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Expanding perspectives for processing with agile high power femtosecond lasers

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Abstract

Femtosecond lasers are reaching the kW level. At the same time new applications are continuously emerging in various industrial sectors: health, production, energy, transport. Femtosecond laser micro processing is today a technology enabling new fields of use and new methods of production. The "agility" of lasers and associated beam engineering make them relevant tools for flexible, reconfigurable production. Temporal and spatial shaping, amplitude and phase control, precise temporal synchronization, and digital processing will see increasing use for applications and be key sources of innovation

Keywords: femtosecond laser, Pulses shaping, femtosecond processing

1. Introduction

Femtosecond laser processing applications have over the past ten years seen a tremendous development. The ability of femtosecond lasers to offer a very precise, high quality laser ablation makes them the tool of choice in fields as diverse as healthcare, consumer electronics manufacturing, semiconductor, energy, and mobility. The continuous increase in available laser average power enables higher and higher industrial throughput, in turn opening new applications.

One of the most striking points, when considering the femtosecond laser applications field, is the very large number and wide variety of possible applications. Such a situation is a direct consequence of the original

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physical nature associated with the laser matter interaction in the femtosecond regime. Allowing the creation of temporary states of matter far from equilibrium, where the temperature of the atomic lattice is no longer directly related to the temperature of the electrons, the nature of the ablation in the femtosecond regime is therefore very different from other lasers. All materials, from the most fragile to the hardest, can be treated. In all cases there is a considerable reduction in the heat affected zone (HAZ), *i.e.* the area modified by thermal diffusion, outside the area irradiated by the laser. This characteristic of the interaction leads to the greatest precision of treatment reachable with a laser.

Two major trends will sustain the further development of femtosecond laser processing. The availability of industrial, kilowatt class femtosecond lasers will open new markets for large area and high-speed processing, with applications in aeronautics, energy, mobility, etc. The second major trend is the development of all the functions necessary for the proper use of the available Watts. Coupling a high-power laser with advanced beam engineering techniques results in an agility which is key for process development.

However, making use of a new generation of high average power femtosecond lasers for high precision manufacturing presents a specific set of challenges, which will benefit from close collaboration between the photonics industry and application specialists. Thermal management of the beam on the workpiece, which was a minor subject when using low or medium average power lasers, is now of the upmost importance. Temporal and spatial shaping, amplitude and phase control, precise temporal synchronization, fiber delivery, which have been demonstrated at the laboratory level will see increasing use in real life applications. Moreover, digital processing, machine learning and the flexibility enabled by the Industry 4.0 framework will also be key sources of innovation.

2. High power femtosecond laser

Femtosecond laser applications have been enabled by a continuous and rapid increase of the laser average power over two decades. The current state of the art for industrial applications is 50-300W, with kW average powers having been demonstrated in several laboratories worldwide and being actively developed to industrial maturity.

The hybrid fiber/crystal concept[1] allow both short pulse duration and high pulse energy. Moreover, this concept facilitates the implementation of fully user controllable pulse repetition rates. The laser architecture consists of a fiber-based seed module with a 40 MHz broadband passively mode-locked oscillator, a pulse picker, and several fiber amplifiers (Fig. 1). The wide gain bandwidth of Yb-doped fibers is the key to the generation of short femtosecond pulses. In standard operation, the laser source allows pulse-to-pulse picking and modulation of the amplified pulse train up to 2 MHz by using the external modulator.

