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Advanced metal ablation based on highly flexible ultra-short pulsed laser platforms

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Abstract

Considering the energy efficiency and the ablation quality, micromachining of several metals is examined for different processing regimes depending on timescales from fs to µs. Choosing an optimized temporal energy deposition can address a variety of machining aspects like ablation efficiency and surface morphologies. Using the unique features of the TRUMPF TruMicro series, the temporal energy deposition can be influenced during operation on a femto- up to a microsecond timescale by tuning parameters such as the ultrashort pulse duration or employing bursts in the MHz- and GHz-regime. This enhanced flexibility paired with patent-pending process strategies leads to cutting-edge processing speeds and surface qualities.

Keywords: micromachining; industrial lasers; metals; ultrafast; temporal energy deposition; pulse tunability; burst optimization;

1. Introduction

Ultra-short pulsed (USP) laser material processing provides many advantages compared to traditional processes and has found a large number of applications in various fields. The significantly reduced heat affected zone and the ability to machine a multitude of different materials are among the most outstanding advantages. In order to address the growing field of applications, target materials and customer requirements, an easy machine integration, a superior reliability in industrial environments as well as a high degree of pulse parameter flexibility is required. Beside other important laser features, different pulse durations, burst patterns, pulse energy levels and pulse repetition rates are needed to optimize the spatial and temporal energy deposition [Kanal et al., 2017].

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TRUMPF's TruMicro ultra-short pulsed laser portfolio is designed to fulfill these demands by employing the know-how of many tens of thousands of operational hours for individual lasers and accumulated tens of millions of operational hours in industrial environments [Jansen et al., 2018].

Beside the machining of brittle materials like glasses and ceramics where USP-laser processes offer unrivaled advantages for some applications, USP-metal ablation has also found several key applications within the last decade like injection nozzle drilling [König, 2011]. Among metal drilling and cutting processes, also high-quality engraving applications (see fig. 1) have found a huge interest in different industrial fields like the watch or jewelry industry. Established engraving processes like chemical etching can be replaced by more environmentally friendly and more flexible processes if the laser-based process can fulfill several aspects like productivity and machining quality.

In contrast to nanosecond processing where post-processing might be necessary, USP lasers offer the possibility to machine smallest feature sizes without any burr or heat affected zones (HAZ). To enable these unique advantages of USP lasers, it is crucial to understand the effect of different processing parameters on surface quality and ablation rate. Since these two key aspects are directly linked to the temporal and spatial energy deposition during machining, a flexible laser and machining system can be the key for industrial implementation of such a new production technology.

Spatial as well as temporal energy deposition can be optimized by tuning various parameters of the laser itself and the subsequent system technology. In contrast to the temporal energy deposition, which is primarily optimized by tuning laser parameters, for the spatial energy deposition, the interplay of the laser and system technology after the laser itself is the key for an efficient production process. Here, especially the optical setup as well as the beam deflection system are important aspects beside the laser parameters, that are responsible for the efficiency of machining with ultrashort laser pulses.

The optical setup (for example the usable maximum spot size) is often constrained for a high-quality metal engraving, due to certain demands of the specific application like small feature sizes. On the other hand, the efficiency of ablation strongly depends on the applied fluence [Raciukaitis et al., 2009]. This correlation shows that spatial and temporal energy deposition are directly linked to each other and all parameters must be tuned to the special demands of a certain application and material. Therefore, in this paper we will focus on the flexible energy deposition on a femto- to a microsecond- timescale in order to address a variety of machining challenges like the surface roughness and ablation rate.

Fig. 1. High-quality engravings in (a) titanium, (b) stainless steel (DIN EN 1.4404) and (c) copper. Highly flexible laser systems can address all kind of surface qualities by tailoring the temporal energy deposition on several orders of magnitude from a fs- to µs-timescale.

