MICROMACHINING WITH ULTRA-SHORT LASER PULSES IN BURST-MODE

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Modern ultrafast laser systems often allow for so-called burst-mode operation. This means that trains of ultrashort pulses are emitted with intra-burst repetition rates in the MHz- or GHz-range. These operation modes offer new possibilities in micromachining of different materials such as milling, drilling, or cutting. In this article, we give a short overview of recent developments and cite some achievements in micromachining applications of different materials in these new burst-regimes.

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Ultrafast laser processing has become a key technology for high-precision manufacturing in industries such as the automotive, the electronics and the watch industries, the medical technology, and the jewellery. Pulses with durations ranging from femtoseconds to picoseconds are used to process virtually any material with minimal burrs, negligible heat-affected zones, and excellent edge quality. This results in robust and reproducible processes for tasks such as micro drilling of injector nozzles or through holes in glass, stent cutting, trimming of electronic components, laser turning, and functional surface structuring. The high flexibility of beam guidance and scanning systems allows for easy integration into automated production lines and multi-axis platforms. As average power increases towards several 100 W and beam shaping options continue to improve, ultra-fast laser processing is increasingly being used to replace or supplement conventional mechanical and chemical processes in series production. In addition to spatial beam shaping, temporal beam shaping with pulse trains or “bursts” containing several pulses is also possible, paving the way for increased performance.

BURST REGIMES

Due to the increase in average power, strongly focused ultrashort pulse lasers often deliver much more pulse energy than is required for efficient single-pulse ablation of metals. In order to be able to use the high pulse energies more flexibly, they are redistributed into packets of several closely spaced ultrashort sub-pulses, known as bursts, which usually consist of two to several hundred or even thousand pulses. The burst is characterized by the number of pulses, their individual energy, and, in particular, the inter-pulse delay between successive pulses within the burst. Inter-pulse delays of a few tens of nanoseconds are usually referred to as MHz-bursts, while hundreds of picoseconds correspond to so called GHz-bursts (cf. Figure 1).

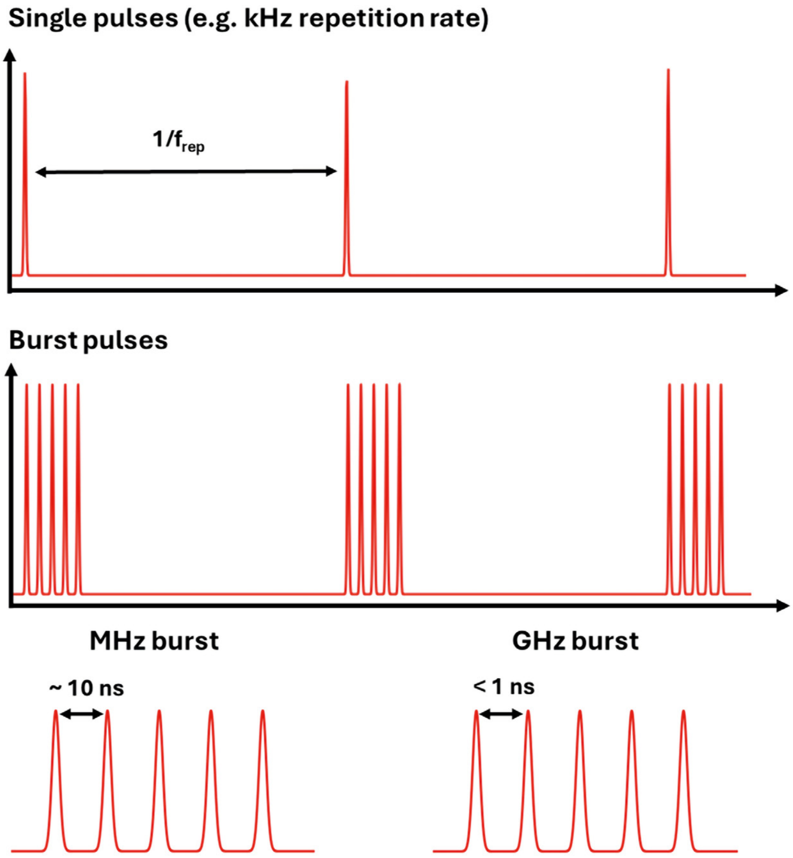

Figure 1. Schematic representation of ultra-short pulse and burst regimes in the time domain, illustrating the redistribution of the energy of an individual pulse into multiple closely spaced sub-pulses and distinguishing between MHz and GHz intra-burst delays. Combinations of both MHz- and GHz-burst pulses are called bi-bursts, which are not shown for the sake of simplicity.