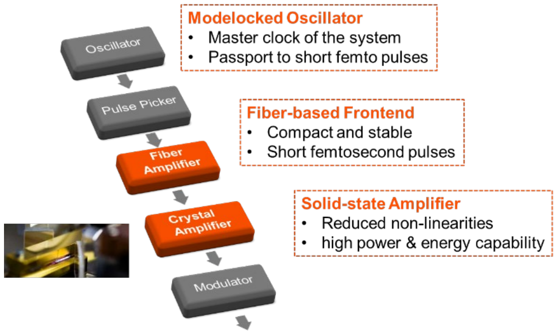

Fig. 1 Linear architecture of AMPLITUDE high power femtosecond lasers

Indeed, beside the fundamental wavelength (IR, 1030 nm), the two photons wavelength (Green, 515 nm), the three photons (UV, 343 nm) and the four photons ones (UV, 257 nm) has also considerably expanded the field of femtosecond applications. The fs laser high peak powers are ideally suited for frequency conversion to the green or UV spectral regions. Today, up to 100 W are available at 343 nm and 10 W at 257 nm. Fig. 2 shows typical results for UV (343 nm) conversion from 300 W of IR pulses. High power green and UV femtosecond pulses find applications in the scientific domain – pumping of optical parametric amplifiers for spectroscopy or imaging – as well as in industry. Industrial applications tend towards the frequency converted light whenever the additional advantage given by the lower laser wavelength dominates over the power loss owing to the conversion efficiency lower than 1. Examples are precision machining of copper parts with green light as the reflection coefficient of copper is much lower at 515nm or machining of complex material composites in particular in the photovoltaic or semiconductor sectors. The obtained beam quality is particularly interesting for targeted high-definition applications.

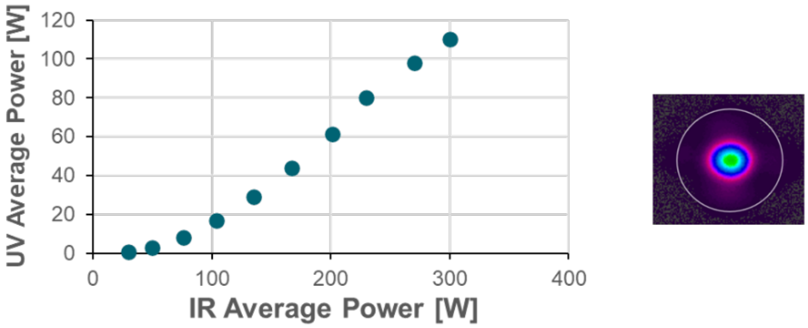

Fig. 2 : IR/UV conversion up to 100 W UV mean power. The M^2 factor is 1.25x1.29 (astigmatism 5%)

The scaling to high powers and high pulse energies, and ultimately to the kW level, is accessible thanks to the choice of crystal-based laser amplifiers with high gain and superior thermal management. Fig. 3 shows the efficient power extraction curve of a fiber-/crystal femtosecond amplifier up to kW average power: 1210W, 1.2mJ at 1MHz (before pulse compression). The spectral Bandwidth is 1.7nm and the pulses can be compressed to 600 fs (sech²).

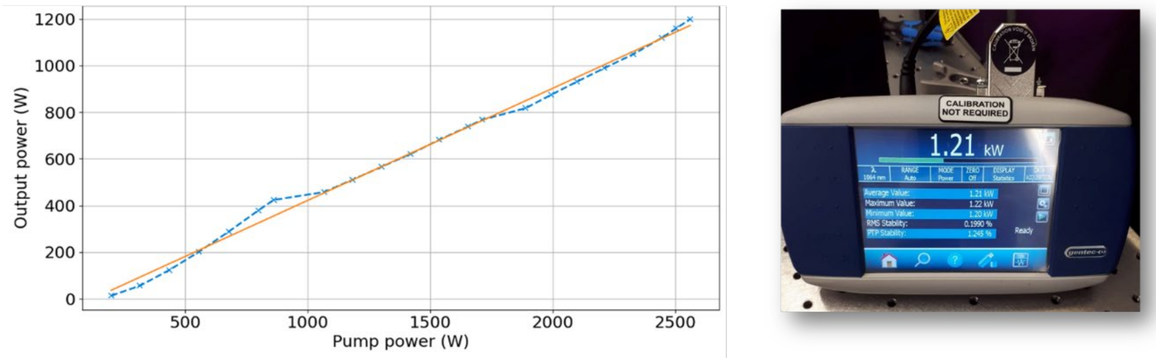

Fig. 3 : Preliminary results for kW fs laser (AMPLITUDE)

3. Laser agility

As already pointed out in the introduction, the most striking point with femtosecond lasers is the extremely large variety of possible applications. Additional elements and features added to primary laser performances increase the agility of femtosecond for laser process development. The exact amount of energy deposited on the sample, in space and time, is a key point for a precise process control.