Due to the flexibility of the TruMicro Series 2000 (fig. 2, left and center), automated tests for determining important material characteristics like ablation efficiency (AE) and quality aspects were performed. Therefore, the ablation of small pockets (fig. 2 (c)) was evaluated for numerous laser parameters influencing the temporal energy deposition. Characterizing the best parameters for each process phase (e.g. high-speed ablation, surface roughness setting, color adjustment), a combined processing strategy enables the possibility to merge highest processing speeds with best surface qualities. By tailoring the temporal energy deposition on several orders of magnitude from a fs- to µs-timescale, flexible ultra-short pulsed laser platforms like TruMicro 2000 enable unique features and possibilities to address all kind of machining challenges.

2. Experimental Setup

For determining important material characteristics like ablation efficiency and machined surface quality, we used a TruMicro Series 2000 (fig. 2 (a)), integrated into a TruLaser Station 5005 (fig. 2 (b)). The machine supports full NC-programming, which offers the possibility to automate a wide field of parameter testing without interrupting the machine, e.g. to exchange the workpiece.

The collimated beam diameter (5 mm) was focused with a f = 100 mm f-theta telecentric lens, resulting in a spot-diameter (1/e²) of ~30 µm. To cover a useful range of fluence levels, the laser was set to a suitable repetition rate and pulse energy level.

Fig. 2. (a) TruMicro Series 2000. (b) TruLaser Station 5005. (c) Ablation of small pockets to evaluate ablation efficiency and surface quality depending on the applied laser parameters.

The fluence level itself was varied for each material with the built-in linearized and stabilized external modulator, enabling the control of the pulse energy level output. Due to the integrated “Quad-loop-stabilization” [Jansen et al., 2018], pulse energy fluctuations as low as < 2 % are guaranteed and a constant user defined pulse energy is applied to the workpiece. The maximum single-pulse energy level was 100 µJ, the maximum (cumulated) burst energy was 300 µJ. The beam deflection was realized with a SCANLAB excelliSCAN 14 galvanometer scanner, the scan speed was chosen with respect to the used repetition rate of the laser to provide useful pulse overlaps in the region of 50-90 %. By choosing a fixed line distance, the ablation of small pockets (1x0.5 mm²) was realized (fig. 2 (c)). The number of passes, i.e. the total number of pulses or energy per area, was adjusted in order to achieve a depth of at least several tens of micrometers for each parameter.

The depth of ablation and surface roughness were measured with a laser scanning microscope. Regarding the temporal energy deposition, different pulse durations as well as different burst settings were applied. The laser offers the unique feature of a fast tunable pulse duration within 300 fs to 20 ps (100 fs increments, < 800 ms (!) switching time), without affecting fundamental parameters like beam quality, beam pointing or energy stability, which can be a crucial factor when comparing single laser parameters with one flexible laser system. In terms of temporal energy deposition also pulse-bursts were studied with a temporal pulse separation of 20 ns (50 MHz), where each pulse has the same energy level within the burst. Finally, also GHz-bursts were investigated, providing a pulse repetition rate of 1.6 GHz. Here, the minimum number of pulses within a GHz-burst was 32. In all tests and laser parameter configurations, the laser was used with a fundamental wavelength of 1030 nm and had a gaussian energy distribution with a beam quality of M^2=1.1.

3. Results and Discussions

For each addressable timescale of temporal energy deposition (see fig. 3), both key aspects of USP-metal engraving: Ablation efficiency (which is directly linked to ablation rate) and ablation quality were evaluated. All generated results in terms of ablation efficiencies at the specific timescales are at the optimum energy / fluence levels [Neuenschwander et al., 2014]:

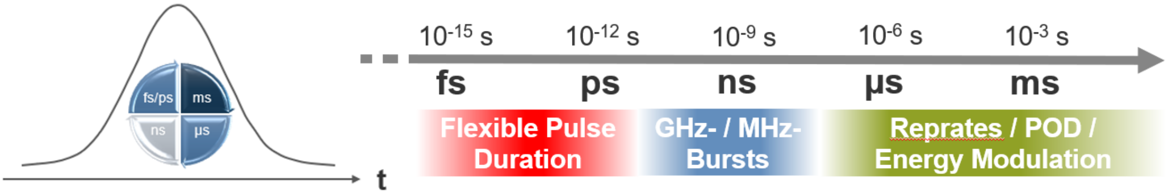

Fig. 3. Overview of laser features related to their addressable timescales, which all influence the temporal energy deposition and thus ablation rates and machining quality.

