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Study of the ablation efficiency for USP-processing of different materials in the GHz-Burst-Regime

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Abstract

We studied the ablation efficiency on crater formation, line scribing and cavity milling experiments on copper, silicon, stainless steel and ceramics with picosecond GHz burst pulses. The intra-burst repetition rate was 5.12 GHz, the number of pulses per bust was varied between 128, 512 and 1024 within a burst fluence of up to 19 J/cm². For the inter-burst repetition rate of 200 kHz, the used laser system had a maximum average power of 100 W and maximum pulse energy of 500 µJ. The high repetition rate was created through a pulse-divider-module outside of the laser system. The results show a growth of ablation efficiency compared to kHz processing by a minimum of two times for all processing technics on silicon and copper and for crater formation and line scribing on stainless steel. A comparable efficiency remains for ceramics. The resulting machining quality is affected by the heat input but remains comparable.

Keywords: GHz; burst mode; ultrashort pulse; ablation efficiency.

1. Introduction

Industrial material processing with ultra-short pulse (USP) laser systems is nowadays well established. Especially for micromachining, the processes benefits from its accuracy, high flexibility, as well as the availability of compact and reliable laser systems. Nevertheless, the disadvantages of the currently used USP processing techniques are the relatively long processing times due to the low ablation rates in comparison to material processing with other laser systems (e.g., ns- and cw-lasers). To overcome this disadvantage, laser sources with more and more average power and maximum pulse energy are developed. However, fundamentally every material has an optimal energy per area (fluence), for which the processing, in terms of the specific ablation rate (mm³/(W*min)), is most efficient [1]. Therefore, the challenge is to use the high average powers for material processing without losing the above-mentioned advantages. To realize this, several different methods to optimize the spatial and temporal energy input can be used, e.g., beam splitting, beam shaping, and fast beam deflection.

A relatively new method is the usage of high repetition rates (> MHz). Modern laser systems are capable of generating single pulses, which are temporally divided in trains of pulses (bursts). In this case, the initial single pulse energy is divided by the number of pulses within the burst. The intra burst repetition rate in general corresponds to the seed laser frequency (mostly few tens of MHz/>10 ns). By carefully choosing the processing parameters (energy per pulse, used number of pulses per burst, as well as inter and intra burst repetition rate) an increase of the ablation efficiency of 10–30 % is possible, compared to single pulse ablation [2].

A few years ago, this method was extended towards repetition rates into the range of GHz, and a significant increase of the ablation efficiency for copper and silicon could be demonstrated [3]. Since this publication, various research teams with different laser- and processing parameters have dealt with this subject. However, the works are showing controversial results in terms of an increased ablation efficiency, the resulting machining quality as well as the transfer onto other materials and processing techniques (e.g., line scribing and cavity milling) [3–6]. Due to the strong dependency on the laser parameters used and the different results, further investigations are necessary in order to better assess the influence and benefits of this processing method.

In this work, we compare the specific ablation efficiency between kHz and GHz machining in terms of crater formation, line scribing and cavity milling in the available process parameter space. The experiments were carried out on four different materials: silicon, copper, stainless steel and ceramic.

2. Experimental setup and analysis methods

The experiments were performed with a micromachining laser system of industrial design. The used laser source was an *Amphos A100* with a fundamental wavelength of 1030 nm and a pulse duration of 0.95 ps. The system has a maximum average power of 100 W with a pulse energy of 500 µJ at a repetition rate of 200 kHz. The internal burst mode divides the pulse energy of one pulse into the number of pulses in the burst (2–100). The intra burst repetition rate corresponds to the seed laser frequency of 40 MHz/0.25 ns. To achieve a repetition rate in the range of GHz, an additional external pulse-divider-module from *Active Fiber Systems GmbH* was used. Via polarization-dependent beam splitters and 7 delay lines one pulse was divided into 2^7 (128) pulses with a repetition rate/time interval of 5.12 GHz/195 ps, see Fig. 1a. The individual pulse energies were homogenized as much as possible in this configuration, see Fig. 1b. In combination with the initial burst mode, the resulting number of intra burst pulses was set.