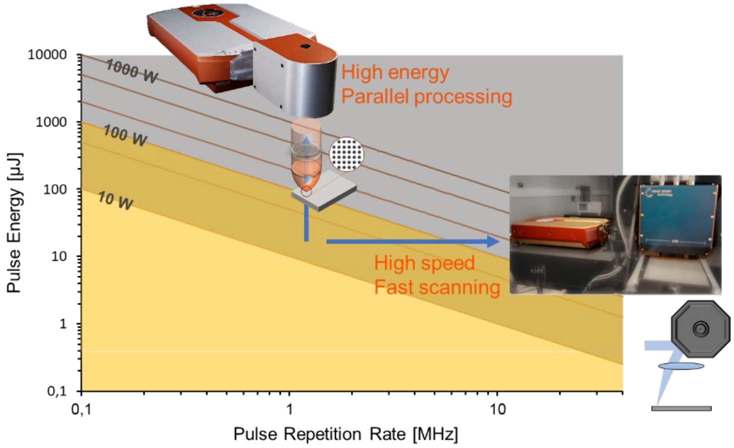

Fig. 4 : Two different axes for laser agility relying on either high repetition rate or high energy.

In the diagram of the laser parameters space of pulse energy and repetition rate, two main trends in application developments can be identified, which correspond to a different "agility" of the laser. Scaling the laser average power over the pulse repetition rate is typically associated with a fast beam movement, as is provided e.g. by polygonal scanners, reaching several hundred meters per second of scanning speed, where conventional (Galvo) scanners do not exceed 40 m/s. The challenge of implementation is then focused on synchronizing and triggering the laser pulses with the fast-moving tools. On the other hand, power scaling via an increase in pulse energy allows for the use of beam splitting in multiple beamlets, traditionally carried out by diffractive optical elements (DOE). The challenge in this case, in addition to producing high energy pulses, is the ability to achieve homogeneous energy spot sizes of the beamlets.

The Holy Grail for perfect process control is for the user being able to send the laser pulses to the sample with excellent precision in both time and space: right time, right position. Conventional ultrafast laser control allows only to control and modulate the output pulse train with the external modulator, the output pulse train repetition frequency or pulse period being constant and set by the preselected pulse picker settings. This conventional laser control is a direct consequence of the gain dynamics and the operation conditions of these industrial fs lasers at pulse repetition rates in the kHz to MHz range. Especially when associated to fast beam moving systems, the corresponding positioning precision for the laser pulses can then be compromised, and with this the process results, either in quality or in processing time. The recent development of the FemtoTrig® option (patented) has solved the gain dynamics problematics and allows to freely trigger and control the laser pulses directly on the oscillator period level. In other words, the user can freely and arbitrarily select the pulses from the oscillator pulse train that he wants to be amplified and to arrive on the sample at the right time and on the right position. This new and innovative function gives the user unprecedented process control options with ultrafast lasers with strong benefit to the applications as can be seen in the following. Two main consequences can be pointed out already: first, laser and system technology as e.g. axes or scanner mirrors or polygons can now be synchronized with much higher precision and up to much higher speeds; second, dead times during processing, caused by acceleration and deceleration phases of the beam movement or by additional moving trajectories as sky writing, can now be eliminated and process times reduced. Prominent examples of a productivity gain through FemtoTrig® are the realization of more complex shapes*, i.e.* curved shapes or free forms in general.