3.1. Energy deposition on a fs- to ps- timescale

Looking at the efficiency of temporal energy deposition on a femto- to picosecond timescale, a clear trend can be seen toward shorter pulses: For volume ablation on metals (fig. 4), decreasing the pulse duration from 20 ps to 300 fs can improve ablation efficiency by a factor of up to 5 (titanium, steel). Depending on the material, a plateau can be seen for shorter pulse durations. This plateau is reached at around 1 ps for all investigated metals. Shorter pulse durations below this point do not result in a further increase of ablation efficiency within measuring tolerances. For copper, brass and aluminum the decrease of efficiency starts slightly slower at around 5 ps and is less pronounced than for the other materials in the investigated regime.

The differences in energy efficiency decrease depending on the pulse duration for the investigated materials can be explained by different electron-phonon interaction times. The general trend of energy efficiency in the USP-regime is well known [Jaeggi et al., 2011] and can be linked to a change in laser induced stress and pressure waves inside the material [McDonnell et al., 2019], influencing photomechanical ablation mechanisms.

It should be noted that all effects on a fs- to ps-timescale regarding quality are closely linked to longer timescales as well as the spatial energy deposition. E.g. a high spatial pulse overlap typically decreases machining quality. While energy efficiency increases for all investigated metals for shorter pulses, longer pulses in the USP-regime can also be beneficial for quality aspects of micromachining on some materials.

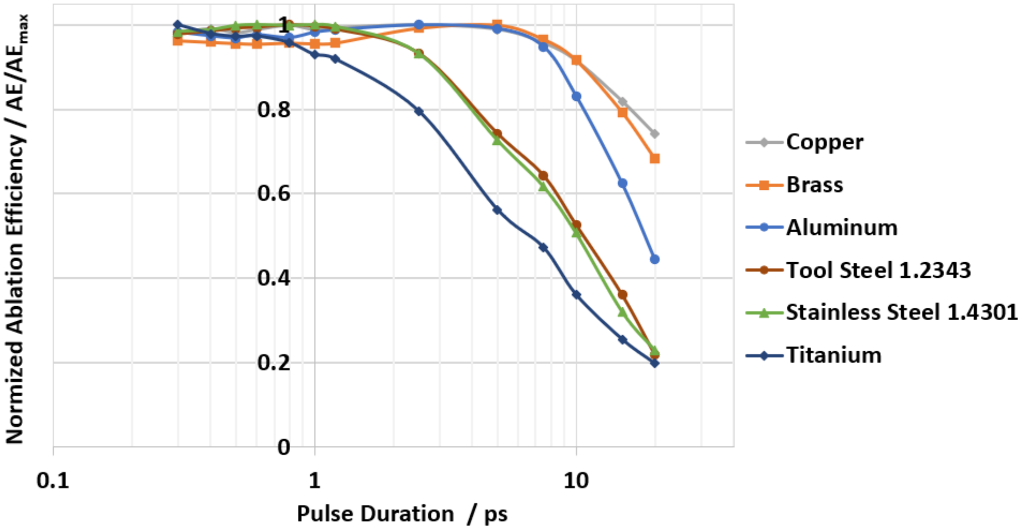

Fig. 4. Normalized ablation efficiency depending on the pulse duration for various metals. For the optimum fluence, depending on the material, the ablation efficiency can be up to 5 times higher by decreasing the pulse duration from 20 ps to 300 fs. For most metals, an efficiency plateau is observed at around 1 ps below which a further decrease of pulse duration does not result in an increased efficiency.

