Editorial

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Ultrashort pulse lasers in high-rate laser micro processing – Quo vadis?

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High-rate laser processing is the technical term denoting the employment of high-power lasers in combination with innovative laser beam deflection methods and by further implementing advanced process control algorithm and smart processing strategies. The primary goal of the high-rate laser technology is scaling-up processing speed and productivity for high-throughput machining in order to fulfill the specific requirements and needs of industrial production processes in terms of processing time, quality, flexibility, and cost effectiveness. One of the first mention of high-rate laser processes was by Kim and coworkers in 2004, reporting on through-wafer via hole drilling. In this maskless process using a q-switched CO_2 laser up to three orders of magnitude higher etching rates were produced compared to conventional plasma etching at that time [1]. In 2010, for the first time, Exner et al. demonstrated polygon scanner based micro processing of metals by deflecting a 3 kW single-mode continuous wave laser at 300 m/s speed reaching up to 12 m/s effective cutting speed and 4500 cm^2/min area processing rate [2]. The first employment of ultrashort pulse lasers (USPL) in high-rate micromachining was realized by Loeschner et al. producing microscopic features at stainless steel at 0.77 m^2/min area processing rate. This was achieved by implementing a two-dimensional raster scan regime at 800 m/s beam moving speed and 76 W USPL average laser power [3]. A further upscaling of the processing rate is pointed out in a recent study by Schille et al. showing the production of laser induced surface features on metals at unprecedented 3.76 m^2/min processing rate with a combined multi-beam with ultrafast beam scanning approach [4].

In the particular case of micromachining, USPL featu res excellent beam performances for high-efficient, high-precision, and flexible materials processing. The main advantages of the ultrashort pulses are the localized and defined energy input on the material as well as reduced heat load to substrate for almost melt free processing allowing high-quality products. This attracts the USPL technology as a fascinating tool for innovations in micro fabrication and advanced surface engineering. In the meantime, the benefit of the ultrashort pulses in ablation has been verified in numerous research studies, i.e., applying USPL for drilling, engraving, and profiling or rather microscopic surface feature production, which holds great promise for innovative applications in research, industry, medical engineering, and daily life. The average laser power employed in these fundamental studies was often only a few Watts, hence, the processing speed and throughput was lacking which is a drawback to bring USPL machining to industrial production. The amazing progress of the technological development of USPL during the last decade reaching kilowatt class level, Figure 1, will potentially remedy this limitation by upscaling the processing rates with laser power for substantially increased productivity. Therefore, three different USPL architectures (fiber, thin-disk, and slab) have proven during the past being effective for delivering kilowatt laser powers. An actual trend is combining the different architectures in “hybrid” systems to break new ground reaching USPL average powers in the order of 100 kW in future [5].

The average power, however, is a function of the pulse energy and pulse repetition frequency (PRF), $P_{\mathrm{av}} = Q_{\mathrm{P}} \cdot f_{\mathrm{R}}$. So it becomes clear that kilowatt USPL average powers can be delivered by (i) ultrashort pulses of high energy (millijoule) at moderate PRF (hundreds of kilohertz) or (ii) by pulses of moderate pulse energy (microjoule) at high PRF (megahertz). On the one hand, from application point of view, this is on particular interest because of pulse energies of a few microjoules are required to supply fluences in the range of 1 J/cm^2 which are sufficiently high enough for efficient material ablation in micromachining applications [6–8]. Thus, in order to employ kilowatt USPL average powers, such low-fluence pulses must be irradiated to the substrate at 10–100 MHz PRF. On the other hand, earlier

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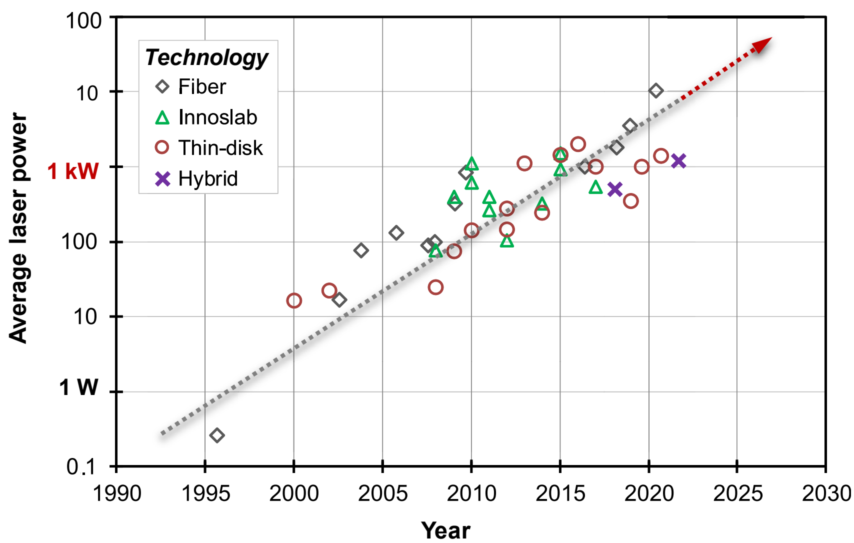

Figure 1: Progress of laser technology.

studies identified heat accumulation and laser beam shielding as main laser matter interaction phenomena for highly-repetitive pulse irradiations at MHz PRF, both affecting the machining process negatively in terms of efficiency and quality. In consequence, the outstanding question is how to bring the available optical energy efficiently to the substrate when using kilowatt-class high-power USPL in materials processing.