In the GHz regime, the influence of 128, 512 and 1024 intra burst pulses on the specific ablation efficiency was investigated and compared to the results of conventional processing with 200 kHz. The laser beam was guided by a two-axis galvo scanner (IntelliScan se 14; *SCANLAB GmbH*). For the kHz-experiments, the beam is focused with a 100 mm f-theta lens, resulting in a beam diameter of 45 µm ($1/e^2$) and a maximum fluence of 30 J/cm². For the GHz-experiments, the beam is focused with a 79 mm aspheric lens, resulting in a beam diameter of 53 µm ($1/e^2$) and a maximum fluence of 19 J/cm².

For line scribing, lines with 2 mm length and single pulse width and for cavity milling squares with an edge length of 2 x 2 mm were processed. For the kHz-experiments the pulse distance was varied between 2.2–29 µm and for the GHz-experiments between 8–29µm. The line distance was varied between 4.5–31.5 µm (kHz) and 5–37µm (GHz), see Fig. 1c. For crater formation, a fixed number of pulses was applied on a fixed position. To take account of accumulation effects, 64 (kHz) and 20 (GHz) pulses/passes were applied for every process. Additionally, for cavity milling, the orientation of the scanning lines was rotated by the angle of 2.8° (kHz) and 4.5° (GHz) after every pass.

The experimental design and subsequent analysis of the results was performed using the computer-aided engineering (CAE) software *optiSLang*. The resulting multidimensional parameter spaces were filled with sampling points (parameter combinations) using the *Advanced Latin Hypercube Sampling* method.

After the processing, the material samples were cleaned in an ultrasonic bath, subsequently measured with a laser-scanning microscope and evaluated with the corresponding analysis software. For crater formation the ablation volume, for line scribing an averaged cross-section and for cavity milling the ablation depth was measured. Finally, the specific ablation rate was calculated based on the process and removal parameters, according to [4].

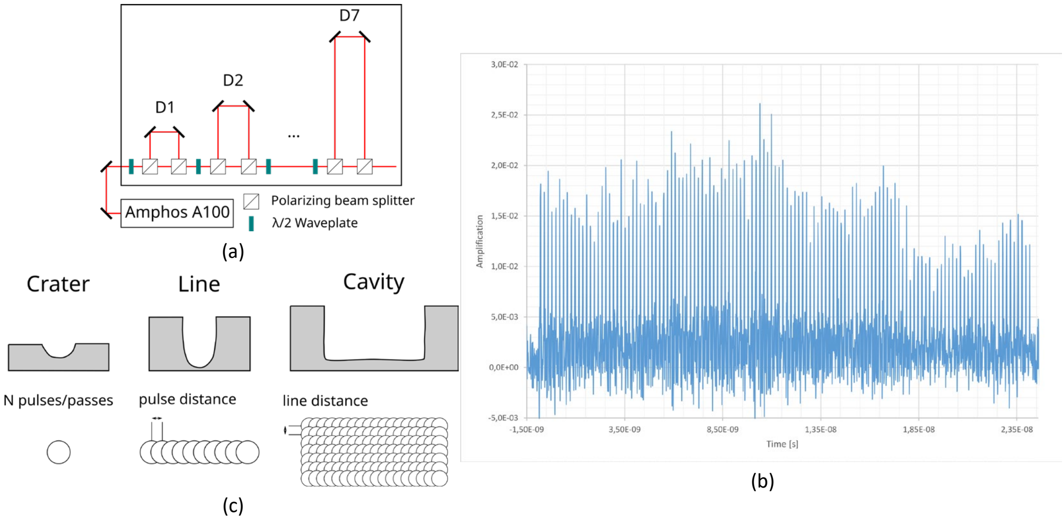


Fig. 1. (a) Schematic drawing of the generation of the 128 pulses with a time delay interval of 195 ps/5.12 GHz; (b) Measured 128 pulse burst energy distribution at 5.12 GHz. The non-constant pulse energy pattern is explained by small material imperfections of the used optical elements and slightly misaligned orientation of the polarization; (c) Schematic drawing of the processing strategies.