Fig. 5 qualitatively shows the processed surfaces of the investigated metals. For each material, all parameters are kept constant except the pulse duration. Each individual microscope image includes the raw material in the top half and the machined surface in the bottom half. Again, the optimum fluence level was chosen for every material. Due to different energy levels for an optimum fluence level, different repetition rates and thus pulse overlaps are used for the different materials. It can be seen, that for both steel grades, the best surface qualities are achieved for shorter pulse durations. For pulse lengths exceeding 10 ps, thermally induced surface structures like so-called cone-like-protrusions (CLPs, [Bauer et al., 2015]) can be observed.

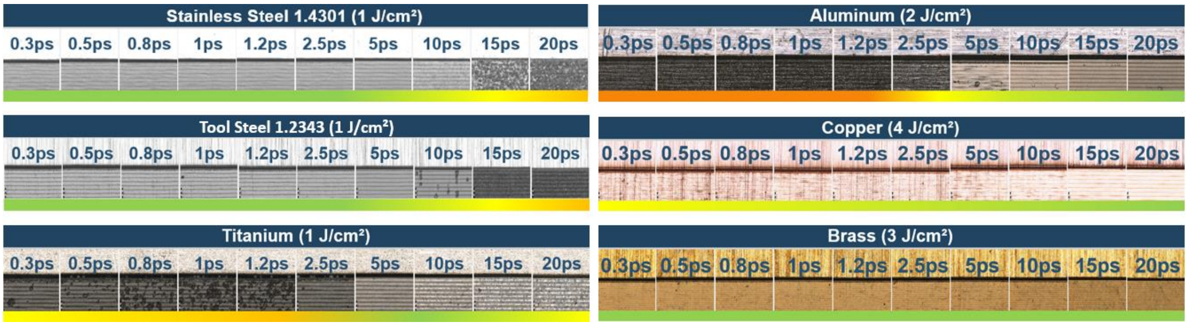

Fig. 5. Machined surface quality trends for different pulse durations and optimum fluence levels. The scan speed and repetition rate varied depending on the material. The number of repetitions was adjusted for an ablation depth of at least 50 µm. Each image shows the raw material in the top half and the machined surface in the bottom half. For the two steel grades, best results are observed for shorter pulse durations, whereas for aluminum and titanium, longer pulse durations can be beneficial regarding surface quality. On copper and brass, only small changes in surface quality are seen in the studied parameter range.

For aluminum, an opposing trend is observed: Undesired thermal structures form for shorter pulse durations, whereas the surface quality in the studied range is best for pulses > 10 ps. Titanium shows a transition between different regimes and the best surface quality results at single-pulse machining at several picoseconds. On copper and brass, only small changes in surface quality are seen for the investigated pulse durations. Here, even for high pulse overlaps and repetition rates, no formation of thermally induced surface structures like CLPs occur. This diverse behavior is believed to be caused by material dependent changes in the ablation mechanisms. These examples demonstrate the need for a flexible laser processing system, which allows the intra-process tuning of pulse parameters to achieve the best possible results depending on the material.

3.2. Energy deposition on a fs- to ns- timescale

In addition to tuning the energy deposition on a femto- and picosecond timescale, the optimization on a nano- up to microsecond-timescale is possible due to so-called pulse bursts, which can be beneficial on metals for the improvement of thermal effects such as the formation of CLPs. The literature covers efficiency and quality aspects of bursts in the MHz- and GHz-regime [Sailer et al., 2015, Domke et al. / Murj et al., 2019]. For USP-metal ablation two different time regimes regarding energy efficiency can be observed. If the pulse duration is below approx. 1 ps (compare fig. 4) and the subsequent pulses have a temporal delay of several tens of nanoseconds, the energy efficiency typically is only slightly affected due to shielding effects (fig. 6, regime 1).