The Fig. 5 gives a practical example of the value of the FemtoTrig® option. The timing and positioning precision can further be increased by increasing the oscillator pulse repetition rate, e.g. from 40MHz to 80 or 100MHz or even beyond. Limiting factor is currently the bandwidth of the synchronisation electronics relying on state-of-the-art FPGAs.

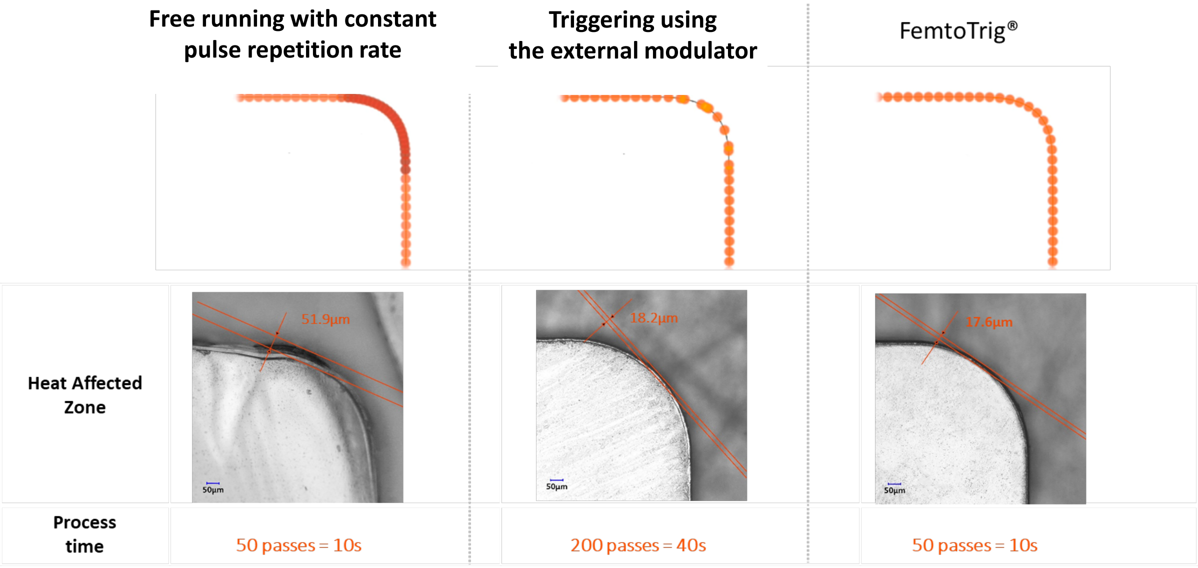

Fig. 5 Comparison of process results obtained in 3 different modes of operation and Laser Controls. Samples: Multilayers of organic materials. Process parameters : Curvature radius of trajectory 0.5 mm, Scan speed: 1.5m/s, nominal laser repetition rate (PRR): 400 kHz, , no pulse overlap. Left: Laser is running at constant, nominal pulse repetition rate, no triggering, only gating of the modulator to start/end the process. To obtain the process result, multiple passes are necessary in this operation mode leading to higher deposited power in the corners and leading to a significant heat affected zone (HAZ). Mid: The laser is still operated at constant, nominal PRR, but the modulator is used for triggering. Triggering avoids the HAZ but still multiple passes are required to obtain the process result. Quality is good, but processing time is long. Right: FemtoTrig® is used. This results in best quality and fastest process as the corners can be processed much faster. Process time reduction was a factor of 3 to the previous case.

Another aspect of temporal shaping is the use of busts of pulses. The term "burst" is here used for a train of pulses consisting of a number N of pulses separated by typically only one oscillator period (25ns for a 40-MHz oscillator, 1ns for a 1-GHz oscillator). The bursts are generated in the fiber-based seeder by simply lengthening the pulse picker window (Fig. 3). Correspondingly, the notion of pulse repetition rate (PRR) transforms into burst repetition rate (BRR).

