https://iopscience.org/ijem

SCIE, EI, SCOPUS, INSPEC, CAS, DOAJ, etc.

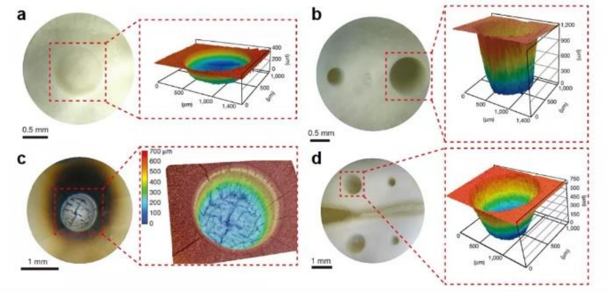
International Journal of Extreme Manufacturing

Will GHz burst mode create a new path to femtosecond laser processing?

Koji Sugioka

Highlights:

- This perspective gives the history, current status, and future challenges and prospects of this new strategy to answer the question, 'will GHz burst mode create a new path to femtosecond laser processing?'



View online: https://iopscience.iop.org/article/10.1088/2631-7990/ac2479

Article Download: https://iopscience.iop.org/article/10.1088/2631-7990/ac2479/pdf

Citation: Koji Sugioka. Will GHz burst mode create a new path to femtosecond laser processing? *Int. J. Extrem. Manuf*. **3**, 043001(2021).

Related articles:

Underwater persistent bubble-assisted femtosecond laser ablation for hierarchical micro/nanostructuring

Dongshi Zhang, Bikas Ranjan, Takuo Tanaka and Koji Sugioka

Citation: Zhang D S, Ranjan B, Tanaka T, Sugioka K. Underwater persistent bubble-assisted femtosecond laser ablation for hierarchical micro/nanostructuring. *Int. J. Extrem. Manuf*. **2**, 015001(2020).

Femtosecond laser shockwave peening ablation in liquids for hierarchical micro/nanostructuring of brittle silicon and its biological application

Dongshi Zhang, Liang-Chun Wu, Masashi Ueki, Yoshihiro Ito and Koji Sugioka

Citation: Zhang D S, Wu L C, Ueki M, Ito Y, Sugioka K, Femtosecond laser shockwave peening ablation in liquids for hierarchical micro/nanostructuring of brittle silicon and its biological application. *Int. J. Extrem. Manuf*. **2**, 045001(2020).

Irregular LIPSS produced on metals by single linearly polarized femtosecond laser

Dongshi Zhang, Ruijie Liu and Zhuguo Li

Citation: Zhang D S, Liu R J, Li Z G et al. Irregular LIPSS produced on metals by single linearly polarized femtosecond laser. *Int. J. Extrem. Manuf*. **4** 015301(2022).

Hybrid femtosecond laser three-dimensional micro-and nanoprocessing: a review

Koji Sugioka

Citation: Sugioka K. Hybrid femtosecond laser three-dimensional micro-and nanoprocessing: a review. *Int. J. Extrem. Manuf*. **1**, 012003 (2019).

Will GHz burst mode create a new path to femtosecond laser processing?

OPEN ACCESS
IOP Publishing
International Journal of Extreme Manufacturing
Int. J. Extrem. Manuf. 3 (2021) 043001 (4pp)
https://doi.org/10.1088/2631-7990/ac2479

Perspective

Will GHz burst mode create a new path to femtosecond laser processing?

Koji Sugioka

RIKEN Center for Advanced Photonics, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan
E-mail: ksugioka@riken.jp

Abstract

The GHz burst mode of femtosecond laser pulses can significantly improve ablation efficiency without deteriorating ablation quality. However, various parameters involved in GHz burst mode make it difficult to optimize the processing for practical implementation. In this Perspective, the author gives the history, current status, and future challenges and prospects of this new strategy to answer the question, 'will GHz burst mode create a new path to femtosecond laser processing?'

