Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 41 (2013) 794 – 801

Physics Procedia

Lasers in Manufacturing Conference 2013

From fs to sub-ns: Dependence of the material removal rate on the pulse duration for metals

B. Neuenschwander*, B. Jaeggi, M. Schmid

Bern University of Applied Sciences, Institute for Applied Laser, Photonics and Surface Technologies ALPS, Pestalozzistrasse 20, 3400 Burgdorf, Switzerland

Abstract

Ultra short laser pulses are used, when high requirements concerning machining quality are demanded. The cost-effectiveness plays an important role for a successful transfer of this technology into industrial applications. Therefore systems with longer ps-pulses could offer an attractive alternative compared to short ps- and fs systems. Beside fiber based systems with ~50 ps pulse durations also small systems with sub-ns pulses are available today. In contrast to the dramatic drop of the material removal rate when the pulse duration is raised from 10 ps to 50 ps the impact is weaker for a further increase to 540 ps and the removal rate even increases when the pulse duration is raised to 1.4 ns. As no crater formation is observed and the surface quality is better than for 1.4 ns pulses, sub-ns pulses could be an attractive alternative to machine steel compared to fiber based systems with ~50 ps pulse duration.

Micro machining; sub-ns to fs; Ablation efficiency and surface quality

1. Introduction

Systems with 10 ps or shorter pulses show clear advantages concerning machining quality, heat affected zone, debris etc as shown in Chichkov et al 1996 and Dausinger et al 2003. But even if the excellent machining quality is one of the key advantages of these systems, it may be more cost effective to use fiber based amplifier technologies without CPA. The pulse duration of these systems is in the range of several

* Corresponding author. Tel.: +41-34-426-42-20; fax: +41-34-423-15-13.
E-mail address: beat.neuenschwander@bfh.ch

doi:10.1016/j.phpro.2013.03.150

10 ps, see Kanzelmeyer 2011. For metals the ablation efficiency significantly drops by about a factor of 5 when the pulse duration is raised from 10 *ps* to 50 *ps* as shown by Schmid 2011, for non metals this drop is less pronounced but still present as shown by the authors at Icaleo 2011. Another alternative may be offered by actively Q-switched DPSS with pulse durations in the sub-ns range. But the results of these systems should also be compared with fiber based Q-Switched systems with pulse durations in the short ns-range. Therefore investigations concerning the removal rate and the machining quality have been done for the pulse durations of 10 ps, 50 ps, 540 ps and 1.4 ns at 532 nm wavelength on cu-DHP and stainless steel 1.4301.

2. Theory

It has been shown by the authors at icaleo 2010 that the removal rate per average power depends on the applied fluence per pulse and reads for a Gaussian beam:

$$\frac{\dot{V}}{P_{av}} = \frac{1}{4} \cdot \frac{\delta}{\phi} \cdot \ln^2\left(2 \cdot \frac{\phi}{\phi_{th}}\right) \qquad with: \quad \phi = \frac{E_p}{\pi \cdot w_0^2} \tag{1}$$

with ϕ_{th} the threshold fluence and δ the energy penetration depth. This removal rate shows a maximum value for an optimum applied fluence ϕ_{opt}:

$$\frac{\dot{V}_{\max}}{P_{av}} = \frac{2}{e^2} \cdot \frac{\delta}{\phi_{th}} \qquad for \quad \phi_{opt} = \frac{e^2}{2} \cdot \phi_{th} \tag{2}$$

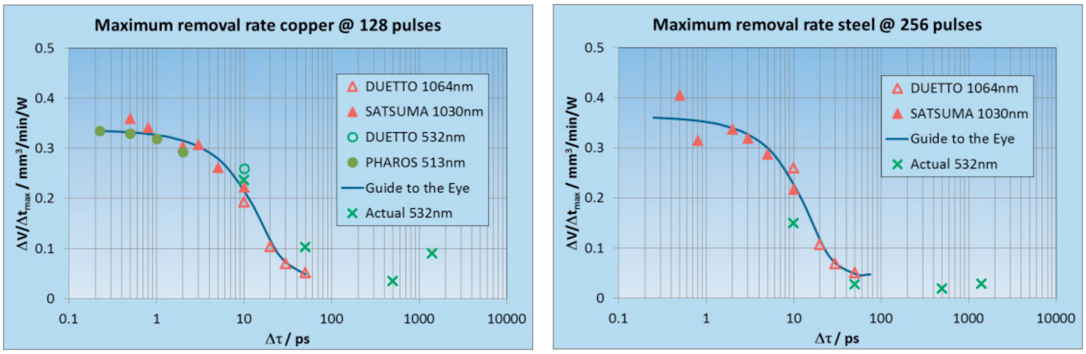

Fig. 1. Maximum removal rates as a function of the pulse duration for copper (left) and stainless steel (right).