Longer pulses as well as short temporal pulse delays, respectively high repetition rates, both result in a decrease of energy efficiency (fig. 6, regime 2). The time between several tens of ps and several ns thus is needed for the decay of the optical dense ablation plume after irradiation with an ultra-short pulse. In the literature, the effect of re-deposited ablation products is also discussed, which can be responsible for an alternating effect on efficiency depending on an even or odd number of pulses within the burst.

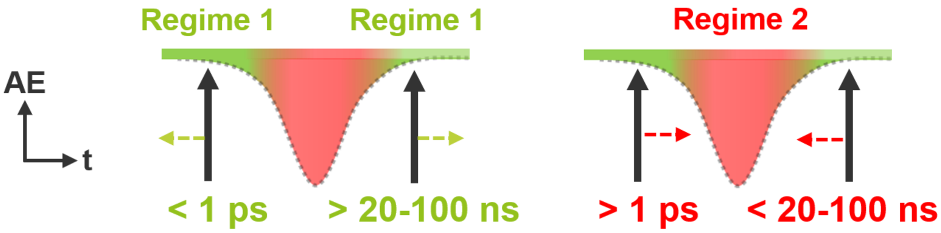

Fig. 6. Different material dependent temporal energy deposition regimes for ultra-short pulsed metal ablation. If the pulse duration is below 1 ps and the subsequent pulse has a temporal delay of several tens of nanoseconds (regime 1) the energy efficiency typically is only slightly affected due to shielding effects which result in lower ablation efficiencies. In regime 2 where the pulse duration is above 1 ps and / or the temporal pulse delay of the subsequent pulses is below several tens of nanoseconds, a drop in ablation efficiency is observed.

Fig. 7 shows the results of maximum measured efficiencies depending on the number of pulses per bursts (50 MHz) for titanium as well as for both investigated steel grades. For these materials a clear trend can be seen: For an increasing number of pulses within a 50 MHz-burst the efficiency decreases down to approx. 75% of the single-pulse efficiency. After 3-4 pulses a plateau can be observed at which a further increase of pulses per burst does not result in a further efficiency decrease. In contrast to steel and titanium, the machining of copper, brass and aluminum shows stronger shielding effects for 20 ns / 50 MHz pulse bursts (fig. 8). Here, the mentioned alternating efficiency effect is clearly present: Whereas a second pulse results in a drastic efficiency decrease of around 50%, which would mean that the second pulse does not contribute to ablation

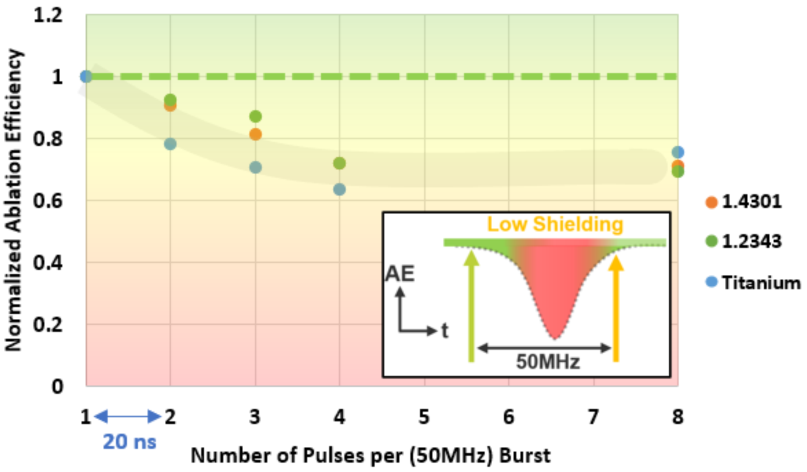

Fig. 7. Normalized (with respect to single pulse efficiency) ablation efficiency depending on the number of pulses per 50 MHz-burst. On steel as well as titanium an increasing number of pulses per burst results in a decrease of ablation efficiency down to approx. 75% of the single pulse efficiency. All tests were done at a constant scan strategy, spot size and pulse duration (300 fs).

at all, a burst of three pulses is able to significantly boost ablation efficiency back to the single-pulse level. Thus, the third pulse must have an even higher efficiency than a single pulse without pulse groups.