BURST MACHINING OF METALS

When applied to metals, burst processing allows access to interaction regimes that differ fundamentally from those with single pulses. As the sub-pulses within a burst interact with a surface that is already electronically excited, melted, or partially shielded by plasma and vapor, both absorption and energy distribution can change significantly. Depending on the regime used, this can lead to increased ablation efficiency, altered surface morphologies, and improved surface quality at similar or even higher throughput compared to machining with single pulses [1].

Double-pulse experiments show that the second pulse can substantially modify the ablation dynamics by interacting with the transient plume and molten layer, which may either reduce or, for certain delay ranges and materials, partially recover the ablation efficiency compared to single-pulse irradiation. Fine tuning of melted layers can lead to very high surface qualities with Arithmetic Average Roughness of Ra ≈ 100 nm. In practical, in machining strategies such as for scribing and milling, the intra-burst structure determines how energy is distributed across successive phases of excitation, melting, and material removal. Precise polishing strategies can be applied, particularly using longer pulse packets in the GHz range, which consist of dozens or hundreds of sub-pulses and exhibit physical effects comparable to ns laser pulses. This results in smoother topographies and reduced heat-affected zones, but usually at the expense of ablation efficiency. MHz-bursts with intra-burst delays of 10 ns and longer, on the other hand, typically interact with expanded and hence more transparent ablation clouds and melt layers, which can promote high removal rates and efficient material ejection, but can also lead to remelting, resolidified edges, or increased micro-roughness if not carefully tuned. Selecting and switching between these modes and adjusting the number of pulses per burst provides a good way to balance throughput and surface quality for a given metal and target geometry.

Representative micromachining results achieved with metals using burst mode operation include deep grooves, cavities produced with 2.5D milling strategies (projection in a plane of the 3rd dimension), and finely structured surfaces with customized roughness and morphology. In grooves and cavities, burst machining can significantly improve sidewall morphology and the amount of redeposited material with appropriate intra-burst parameters and materials, while maintaining or slightly increasing removal efficiency compared to single-pulse machining. On flat surfaces, burst processing can be used to create deterministic micro- and nanostructures or to control the transition between rough, highly light-absorbing textures and smoother functional surfaces. An example of a geometry after laser milling of copper with MHz-bursts is shown in Figure 2.

BURST MACHINING OF BANDGAP MATERIALS - SEMICONDUCTORS

Materials featuring a bandgap such as semiconductors and dielectrics have longer thermal diffusion times and are thus extremely well-suited for taking advantage of burst-mode processing which is based on beneficial and controlled heat accumulation. For bandgap materials, bursts should typically contain several tens or hundreds of sub-pulses.

The burst-mode constitutes a very interesting and promising approach for in-bulk modifications with femtosecond pulses in semiconductors. These materials are characterized by a very high non-linear index that prevents localized energy deposition at the focal point. Thus, distributing the energy over many sub-pulses constituting a burst is a suitable strategy for overcoming the limitations observed with repetitive ultra-short single pulses. The group of David Grojo in Marseille recently carried out pioneering work based on THz-bursts for semiconductor processing, for example on Gallium Arsenide, where bursts formed by an array of subsequent birefringent crystals of different lengths were used [3]. Figure 3 shows luminescence microscopy images for single pulses and bursts with increasing number of sub-pulses (pulse duration and pulse spacing are 180 fs). Image S corresponds to the longest pulse train containing 64 sub-pulses and shows intense and very localized luminescence confirming successful and localized energy deposition with this approach.