A feasible method to distribute the optical energy over large areas is raster scanning of the laser beam across the substrate surface. Thereby, the laser beam moving speed, also referred to as scan speed, and the chosen PRF determine the resulting geometrical distance between the impinging pulses within a scanned line. The state-of-the-art technique for flexible raster scanning are galvanometer scan systems providing scan speeds typically in the range up to 20 m/s. Herewith, the geometrical pulse distance is comparably low when irradiating megahertz PRF pulses which, in turn, causes strong overlapping laser matter interaction areas along with the aforementioned heat accumulation and plume shielding detriments. An expedient approach to this issue is ultrafast movement of the laser beam, i.e., by implementing resonant or polygon mirror based scan concepts reaching scan speeds of hundreds meters per second and above.

An alternative method for using high-average power USPL in micromachining is multibeam processing. Therefore, diffractive optical elements (DOE) are adapted in the beam path to split the laser beam emitted by the laser source in a number of individual beams. These individual beams deliver pulses of optimum fluence for most-efficient material ablation taking place at the expense of flexibility during machining. The multibeam approach is effective for pulses of high energy, while ultrafast raster scanning is more appropriate for high-PRF pulses. For kilowatt class USPL, the combination of beam splitting and ultrafast raster scanning seems to be a promising method as the single pulse energy is too high for efficient machining even at megahertz PRF. As another practicable method, burst mode laser processing by irradiating pulse trains with intraburst pulse repetitions in the range of MHz or GHz and respective micro second to nanosecond time intervals between the intra-burst pulses has been proven for high-efficient machining at high-average laser powers [9–12]. The choice of the most suited processing strategy, however, largely depends on the performance characteristic of the individual USPL system and the specific requirement of the product to be machined, Figure 2.

This special issue of advanced optical technologies on topic high-rate laser processing is dedicated to outline recent advances and progress using high-average power USPL in high-throughput micromachining [13–21]. This comprises recent technological developments of high-average power USPL including the most promising architecture concepts (fiber, thin-disk, and slab), advanced machining strategies implementing ultrafast and multi-beam laser processing approaches as well as machining examples to emphasize the high potential of the USPL technology for high-rate micromachining.

The list of contributors for this special issue reflects the leading-edge experts in the high-rate laser machining research field. A view article and two review papers were invited from the academic and industrial sector for adequate framing this special issue. In addition, six research papers were submitted bridging the gap between USPL systems, ultrafast and multi-beam processing technology and potential areas of applications for USPL micromachining. This allows fostering the current body of

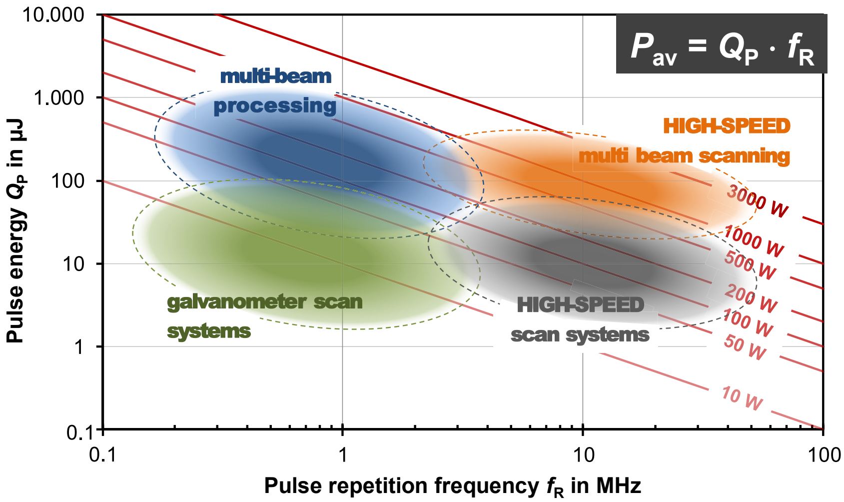

Figure 2: Processing regimes referred to the performance characteristic of high-average power USPL.

knowledge in the field of high-rate USPL processing providing new impulses and ideas for USPL in high-throughput and large-area micro structuring, surface functionalization, and engineering.