In case of copper, an ablation efficiency even slightly above the single pulse efficiency can be measured (compare [Neuenschwander et al., 2015]). This behavior has been reported before and can be attributed to re-deposition and shielding mechanisms experienced by the second pulse caused by the ablated particles generated of the first pulse. The second pulse is assumed to clear the particle plume so that the third pulse is less affected by shielding [Förster et al., 2018]. Despite the fact of a stronger influence of 50 MHz-bursts on these materials, for a sufficiently high number of pulses the ablation efficiency also reaches around 80% of the single pulse level.

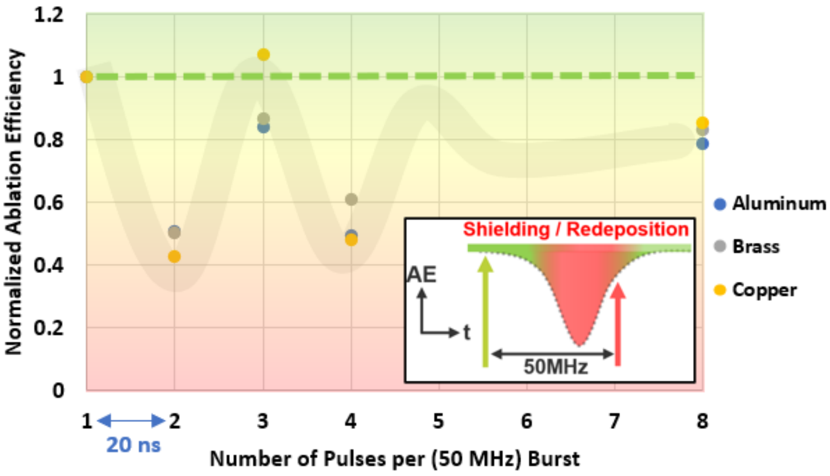

Fig. 8. Normalized (w.r.t. single pulse efficiency) ablation efficiency depending on the number of pulses per 50 MHzburst. On aluminum, brass and copper, an increasing number of pulses per burst results in a decrease of ablation efficiency down to approx. 80% of the single pulse efficiency. All tests were done at a constant scan strategy, spot size and pulse duration (300 fs).

It should be emphasized that no burst setting in the MHz-regime was able to achieve a drastic increase of efficiency on metals. This contrasts with the findings on other materials like silicon, where the processing with pulse groups in the MHz-regime enables a significant increase of ablation efficiency [Sailer et al., 2021].

Compared to the processing with pulse groups in the MHz-regime, pulse trains with even shorter temporal pulse delays in the GHz-regime have gained great interest within the last years. Since the GHz-regime is typically located within regime 2 (fig. 6), where shielding and redeposition effects dominate and reduce ablation efficiency, a different ablation behavior is observed: The ablation efficiency, especially for a low number of pulses within a GHz-burst, is significantly lower than for non-burst processing (fig. 9). With increasing number of pulses in the GHz-burst, the energy deposition increases and the thermal energy penetration depth becomes dominant, which results in a continuous increase of efficiency for an increasing number of pulses due to heat conduction.

For copper and aluminum (both materials with a rather high heat conductivity) an “effective” pulse duration of ~ 60 ns (96 pulses at 1.6 GHz) results in a comparable ablation efficiency of the single-pulse processing. By using an effective pulse duration of 160 ns (256 pulses), an efficiency enhancement by more than a factor of 2 can be obtained on copper and aluminum. For stainless steel and brass, the maximum effective pulse duration was not able to result in a significantly higher ablation efficiency above the single pulse level. Compared to copper and aluminum, steel and brass both have a lower heat conductivity which might be the reason for the differences in relative energy efficiency compared to single pulse processing.