Fair comparisons between different situations should be done at this optimum point to avoid contradictory results. For doing this, normally the threshold fluence ϕ_{th} and the energy penetration depth δ are measured in a specific ablation study. But both measures depend on the pulse duration and, due to incubation, on the applied number of pulses as well (as e.g. presented by the authors at Icaleo 2012 and SPIE 2013). Different studies were performed by the authors and also Lopez in 2012 to deduce the maximum removal rate for pulse durations between 250 fs and 50 ps. The obtained results for copper (128 pulses) and for steel (256 pulses) are summarized and provided with a guide to the eye in fig. 1. This figure also contains the results of the actual study which will be discussed later on. For both investigated metals the maximum removal rate rests approximately constant for pulse durations up to a few ps followed by an enhancing decrease up to about 30 ps. This increase of the removal rate for shorter pulse durations is mainly caused by an increased energy penetration depth δ as the threshold fluence often rests almost constant in this range. Further for copper and pulse durations of 2 ps ad shorter almost no difference between the NIR and green radiation is observed.

3. Experimental Set-Up

A Duetto emitting 10 ps pulses, a Helios GN 50k-60 having a pulse width of 540 ps and an IPG GLP-5 with 1.4 ns pulses were used at a repetition rate of 50 kHz and a wavelength of 532 nm. To generate 50 ps pulses a corresponding etalon was additionally introduced into the seed laser of the Duetto system. The beam quality factor M^2 was always better than 1.3 and all three systems were focused via a galvo scanner onto the target. The spot radius amounted 11 µm for the Duetto and the Helios respectively 8 µm for the IPG system. With all three laser systems hatched squares with a side length of 1 mm were machined into copper DHP and steel 1.4301 with a hatch distance near the spot radius i.e. 11 µm for the Duetto and Helios and 9 µm (limit of the scanner) for the smaller spot of the IPG system. The hatch angle was turned by 10° from slice to slice. For the bigger spot size the marking speed amounted 275 mm/s or 550 mm/s resulting in a pitch (distance from pulse to pulse) of 5.5 µm and 11 µm. The corresponding values were changed to 200 mm/s and 400 mm/s going with a pitch of 4 µm and 8 µm for the IPG laser. For the lower marking speed 18 slices were marked whereas this number was doubled for the higher speed resulting in a constant accumulated energy per unit area for both marking speeds. This procedure was repeated 4 times for copper and 5 times for steel to obtain a measurable depth of the squares. For each pulse duration, material and marking speed a series of squares with different average powers i.e. fluences were machined. On the one hand the depth of the ablated squares was measured with a KLA-Tencor Alpha-step IQ. On the other hand the absolute machining time was calculated from the marking speed, the side length, the hatch distance, the number of slices and the number of repeats. From this the removal rate could be calculated by dividing the ablated volume by the machining time and the average power. The threshold fluence and the energy penetration depth were then deduced via a least square fit of the model function (1) to the measured data and from this the maximum removal rate was calculated following (2). The machined squares were additionally analyzed under an optical microscope to analyze the discoloring due to thermal effects. The surface quality was analyzed with SEM pictures.

4. Experimental Results

4.1. Removal rate

Fig. 2 shows the measured removal rates and the corresponding least square fits with the model function (1) for both materials and the pulse duration of 540 ps. A quite good agreement between the experiment and the model can be observed. Similar results have also been achieved for all other pulse durations. For all situations the removal rate for the lower speed exceeds the one for the higher speed with doubled slices. This difference is less pronounced for the shorter pulse durations of 10 ps and 50 ps. Heat accumulation could serve as an explanation of this effect. The deduced threshold fluences, penetration depths and corresponding maximum removal rates are summarized for all pulse durations in table 1 for copper and table 2 for stainless steel. Additionally the average values of the maximum removal rates are plotted as green crosses in fig. 1. For pulse durations longer than 50 ps the maximum removal rates first further drop until a minimum will be reached and then raise in the ns-regime. The minimum value is expected to be located between 100 ps and 1 ns and will depend on the material. The energy penetration depth first decreases with increasing pulse duration and begins then to increase in the ns-regime. The obtained values indicate that the reversal point is reached in the range of several 10 ps for steel and several 100 ps for copper. This following increase is an indication that the classical heat conduction begins to dominate the energy transport which is also confirmed by the increase of the threshold fluence for this pulse duration.