BURST MACHINING OF BANDGAP MATERIALS - DIELECTRICS

For dielectrics, longer inter-pulse delays between the sub-pulses can be very efficient as the heat diffusion time scales are much longer than in semiconductors. MHz-bursts have been investigated for glass processing for more than two decades, in early times since 1999, with

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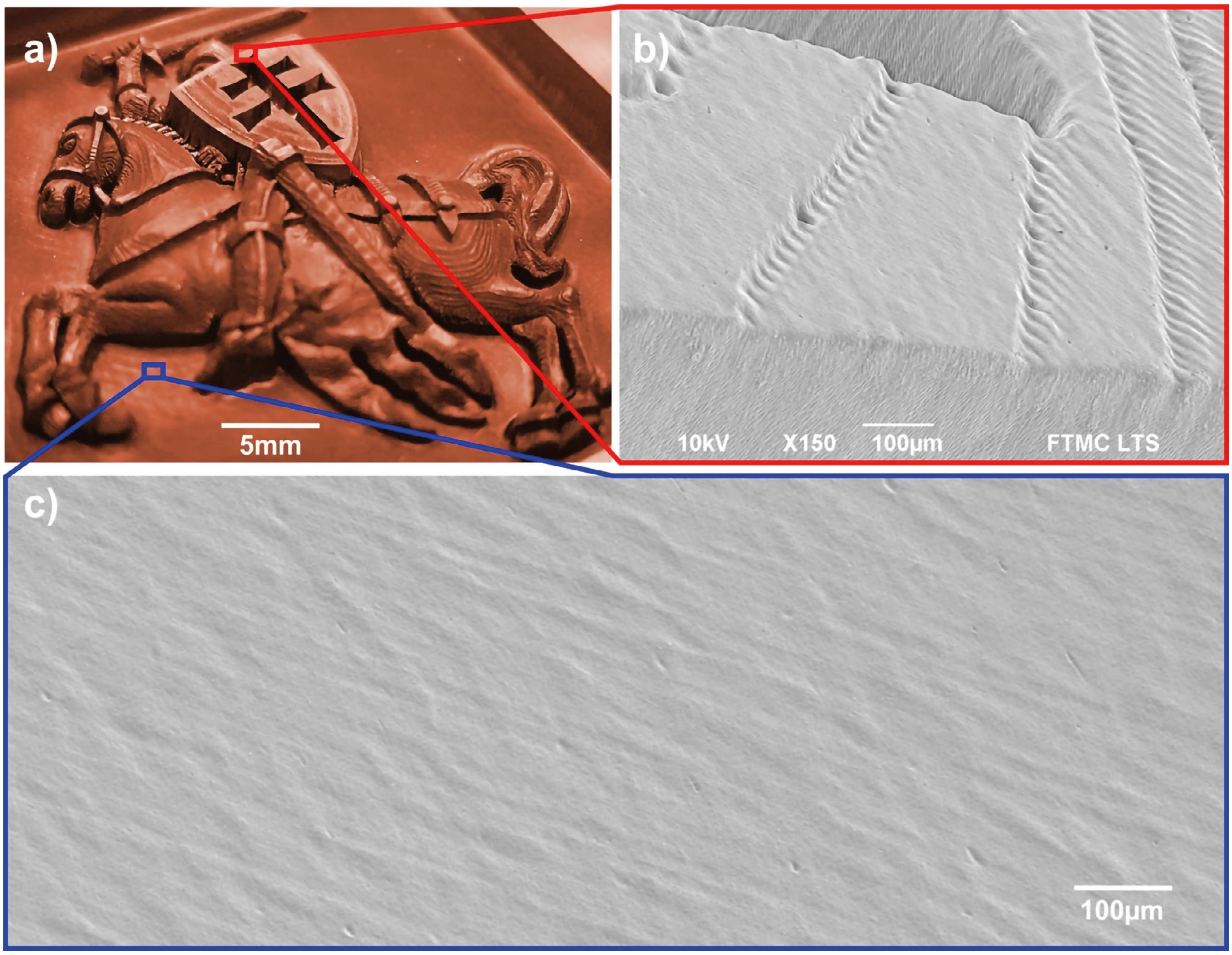
Figure 2. Example of efficient laser milling. (a) Optical image of laser milled coat of arms of Lithuania in a copper plate. (b), (c) SEM images of laser-milled surface illustrating high quality layer-by-layer removal. Reproduced under the terms of a Creative Commons Attribution 4.0 International License, (https://creativecommons.org/licenses/by/4.0/ (accessed on 04 March 2026)) [2]. Copyright 2019, the authors, published by Springer Nature.