The study of the laser-matter interaction using bursts has led to many works. The role of a pulse-to-pulse thermal accumulation has been widely demonstrated, as a phenomenon either beneficial if one considers its contribution to an increase in ablation efficiency or limiting if one considers the possible degradation of the machining quality due to these thermal effects. Other limiting or beneficial mechanisms are also studied such as shielding effects or the increase the surface roughness. The use of GHz bursts of pulses has led to new and interesting perspectives.

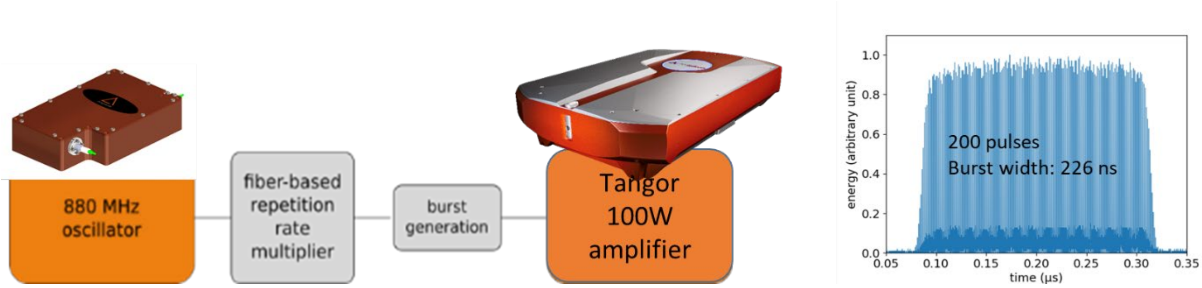

Fig. 6 : Principle of GHz bursts generation. Burst energy 2mJ**,** Burst rate: 50kHz, 200 pulses with 10-µJ pulse energy.

First publications on the subject have shown that ablation in the GHz regime reduces the thresholds and increases the ablation efficiencies by an order of magnitude.[2,3] The GHz ablation mechanisms are a combination of thermal and non-thermal ablation mechanisms, each can dominate at specific burst parameters and laser fluences. The optimization of laser parameters is thus not that simple. Nevertheless, systematic studies made on a wide range of parameters have shown that a rather simple interpretation of GHz ablation can be given.[4,5]

In a first step, matter is slowly heated by thermal accumulation, without ablation, thanks to the first pulses of the burst. The thermal rise then reduces the ablation threshold. In a second step, when the ablation threshold is reduced down to the pulse fluence, each subsequent pulse ablates matter very efficiently, since optimal fs ablation is always reached just above the ablation threshold. A first very efficient thermal process thus occurs, whose signature is always seen in GHz ablation. If the following non-thermal fs ablation phase has not enough time to efficiently occur, due to a too small number of pulses in the burst, the thermal nature of ablation and its consequences on the quality are enhanced. With an optimal burst fluence and an optimal number of pulses in the burst, high-volume ablation is achieved with a ratio of ablated volume/redeposited volume compatible with an acceptable surface quality. On the contrary, when the fluence of each pulse of the burst is higher than the ablation threshold, the ablation starts from the first pulse and the first step of accumulative heating cannot take place. The ablation process is thus similar to those occurring in the MHz-burst regime as shown by results obtained in such conditions.[6,7]

After reviewing several shaping of a femtosecond pulse trains, a second beam manipulation category concerns the spatial shaping of the laser beam. Changing a round spot to a square spot has been a goal since a long time. Recently new applications have emerged using an optical modification of the phase of the laser beam. For example, the generation of Bessel beams has enabled many applications in the field of glass cutting.

The use of ultrashort lasers combined with Bessel-like beams is becoming an attractive method for glass cutting as process speed and quality constantly improve. Laser technology potentially offers cutting of the arbitrary complex shapes even for thick glasses, with non-ablative methods. Micro-crack along the laser trajectory can be generated by combining non-diffractive beam shapes and femtosecond bursts which enables glass cleaving with minimal mechanical force. [8] Flexible optimization of the burst parameters allows to maximize the crack length, which improves the throughput and minimizes damage while cutting glasses up to 3mm thickness in a single pass.