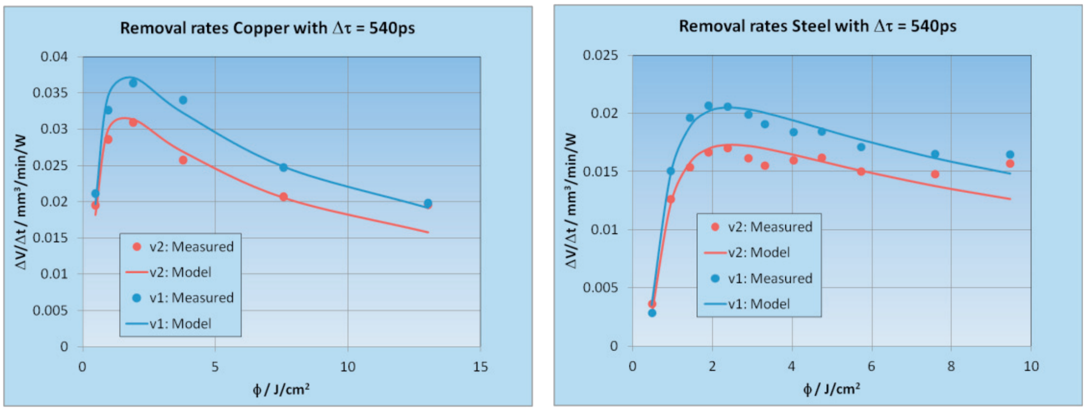

Fig. 2. Deduced removal rates from the machined squares and the corresponding model function from the least square fits for copper (left) and stainless steel (right) for a pulse duration of 540 ps.

Table 1. Deduced threshold fluence, penetration depths and maximum removal rate for copper

$\Delta\tau$ / ps	#slices	ϕ_{th} / J/cm^2	δ / nm	$\Delta V_{max}/\Delta t$ / mm^3/min/W
10	4x18	0.32	47.5	0.24
10	4x 36	0.26	37.5	0.24
50	4x 18	0.27	17.2	0.105
50	4x 36	0.23	14.6	0.101
540	4x 18	0.43	9.9	0.037
540	4x 36	0.40	7.9	0.032
1400	4x 18	0.68	42.3	0.101
1400	4x 36	0.89	43.0	0.078

Table 2. Deduced threshold fluence, penetration depths and maximum removal rate for stainless steel

$\Delta\tau$ / ps	#slices	ϕ_{th} / J/cm^2	δ / nm	$\Delta V_{max}/\Delta t$ / mm^3/min/W
10	5x18	0.055	5.17	0.152
10	5x 36	0.049	4.46	0.147
50	5x 18	0.227	3.81	0.027
50	5x 36	0.189	3.06	0.026
540	5x 18	0.66	8.3	0.020
540	5x 36	0.67	7.2	0.017
1400	5x 18	0.69	13.8	0.033
1400	5x 36	0.91	14.1	0.025

Further it can be seen from fig. 1 that for copper the maximum removal rate for pulses of 10 ps and 50 ps is higher for 532 nm compared to 1064 nm whereas steel shows the opposite behavior. For longer pulses where the energy transport is dominated by heat conduction the energy penetration depth in (2) should mainly depend on the pulse duration. As the reflectivity of a metallic surface generally decreases with decreasing wavelength a lower threshold is expected for the green wavelength and therefore a higher removal rate should be observed. However, this has to be confirmed by further investigations.

4.2. Surface quality

An overview of all ablated squares in steel is shown in fig. 3. The average power going with the pulse fluence is raised from left to right. The maximum power amounted about 1 W for 10 ps, 50 ps and 1.4 ns respectively 2 W for 540 ps. For 10 ps and 50 ps the squares become black at higher powers due to crater formation which occurs at short pulse durations. This crater formation disappears for longer pulses but a thermal discoloration appears which is much stronger for 1.4 ns. Similar results without crater formation were obtained for copper.