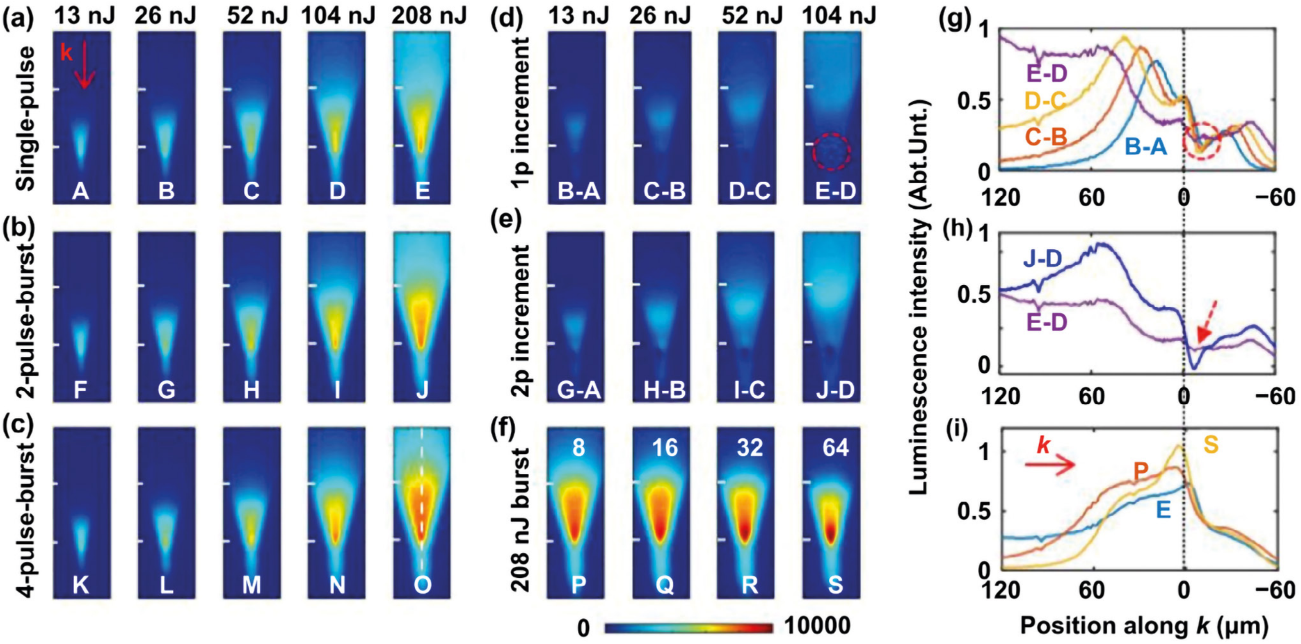


Figure 3. (a)–(c) Luminescence map excited by different pulse energies (written on the top) and different trains of pulses (written left to the images). Each image is represented by a letter written at the bottom of the image. The k vector marks the laser propagation direction. (d) Images obtained after subtraction of lower-energy maps on higher-energy maps according to the letters written at the bottom of the image. (f) Luminescence images obtained from irradiation with a total pulse energy of 208 nJ in a burst with different number of pulses in the burst as indicated on the top of each image. (g)–(i) On-axis luminescence intensity signals (white dashed line in image O) for different images. The black dotted line represents the position of the geometrical focus (z = 0 μm) [3]. Copyright 2022 under Creative Commons BY 4.0 license. https://doi.org/10.1088/2631-7990/ac8fc3.

home-made laser systems rendering systematic and comparative studies difficult. However, the benefit of heat accumulation was proven and could be explained by the gentle interaction of the laser with the glass material making it more ductile, and thus, less prone to crack formation.