Femtosecond lasers have opened up new avenues in materials processing due to their distinct features, such as ultrashort pulse width and extremely high peak intensity, which provide superior performance for machining diverse materials to other conventional lasers [1, 2]. Specifically, one of the most important features of femtosecond laser processing is its ability to perform ultrahigh precision micro- and nanofabrication with high quality by suppressing the formation of heat-affected zones (HAZs). Femtosecond lasers are being widely used for commercial applications, including micromachining and trimming of electronic, automotive, and medical components; scribing and dicing of glass and sapphire substrates for smart phones and displays; fabricating anti-reflection surfaces by nanostructuring Si solar cells, scribing and patterning of copper indium gallium selenide, copper indium selenide, and inorganic solar cells; defect repair and edge cutting of micro-light emitting diode displays; and fabrication of medical stents. Improving throughput is urgently demanded to further accelerate their commercialization and industrial applications. One can imagine that throughput can be easily increased by increasing the intensity and/or repetition rate of laser pulses. However, higher intensities suffer from plasma shielding, reducing the ablation efficiency and often inducing thermal damage due to the deposition of excess energy [3]. A repetition rate higher than several hundred kHz induces heat accumulation produces large HAZs, which is not suitable for high precision or high-quality microfabrication [4].

Ilday's group recently demonstrated that bursts of femtosecond laser pulses with GHz repetition rate can enhance the ablation efficiency with improved ablation quality, as shown in figure 1 [5]. They claimed that the target material is ablated before the residual heat deposited by previous pulses diffuses away from the processing region to increase ablation efficiency (one-order higher). They further claimed that the physical removal of ablated materials carries away the thermal energy contained in the ablated mass, resulting in high-quality ablation with no thermal effect. They call this process ablation cooling. These results have