3. Results

3.1. Analysis model and correlations

All parameters used as well as the corresponding measured material removal were entered into *optiSLang* for evaluation. From those data, *optiSLang* created a metamodel of optimal prognosis (MOP) using variance-based sensitivity analysis, which examines the influence of the input parameters on the system responses and thus classifies sensitive parameters. The analysis captures correlations in the entire parameter space and thus determines the best-fitting substitute model (polynomial approach or moving least squares with linear or quadratic basis). The model is visualized via a three-dimensional response surface diagram (RSD), which takes into account the relationships between the input parameters used and the effect on the output parameters, whereby a section of the multi-dimensional parameter space can be represented. The validity of the MOP and the correlations of the input parameters on the output parameters can then be assessed using the coefficient of prognosis (CoP), which is a model-independent measure for the evaluation of the model quality. The resulting values are of qualitative nature but allow an overview of the pronounced dependencies and the correlation of the input parameters on the output parameter. Exemplary, the resulting RSD and the corresponding CoP for cavity milling are presented in Fig. 2a–e. A positive/negative value of the correlation of the input parameter can be interpreted in such a way that an increase/reduction of the parameter causes an increase of the output parameter.

Based on the data evaluated by *optiSlang*, the following trends can be identified with regard to the influence of the input parameters of the three processing strategies: The number of pulses per burst and the fluence per pulse exert the greatest influence on the specific ablation rate with > 50% CoP. There is a positive correlation for the number of pulses per burst, from which it can be deduced that a higher number of pulses improves the efficiency. For the fluence per pulse, there is a negative correlation, which indicates that maximum fluence is not associated with maximum efficiency. The influence of the pulse and line distance plays a subordinate role in cavity milling with < 20% CoP and a material-dependent correlation. For line scribing there is a moderate influence with 20–60% CoP. In connection with the positive correlation, it results that a better efficiency can be achieved with a larger pulse spacing. This behavior can be explained by the influence of the heat input into the material, which is higher for line scribing due to the shorter accumulation time and thus turns out to faster have a negative impact, which can be prevented by a larger pulse spacing/faster scanner movement.

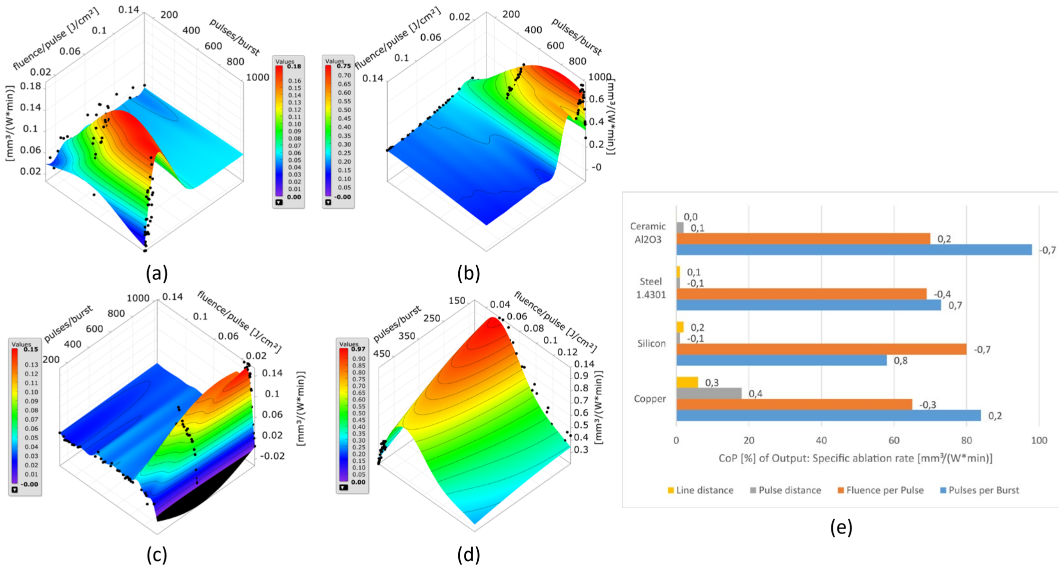


Fig. 2. From the analysis of the cavity milling data via *optiSLang* resulting MOP and visualization as RSD for copper (a), silicon (b), steel (c) and ceramic (d), as well as the associated qualitative evaluation of the model using CoP and the correlations (numbers after the bar) of the input parameter onto the output parameter (e).

3.2. Ablation efficiency

To classify the obtained ablation efficiencies for the GHz machining experiments, the maximum specific ablation efficiency for the used machining parameters at 200 kHz was determined in advance. The obtained values are listed in Tab. 1 and compared with values researched from existing literature [7–10]. The values for crater formation and line scribing are in good agreement with the literature values, for cavity milling, larger deviations are shown. These can be explained by the fact that the literature values generally apply to crater formation, so that for cavity milling accumulation effects like the heat input, exert a greater influence.