Nowadays, MHz-bursts are widely used for ablation-free glass cutting with femtosecond lasers for example to cut screens of smartphones and tablets. The time spacing between sub-pulses is typically several tens of ns and the number of pulses within a burst is not necessarily very high, for example 4 to 20, for MHz-bursts of commercially available femtosecond laser sources based on Ytterbium-doped active media emitting at a wavelength of around 1030 nm and meeting industrial requirements.

The ablation-free cutting process [4] is realized in two distinct steps. First, the glass is pre-cut by defined, oriented cracks arising from the interaction with a needle-formed laser beam, a so-called Bessel-Gauss beams. The spatial beam-shaping into such Bessel-Gauss beams is achieved using an axicon and subsequent imaging to adjust the desired size of the Bessel-beam. Second, the parts are mechanically separated. The cutting process is schematically illustrated in Figure 4. The cracks can be oriented along the laser trajectory using a phase mask.

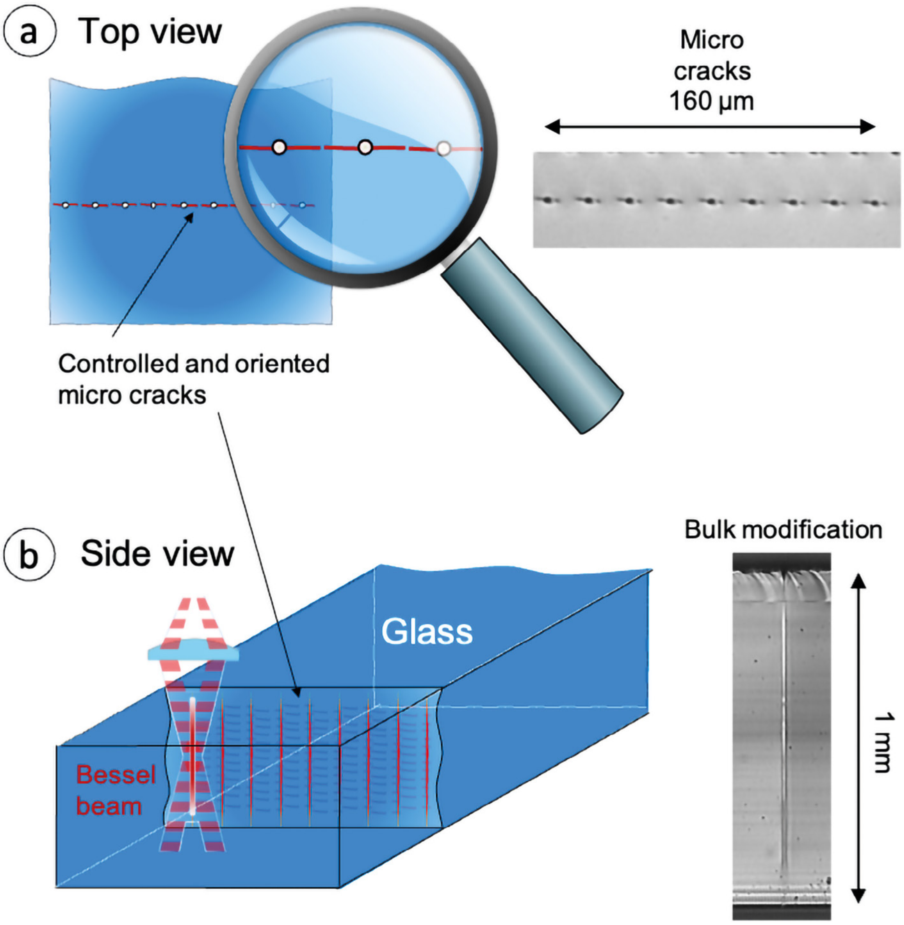
More recently, percussion drilling of different glasses using GHz-bursts was investigated. Here, the time spacing between the sub-pulses is on the order of one nanosecond, and the bursts contain several tens to hundreds of sub-pulses. The energy of the individual pulses is typically much lower than in the case of MHz-bursts.