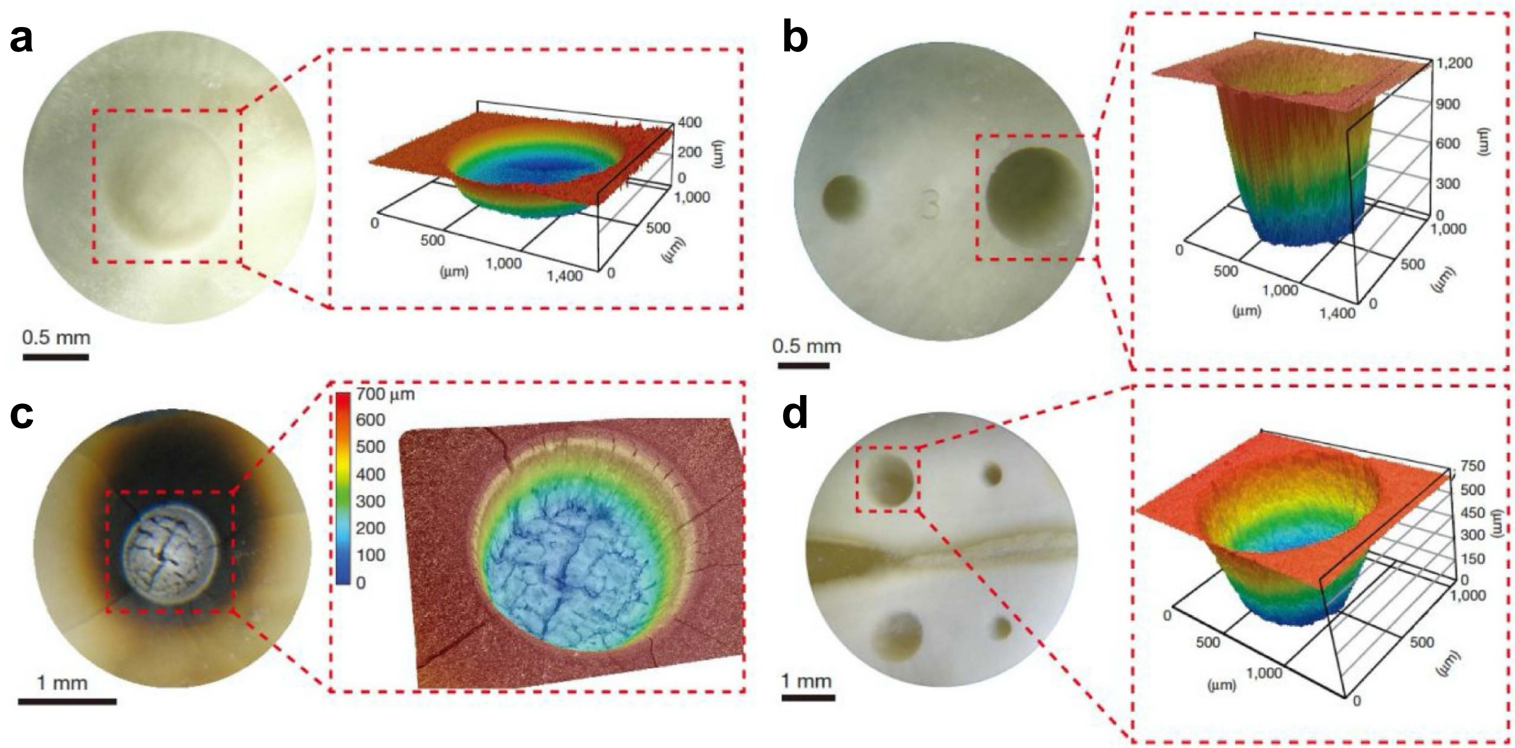


Figure 1. Laser ablation of human dentine by the conventional scheme ((a), 1 kHz uniform repetition rate) and GHz burst mode ((b), 1.7 GHz intraburst repetition rate). Although both schemes avoid thermal damage at sufficiently low average powers, the GHz burst mode creates approximately six times deeper ablation crater despite about a 12 times lower pulse energy. (c) and (d) When the repetition rate, average power and scanning speed are simultaneously increased by a factor of 25, the conventional scheme results in thermal damage, whereas the GHz burst mode completely avoids thermal effects and achieves much higher ablation rate, despite using a 25 times lower pulse energy. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Nature, Kerse *et al* [5].

overturned common sense and significantly impacted the community of laser materials processing.

Despite the community's interest in GHz burst mode, the lack of laser sources has made it more difficult for researchers to perform experiments that further explore this process. However, some laser manufactures have started to develop femtosecond laser systems that can operate in GHz burst mode, allowing some research groups to investigate GHz burst mode ablation of metals, such as cupper, stainless steel, and aluminum [6–12], as well as semiconductors and dielectric materials, such as silicon, silicon carbide, fused silica, and Kapton [6–8, 13]. Typically, GHz burst mode creates ablated surfaces with better quality as compared with the conventional single mode [7, 11, 13]. The superior surface quality may rely on ablation cooling. However, GHz enables gentle heating and melting in a more controlled manner to create smoother ablated surfaces because resolidified layers were evidently observed at the ablated surfaces of some materials, which is regarded as more possible mechanism. Additionally, optimizing parameters, such as the number of intra-pulses, pulse-to-pulse interval (repetition rate of intra-pulses), and the burst energy (total energy of all intra-pluses in a burst), is important to achieve higher ablation quality. On the other hand, ablation efficiency significantly depends on the type of material. Specifically, compared to the conventional single mode, GHz burst mode achieves higher ablation efficiency for semiconductors and dielectrics, including silicon, silicon carbide, fused silica, and Kapton, and achieves lower ablation efficiency for metals [8, 11, 13]. The author speculates that the ablation efficiency should be closely related to the absorption process of laser pulses by the materials. For bandgap materials, laser energy is first absorbed by bound electrons in the valence band to generate free electrons in the conduction band. The excited free electrons can efficiently absorb subsequent pulses in the burst to increase the ablation efficiency. In contrast, for metals, free electrons always absorb the laser energy. Laser energy discretely dispersed in the burst may inhibit efficient energy deposition due to the diffusion or dissipation of heat generated by preceding pulses. Plasma shielding is another important factor affecting ablation efficiency, since plasma dynamics depend on the materials ablated.

GHz burst mode processing involves various parameters, such as the number, duration, and energy of intra-pulses as well as the time interval of each intra-pulse. Additionally, the different energy distributions of intra-pulses in the bursts (e.g. gradually increased, gradually decreased, or mountain-shaped distribution of intra-pulse energy) should provide different results even for the same burst energy. GHz burst in MHz burst (BiBurst) further offers a unique scheme for more practical use [10]. The research on GHz burst mode processing is still in its infancy, and the accumulation of a massive amount of data with different parameters and different materials is necessary. A fully automated data acquisition system for GHz burst mode processing combined with deep learning based on collected big data using an artificial intelligence is a good solution to accelerate practical implementation of this process [14]. A theoretical approach based on physics theories is also important; although, the huge parameters present many challenges. Another key factor is the development of a high-performance laser system which can easily, flexibly adjust parameters in the GHz bursts mentioned above.