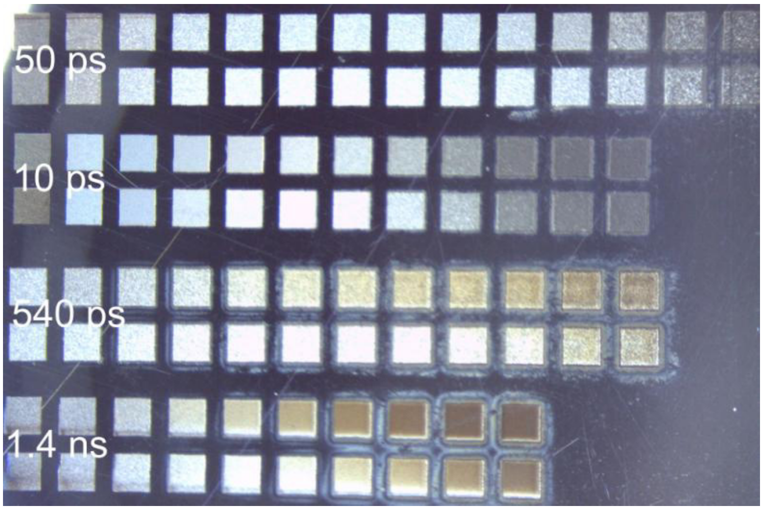

Fig. 3. Overview of all machined squares in steel. The fluence per pulse is raised from left to right and the upper line was marked with lower speed.

SEM pictures of the surfaces obtained for pulses with fluences near the optimum value (2) are shown for all investigated pulse durations in fig. 4 for copper and fig. 5 for steel. The upper line gives an overview and the lower line a detailed look. For copper the surface becomes rougher with increasing pulse duration. The detail pictures show that the amount and the dimension of the “worms” of melted material increases step in the surface quality is observed when the pulse duration is raised from 540 ps to 1.4 ns. The higher hatch distance compared to the spot radius for the IPG system at 1.4 ns may explain the visibility of the hatch lines of the last slice.

For steel a quite flat surface is observed for 10 ps. This surface is covered with small parallel ripples with a typical distance of 380 nm (measured from the SEM pictures) which is more than half of the wavelength of 532 nm. For 50 ps these ripples are much less pronounced and other surface structures, which may indicate the grain boundaries, appear. From the detailed view it can clearly be seen that the crater formation already starts at this moderate fluence. Clear melting effects are observed for 540 ps and 1.4 ns. For the latter pulse duration the melting borders of the single pulses are much more pronounced and again the hatch lines of the last slice are visible in the overview. Also for steel the surface quality is the lowest for the highest pulse duration.

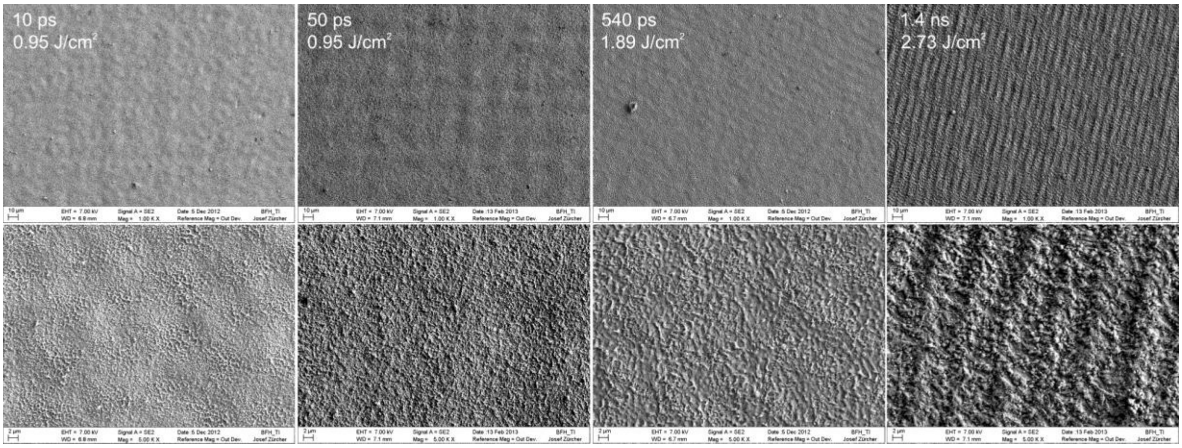

Fig. 4. SEM pictures of the surfaces of machined copper squares with fluences near the optimum value for all pulse durations. The magnification is raised from 1000x (upper line) to 5000x (lower line).