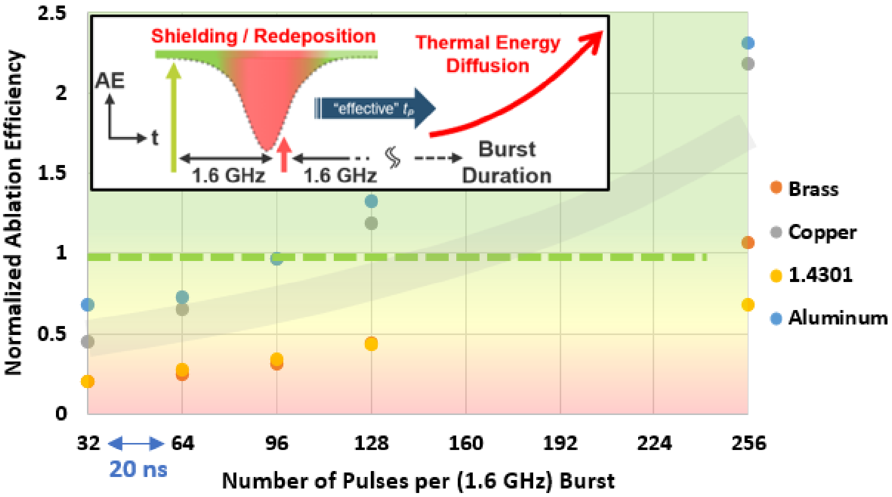

Fig. 9. Normalized (w.r.t single pulse efficiency) ablation efficiency depending on the number of pulses per 1.6 GHz-burst. For all investigated metals the efficiency increases with number of pulses within the GHz-burst due to thermal energy diffusion. On aluminum and copper, both materials with a high heat conductivity, an “effective” pulse duration of 160 ns (256 pulses at 1.6 GHz) can increase ablation efficiency far above the single pulse level.

Besides efficiency effects, the quality of ablation in terms of surface roughness is a key aspect for many industrial applications. Fig. 10 exemplarily shows the quality trends for different processing regimes at their maximum efficiency. For metals, the decrease of ablation efficiency for MHz-bursts (fig. 7/8) is often accompanied with a slight increase in surface quality, i.e. a smoother surface with a lower surface roughness is achieved by using MHz-burst mode. In the GHz-regime however, the surface quality is lower due to increased melt and burr formation comparable to a ns-pulsed ablation process [Domke et al., 2019]. Comparing the two burst modes, best quality (i.e. minimum burr and melt formation) is achieved for MHz-regime processing for

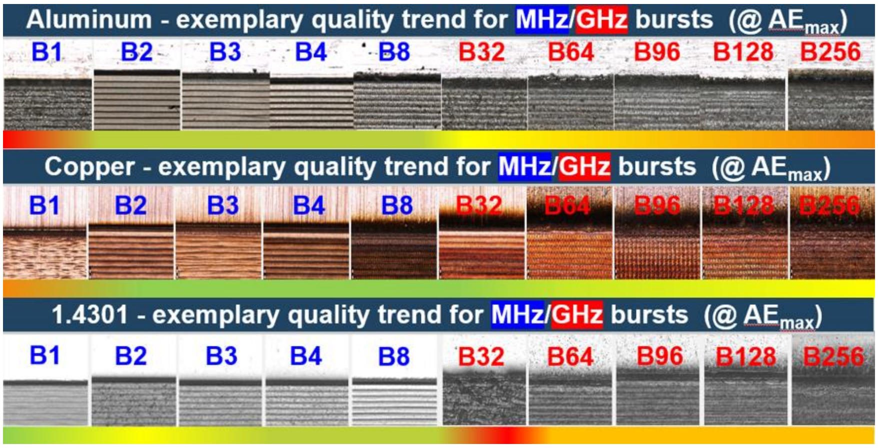

Fig. 10. Quality trends for optimum fluence / energy levels depending on different temporal energy deposition regimes. The decrease of ablation efficiency for MHz-bursts is typically accompanied with a slight increase of surface quality. For GHz-burst processing, an increased melt formation can be observed as well as burr on the edge of ablation, comparable to a ns-pulsed ablation process.