The relatively slow processing speed of femtosecond laser ablation is a bottleneck for industrial implementation, which will be overcome by significantly enhancing ablation efficiency without deteriorating ablation quality with GHz burst mode. Furthermore, GHz burst may offer a new possibility for processing other than ablation. In particular, the capability of gentle heating and melting in a controlled manner will be effective for processing based on thermal reactions, such as microbonding, crystallization, and polishing. Applying to the processing specific to femtosecond lasers, including two-photon polymerization, internal optical waveguide writing, and the formation of high spatial frequency laser induced periodic structures, could produce distinct features. Thus, the author believes that GHz burst mode will open new paths to femtosecond laser processing.

Acknowledgments

This work was partially supported by MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant No. JPMXS0118067246.

ORCID iD

Koji Sugioka https://orcid.org/0000-0002-7174-5961

References

[1] Sugioka K and Cheng Y 2014 Ultrafast lasers—reliable tools for advanced materials processing *Light* **3** e149
[2] Sugioka K 2017 Progress in ultrafast laser processing and future prospects *Nanophotonics* **6** 393–413
[3] Ancona A, Röser F, Rademaker K, Limpert J, Nolte S and Tünnermann A 2008 High speed laser drilling of metals using a high repetition rate, high average power ultrafast fiber CPA system *Opt. Express* **16** 8958–68
[4] Eaton S M, Zhang H B, Herman P R, Yoshino F, Shah L, Bovatsek J and Arai A Y 2005 Heat accumulation effects in femtosecond laser-written waveguides with variable repetition rate *Opt. Express* **13** 4708–16
[5] Kerse C *et al* 2016 Ablation-cooled material removal with ultrafast bursts of pulses *Nature* **537** 84–8
[6] Bonamis G, Audouard E, Hönninger C, Lopez J, Mishchik K, Mottay E and Manek-Hönninger I 2020 Systematic study of laser ablation with GHz bursts of femtosecond pulses *Opt. Express* **28** 27702–14
[7] Metzner D, Lickschat P and Weißmantel S 2020 High-quality surface treatment using GHz burst mode with tunable ultrashort pulses *Appl. Surf. Sci.* **531** 147270
[8] Hodgson N, Allegre H, Starodoumov A and Bettencourt S 2020 Femtosecond laser ablation in burst mode as a function of pulse fluence and intra-burst repetition rate *J. Laser Micro Nanoeng.* **15** 236–44
[9] Metzner D, Lickschat P and Weißmantel S 2021 Optimization of the ablation process using ultrashort pulsed laser radiation in different burst modes *J. Laser Appl.* **33** 012057
[10] Žemaitis A, Gaidys M, Gečys P, Barkauskas M and Gedvilas M 2021 Femtosecond laser ablation by bibursts in the MHz and GHz pulse repetition rates *Opt. Express* **29** 7641–53
[11] Obata K, Caballero-Lucas F and Sugioka K 2021 Material processing at GHz burst mode by femtosecond laser ablation *J. Laser Micro Nanoeng.* **16** 19–23
[12] Balachninaitė O, Tamulienė V, Eičas L and Vaičaitis V 2021 Laser micromachining of steel and copper using femtosecond laser pulses in GHz burst mode *Results Phys.* **22** 103847
[13] Mishchik K, Bonamis G, Qiao J, Lopez J, Audouard E, Mottay E, Hönninger C and Manek-Hönninger I 2019 High-efficiency femtosecond ablation of silicon with GHz repetition rate laser source *Opt. Lett.* **44** 2193–6
[14] Kobayashi Y, Takahashi T, Nakazato T, Sakurai H, Tamaru H, Ishikawa K L, Sakaue K and Tani S 2021 Fully automated data acquisition for laser production cyber-physical system *IEEE J. Sel. Top. Quantum Electron.* **27** 1–8