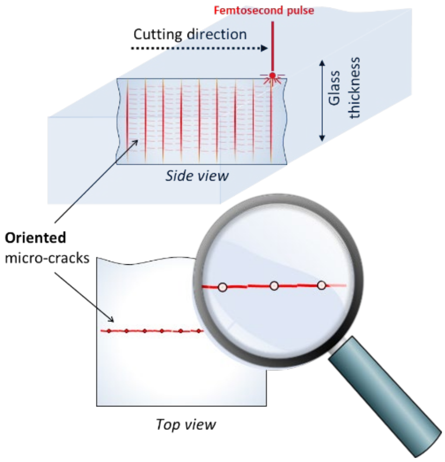

Fig. 7 Combining Bessel beams with burst of pulses: a non-ablative method to cut dielectrics by oriented micro cracks

The relative slowness of the removal processes in femtosecond mode is no longer a limitation and the unique quality of ultra-short processes is therefore accessible to an increasingly important panel of industrial implementation.

In summary, Fig. 8 schematically presents all the agility parameters that can now be available for the development and optimization of femtosecond laser processes.

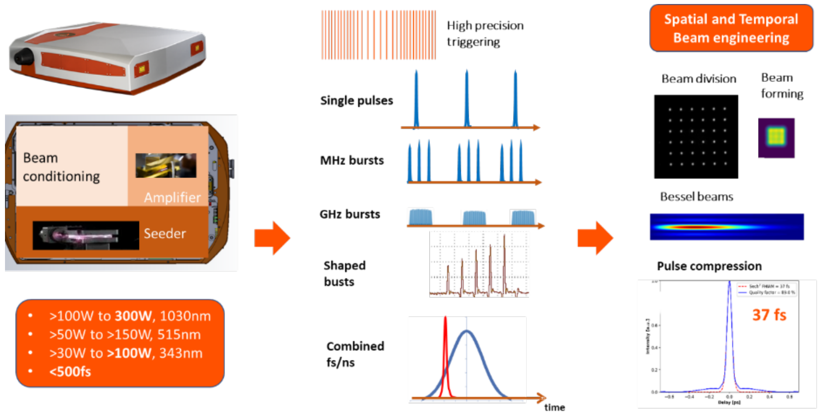

Fig. 8 « Agile » femtosecond lasers: possible functionalization of the laser beam and pulses.

The future development will have to look for efficient and fast process development methods. Using digital simulation tools, as part of a loop that ultimately adjusts laser parameters to the process results will be certainly a fruitful research and development direction in the next years. In this ambitious “4.0” approach, several steps must be mastered (Fig. 9). First, the availability of a "smart" laser source allowing for an easier connection with the external environment. Then the use of beam engineering tools, also connectable and controllable, to act on more parameters than the energy or repetition rate of the laser pulses, for example by addressing the spatial shaping of the pulses. Before the complete system can, after analyzing the processing results, re-enclose on the laser parameters, it is also necessary to have an online measurement system of the process results. This last point is probably the most delicate because most of the devices used to analyze ablation results are difficult to implement online. Moreover, data exploitation is by far the most time-consuming step-in process development.