all investigated metals. One key benefit of flexible laser systems and fast switchable processing modes is the possibility to realize combined processing methods where the energy deposition can be tailored depending on different process phases. Due to the more thermal related ablation behavior, GHz-bursts can efficiently smoothen thermally induced surface structures (CLPs, fig. 11). For an efficient single pulse processing these thermally induced structures typically prevent the use of higher fluence levels and thus limit the employable pulse energy. Using these patent-pending processing methods enable energy scaling and can help to overcome classic limitations of single pulse operation mode processing.

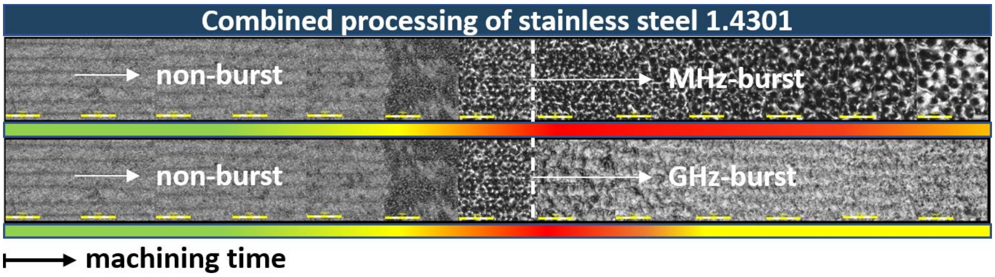

Fig. 11. Combined processing of stainless steel (1.4301). For non-burst processing (left part of the sequences), with increasing ablation depth or machining time, so-called cone-like-protrusions (CLPs, center of sequence) prevent the usage of high fluence levels. By using a temporal energy deposition on a ns-timescale, these structures can be smoothened. Here, especially GHz-bursts allow a fast surface smoothing and thus can enable the usage of higher fluences at non-burst processing in a combined processing method.

3.3. Energy deposition on a fs- to µs- timescale

On an even longer timescale than the nanosecond regime, modern ultra-short pulsed laser systems offer the possibility to address and control energy deposition with different repetition rates and fast energy modulation on a microsecond timescale. Since the employable pulse energy is often constrained due to efficiency and quality aspects, the use of high repetition rates enables fast processing speeds.

In order to overcome challenges caused by the limited dynamics of beam deflection or motion systems, the TruMicro Series offers flexible Pulse on Demand (POD) triggering, with a practically constant delay between an external trigger signal, e.g. generated by a motion controller (scanner or axes system), and the actual emitted laser pulse (trigger to light delay). Residual timing jitter of such POD-generated pulses is ~20 ns for the current TruMicro Series 2000 based on a 50 MHz seed laser, resulting in a spatial jitter of < 1 µm at typical scan speeds of up to several tens of m/s. Typically, the trigger to light delay of lasers with flexible POD is on the order of a few µs and depends on specific laser settings. Since this delay is known for the TruMicro system, it can be considered and fully compensated by an advanced motion system.

4. Conclusion

By choosing a suitable timescale for energy deposition, TRUMPF´s TruMicro series offers the possibility to address a wide variety of efficiency and quality aspects from a femto- to microsecond-timescale.

The diverse behavior of ultrashort pulse metal ablation demands flexible laser sources in order to enable fast intra-process adjustments of parameters that tailor the energy deposition and achieve the best possible results during ablation. For each material, a quickly tunable pulse duration and utilization of burst modes in the MHz- and GHz-regime can increase ablation efficiency as well as surface quality by implementing patent-pending multi-step processing strategies.

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