Modern, commercially available laser systems offer the possibility of switching between operation modes of repetitive single pulses, MHz-bursts, and GHz-bursts. This allows for very accurate studies comparing the three operation regimes as the beam is delivered by the same laser source avoiding fluctuations due to system change or realignment of the beam path.

The GHz-burst approach offers the possibility of drilling holes with a rather different morphology than with standard repetitive single pulses as shown on Figure 5a. The holes produced by GHz-bursts are almost cylindrical and of outstanding quality with smooth and glossy inner walls. Moreover, much deeper drillings are possible compared to machining with repetitive single pulses at near-infrared wavelengths. In fused silica, crack-free holes of very high aspect-ratios of up to 150:1 could be demonstrated. The drilling mechanism has been described as a three-stage process [5]. First, there is surface ablation with free expansion of the plume into the ambient air. Secondly, there is deep ablation and plume confinement due to an interaction of the plume with the inner walls. The confinement induces a saturation of the drilling speed. Finally, termination of the drilling occurs when the fluence within the holes decreases below the ablation threshold due to losses caused by refraction and scattering.

Drilling of through holes (Through Glass Via or TGV) is of increasing interest for the production of glass interposers for applications in microelectronics. Figure 5b shows microscope images of a matrix of through holes in fused silica drilled in GHz-burst operation mode. The holes are very regular and the surrounding material is completely crack-free. The GHz-burst is an interesting and innovative approach for single-step

Figure 4. Schematic illustration of ablation-free glass pre-cutting with a Bessel-beam. (a) Top view of oriented cracks along the glass. (b) Side view of successive shots forming the cutting plane along the laser trajectory. On the right, microscope images.



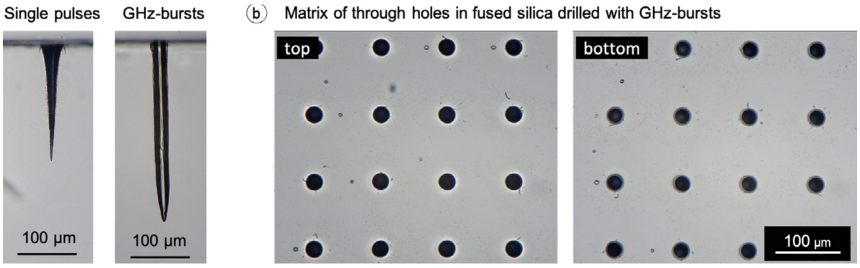


Figure 5 . (a) Microscope images of holes drilled with repetitive single pulses (left) and with GHz-bursts (right) in soda lime glass; note that all other laser parameters are identical (pulse energy, pulse duration, repetition rate, drilling time). (b) Microscope images of a matrix of TGVs in 75 µm thick fused silica seen from the top, inlet (left), and from the bottom, outlet (right).

processing without any use of chemicals and opens the path to a more efficient and more durable production method of TGV with a lower impact on the environment.

CONCLUSION

The GHz-burst mode is still a relatively new technology, and many processes such as milling, surface structuring, and welding of glasses have barely been investigated. Combining the temporal beam shaping by GHz-bursts together with spatial beam shaping into a Bessel-beam has a huge potential not only for cutting, but also for drilling. Very recently, the formation of narrow channel through holes in glass was demonstrated by applying single GHz-bursts. The ability of such a process for chemical-free "on-the-fly" drilling has an enormous potential for industrial applications. For metals, bandgap materials as well as other materials such as ceramics, burst mode processing offers the capability to completely new process regimes and wider process windows. Since surface characteristics as well as energy efficiency and throughput can be tuned independently via the parameters used, multi-step processing with intermediate switching between these different process regimes is becoming more standard in industry. More detailed information about burst processing of metals and bandgap materials can be found in Chapters 16 and 17, respectively, of a recent book [6]. ●

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