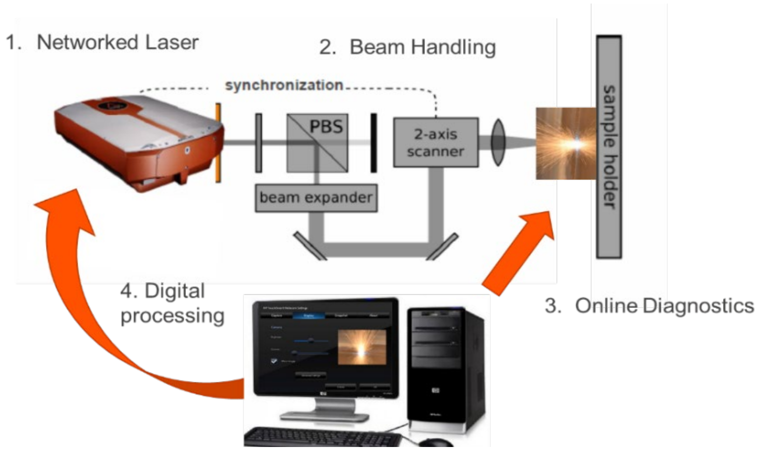

Fig. 9 : schematic representation of a 4.0 approach to optimizing laser parameters for femtosecond ablation processes.

4. Perspectives for application and challenges

The availability of high-power lasers reaching the kW mean power, properly distributed over the material thanks to the agility of the laser, not only reduces the processing time but also allows the access of new processes.

The first applications of femtosecond lasers were mainly for very small sizes. The aim was both to take advantage of the extreme precision of the fs pulses but also to remain in the low ablation volume accessible with the available low laser power. The next years will therefore most certainly see femtosecond lasers no longer restricted to the field of micro machining, but to be deployed in all application areas of “macro” laser machining, where significative production time reductions can be made, for example by removing post laser processing steps.

The average power increase of femtosecond lasers in the coming years will therefore have to go hand in hand with their agility to make efficient the available Watts. The productivity increase thus possible will of course affect all existing industrial sectors, but we can expect the development of several specific sectors where these new possibilities can allow rapid progress. For example, the automotive sector requires high productivity. Since 2009, ultra-short pulse lasers have also been used to micro-structure diesel engine injectors. Reducing engine consumption by surface textured friction reduction is also a major challenge. In aeronautic industry, surface structuring/texturing such as Hybrid Laminar Flow Control (HLFC) microperforated structures can be used to reduce air friction. These structures are positioned on the leading edges of aircraft wings and extend the laminar zone by sucking the first layers of air into contact with the wing. Micro-perforations are manufactured by laser drilling and the technologies used so far induce imperfectly hole shapes, high power femtosecond laser are currently developed for high throughput micro-drilling of large titanium panels used in the HLFC structures fabrication in the aerospace industry (See European MULTIPOINT project, https://multipoint-project.eu/).

Femtosecond lasers for surface modification or texturing can modify material properties with extremely useful functions. Hydrophilicity or hydrophobicity can be used for self-cleaning surfaces, deep black marking of metal is extremely interesting for esthetics purposes, antibacterial properties could be conferred to large surfaces, and reduced friction increases fuel efficiencies. The technical feasibility of all these processes has been abundantly demonstrated and some of them are used in industrial manufacturing.

As discussed above, high power lasers have to be combined with flexible beam manipulation tools to address large surfaces. An example of actual development is the European Multiflex project (https://multiflex-project.eu/). The basic idea behind Multiflex is to setup a high power "Ultrafast laser-dot-matrix-printer", [9] which consists of more than 1 kW laser and a flexible multi beam optics concept. The optical system converts the single laser beam into a pattern of more than 60 beamlets, where each single beamlet can be turned on and off separately. The resulting pattern can be directed onto the workpiece with a fast scanner. By enabling the flexible switching of the separated single beams and a control system for compensating field distortions, arbitrary surface structures can be generated with highest precision and throughput.[10]

In conclusion, femtosecond machining has earned its reputation by its unique precision in many production sectors (ophthalmology, flat screens, ...). The specific nature of laser-matter interaction in femtosecond mode leads to processes that remain slow compared to other conventional laser processes. Increased process productivity, combined with increased laser power, is therefore the key element in the development of femtosecond laser markets. The ambition of the players in this development will therefore be articulated for the next few years around the transformation of the ultra-short laser market. Moving from micro-machining, focused on specific industrial areas such as microelectronics, to Macro-machining, the femtosecond laser can become key tools in many industrial production sectors, especially in Europe where a re-industrialization effort is expected in the coming years.

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