Weber and Graf [13] provide a view on the challenge of using USPL for productive materials processing. They point out that the average power of USPL doubles every three years, subjected to a kind of Moor's law, and no limit is in sight. There is a trend; the high-average power of USPL firstly attained in the laboratory will be available for industrial use about 10 years later. The authors overview the influence of the physical material properties and processing parameters on materials ablation and discusses nine distinct constraints for USPL in material processing including feasible approaches to overcome these limitations.

Wang et al. [14] review the development of high-power modelocked thin-disk lasers (TDL) as promising candidate for average power scaling. From a 1 µm wavelength one-box oscillator, an average output power of 350 W could be delivered at 1 MHz PRF and tens of microjoules pulse energies. Moreover, the authors consider the TDL technology as an interesting seed source for existing multipass amplifiers to reach 10 kW average power and beyond. In addition, they outline the 2 µm wavelength range as a future direction for high-power TDL to expand the possibilities of USPL in materials processing.

Audouard et al. [15] present high-power and flexible USPL in GHz burst mode operation to open new horizons for femtosecond laser processing. They summarize the rapid increase of the USPL average power over the last two decades, starting from solid-state USPL with 1 W average output power, to fiber-based systems reaching up to 50 W, to hybrid fiber/crystal concepts yet enabling actually up to 1.2 kW average powers. The GHz burst mode is shown for significantly increasing the ablation efficiency. Beyond an existing burst-time threshold, GHz burst machining increases the specific ablation rate by a factor of 3 or higher.

In addition, two research papers are focused in this special issue on the technological improvement of USPL architectures for reaching kW-class output power. Eidam et al. [16] summarizes the state-of-the-art of ultrafast fiber amplifiers. The coherent-combination technique for parallel amplification is introduced to overcome the physical limitations of USPL fiber laser in power scaling. By coherently coupling 16 parallel channels, a record value of 10 kW output power was achieved recently.

Ahmed et al. [17] discuss thin-disk multipass amplifier concepts. A maximum output power of 2 kW is reported for a 2-stages thin-disk multipass amplifier scheme amplifying a 105 W average power USPL seed laser beam. The high potential of the TDL technology for high-rate machining is demonstrated by milling of diamond, increasing the productivity by a factor of 140 with a 1 kW laser beam compared to traditional mechanical processes.

Three research papers deal with high-speed USPL laser processes. Roessler and Streek [18] present a two-dimensional polygon mirror scanner, capable to handle kilowatt laser powers at up to 1000 m/s ultrafast beam moving speed. The high precision during ultrafast processing is demonstrated in multi-pass laser drilling by hitting the drilling holes exactly again in several hundreds of scan passes. The developed ultrafast polygon-based scan system in combination with high-average power USPL allows ultrafast machining at highest precision with high innovation potential, i.e., for large-area surface functionalization.

Petelin et al. [19] present a true pulse-on-demand laser design concept for resonant-scanner based high-speed processing. By generating arbitrary pulse patterns, equidistant pulse patterns could be achieved even when combining USPL with high-speed resonant scanners where the beam moving speed changes sinusoidally on the substrate due to the oscillation of the scanner mirror.

Bruening et al. [20] presents a new concept using multi-hundred Watts Innoslab lasers in an 8 or 16 parallel beamlet cylinder micro processing system. The cylinders were machined with 27 mm^3/min maximum ablation rate achieving 5080 dpi processing resolution. The laser made functional geometries processed on the cylinder surface were replicated in roll-to-roll processes to demonstrate the high potential of this high-rate multibeam USPL technology for R2R mass production.

Gafner et al. [21] developed a method combining USPL with DOE for multi-pulse drilling on the fly by fully synchronized galvo scanning. In addition, as an appropriate alternative to ultrafast scanning, optical stamping on the fly is presented. Therefore, a spatial light modulator for beam shaping was arranged in a galvanometer scanner setup to stamp desired beam patterns by using full available laser power at highest efficiency for high-rate material removal.

In conclusion, this special issue on high-rate USPL machining shows impressively the ongoing power scaling of USPL reaching multi kW class level. In addition, it is emphasized only the employment of high-average power USPL in combination with smart machining strategies and efficient processes will bring the USPL technology from the laboratory into industrial production. On the basis of the papers collected in this special issue it can be summarized, high-rate processing for high-throughput and large-are production will establish USPL as a powerful tool for innovations in modern micromachining and surface engineering applications.

Finally, we Guest Editors thank all the authors for their contributions and enthusiasm in writing and illustrating. Also, we would like to express our sincere gratitude to all reviewers and the AOT team for their support making this special issue reality. The print version is on hand now to be explored by you, the reader. Please take a few moments for looking through the diverse aspects of high-rate USPL machining – so you will find your USPL application.

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