Table 1. Comparison of literature values for the specific ablation efficiency *Eff* [mm³/(W*min)] [7–10] and the corresponding ablation threshold F_{th} [J/cm²] in the kHz range with the values determined by our experiments for the different machining strategies.

	F_{th}	$Eff_{Literature}$	Eff_{Crater}	Eff_{Line}	Eff_{Cavity}
Copper	0.23	0.15	0.12	0.13	0.17

Silicon	0.18	0.13	0.10	0.17	0.95
Steel 1.4301	0.05	0.19	0.13	0.37	0.32
Ceramic Al2O3	0.74	0.55	0.42	0.41	1.02

Fig. 3 shows the maximum specific removal efficiencies and associated burst fluence per material obtained from the experiments. As described in 3.1 by the model analysis of *optiSLang*, it is difficult to identify a general trend regarding the influence of the different parameters related to obtaining the maximum specific ablation efficiency. Accordingly, the influence of the parameters is material specific.

However, in general, the results show a growth of efficiency compared to kHz machining of at least two times for all processing technics on silicon and copper and for crater formation and line scribing on stainless steel. A comparable efficiency remains for ceramics. For machining of ceramics, it should be noted that due to the limited maximum fluence, no ablation could be generated for 1024 pulses per burst, and the available parameter space was limited accordingly for 128 and 512 pulses, which reduces the significance of these results. In all cases, the single pulse fluence remains significantly below the ablation threshold.

