
[5] Gillner, A., Jüngst, M. Gretzki, P., 2015. Lasers in Manufacturing Conference, 2015.
[6] Kuang, Z., Liu, D., Perrie, W., Edwardson, S., Sharp, M., Fearon, E., Dearden, G., Watkins, K., 2009. Applied Surface Science 255, p. 6582-6588.
[7] Finger, J. , Hesker, M., 2021. J. Phys. Photonics 3, p. 021004, 2021.
[8] Hofmann, O., Stollenwerk, J., Loosen, P., 2020. Journal of Laser Applications 32, p. 012005.
[9] Bruening, S., Gillner, A., Du, K., 2021. Advanced Optical Technologies 10, p. 315-331.
[10] Thoss, A., Finger, J., 2020. LaserFocusWorld, 5 Feb.
[11] Abbas, A., de Vicente, J., Valero, E., 2013. Aerodynamic technologies to improve aircraft performance. Aerospace Science and Technology 28, p 100–132.
[12] Ocaña, R., Soriano, C., Esmoris, J., and Sánchez, R., 2019. Fiber laser based single pulse drilling for production of perforated titanium sheets for hlfc structures. Journal of Laser Micro Nanoengineering 14, p 54–58.
[13] Stephen, A., Ocaña, R., Esmoris, J., Thomy, C., Soriano, C., Vollertsen, F., Sanchez, R., 2018. Procedia CIRP 74, 403-406.
[14] Führa, B., Russ, S., Hammers-Weber, P., Diego-Vallejo, D., Kahmann, M., Andreev, A., Hesse, T., 2017. Lasers in Manufacturing Conference 2017
[15] Biver, E. , Dupuy, J., Hernandez, Y., Henrottin, A., Pouysegur, J., Ocaña, R. Journal of Laser Micro/Nanoengineering 18, 1.