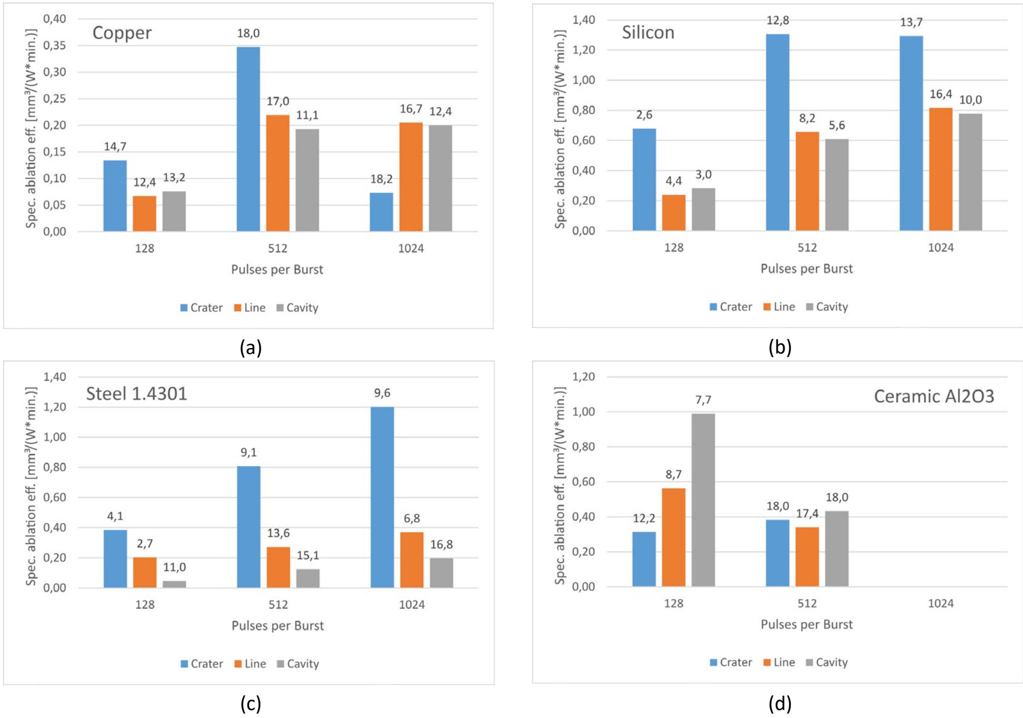


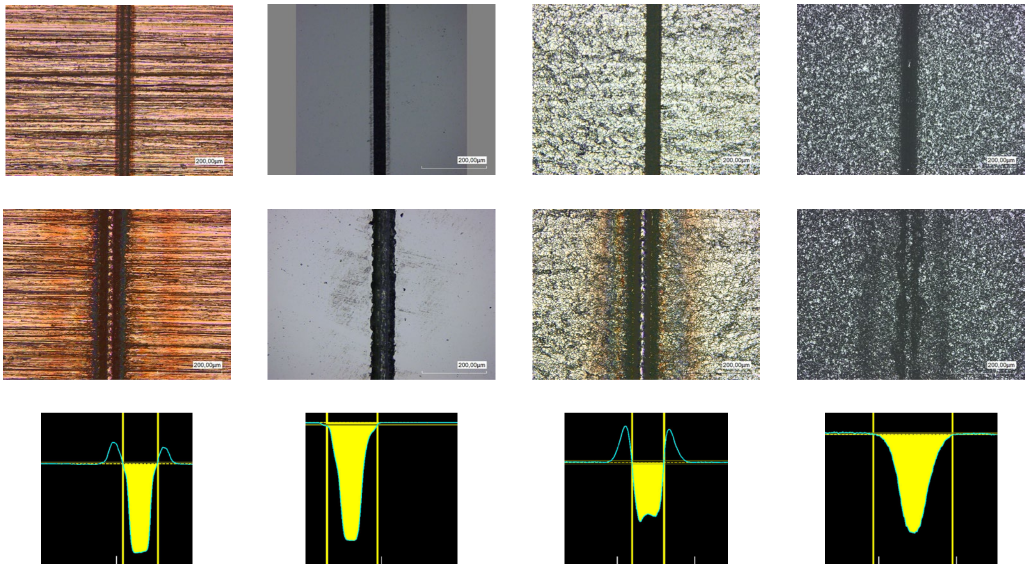
Fig. 3. Presentation of the maximum specific ablation efficiency obtained from the GHz-processing experiments and their associated fluences for the investigated different materials, machining strategies and number of intra burst pulses.

If the results are compared with the results from other research [3–5], two further trends can be identified. First, GHz machining is the most efficient for drilling, but the efficiency decreases in case of line scribing and surface machining. Second, for a fixed intra burst repetition rate, an increasing number of intra burst pulses improves the efficiency when the corresponding burst fluence is also increased (>19 J/cm³).

3.3. Machining quality

The increase in material removal efficiency achieved by GHz-machining can lead to deterioration of the machining quality. For a qualitative classification of the ablation, Tab. 4 compares exemplary microscopic images for the parameter combinations with the highest specific ablation efficiency of the kHz-machining with those of the GHz-machining for line scribing. In addition, the corresponding averaged profile sections for GHz-machining are shown.

For kHz processing, it shows a high quality without significant heat influence, material redeposition and a clearly defined kerf. For GHz-machining, all materials show that an irregular cutting edge is formed. For the metals, it is also evident that material is re-deposited outside the kerf, and that a heat-affected zone of approx. 150 µm is formed.



(a) (b) (c) (d)

Fig. 4. Microscopic images of the kerf of the parameters with the highest specific removal efficiency for kHz (first line) and GHz (second line) machining of copper (a), silicon (b), steel (c) and ceramics (d). The third line shows the averaged profile section for GHz machining.

4. Conclusion

The experimental study carried out shows the possibilities of increasing the specific ablation efficiency for the machined materials and processing strategies by using repetition rates in the GHz range in combination with high average powers and moderate fluences up to 19 J/cm².

In addition, it was shown that repetition rates in the GHz range could also be generated for existing laser systems with calculable effort using an external pulse divider module. However, if possible, one should do without an additional module and use an adapted usp laser system, which internally generates the repetition rates needed.

The experimental design and evaluation regarding the influence of different machining parameters was supported by the computer-aided engineering (CAE) software *optiSLang*. That way it can be shown that the number of pulses in the burst at a given processing frequency, and the fluence used, have the greatest influence on the material removal process. The fluence of the sub pulses in any case remains clearly below the ablation threshold. The influence of the pulse and line distance are comparatively negligible but must still be taken into account in order to optimize the material removal results; larger distances have a positive effect on the efficiency. With regard to the machined metals, a non-negligible heat influence is also evident for all relevant configurations investigated, which ensures that some of the removed material is deposited as debris at the edge of the ablation surface and does not evaporate. In general, there is a strong dependence of the resulting ablation of the GHz processing on the laser parameters used.

Acknowledgements

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