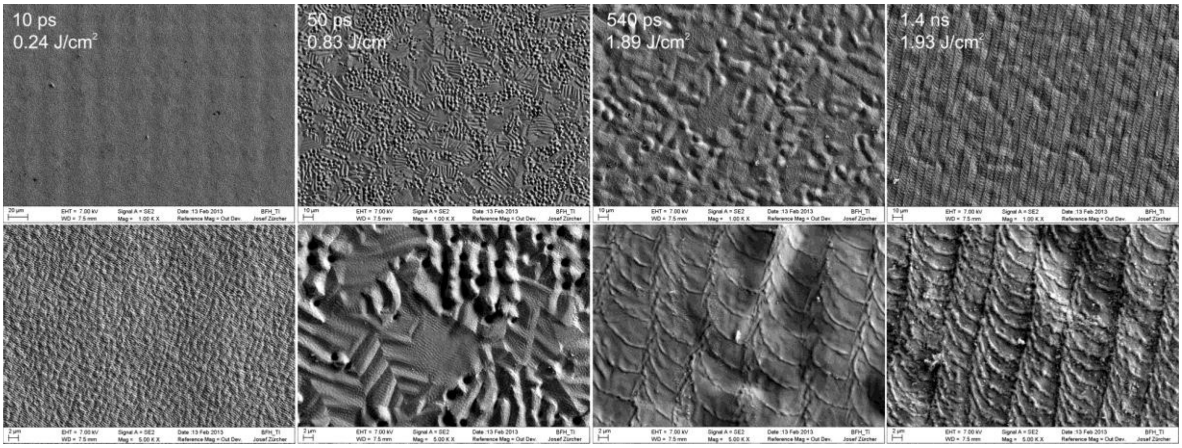

Fig. 5. SEM pictures of the surfaces of machined steel squares with fluences near the optimum value for all pulse durations. The magnification is raised from 1000x (upper line) to 5000x (lower line).

Examples of the surface quality for identical fluences are shown in fig. 6 for copper respectively fig. 7 for steel. Two points have to be mentioned: As for 1.4 ns the spot radius differed from the other situations the fluence values also differs for this pulse duration. Second, as the fluence value is kept constant, the corresponding location in the curve (1) or fig. 2 may be on the left side of the maximum for one pulse duration whereas it is on the right side for the others or vice versa. For copper for both fluences again a decrease in the surface quality is observed when the pulse duration is raised. The surface quality also decreases when the fluence is increased. For steel the decrease in the surface quality with higher pulse duration is not that pronounced for low fluences. Here 540 ps could be preferable compared to 50 ps due prevented crater formation, but the removal rate would be much lower. High flueces will lead to strong crater formation for 50 ps and 10 ps and strong melting effects for 540 ps and 1.4 ns.

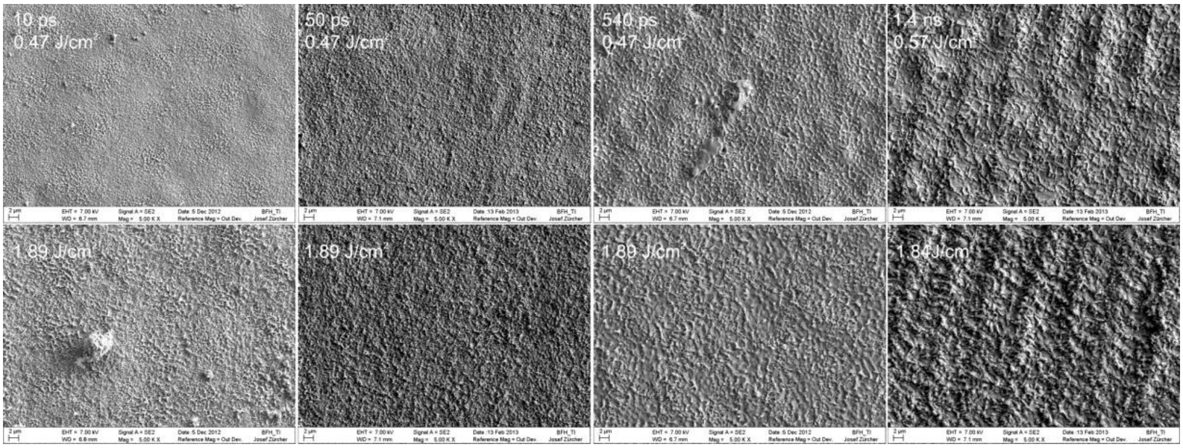

Fig. 6. SEM pictures of the surfaces of machined squares in copper with two different fluences.

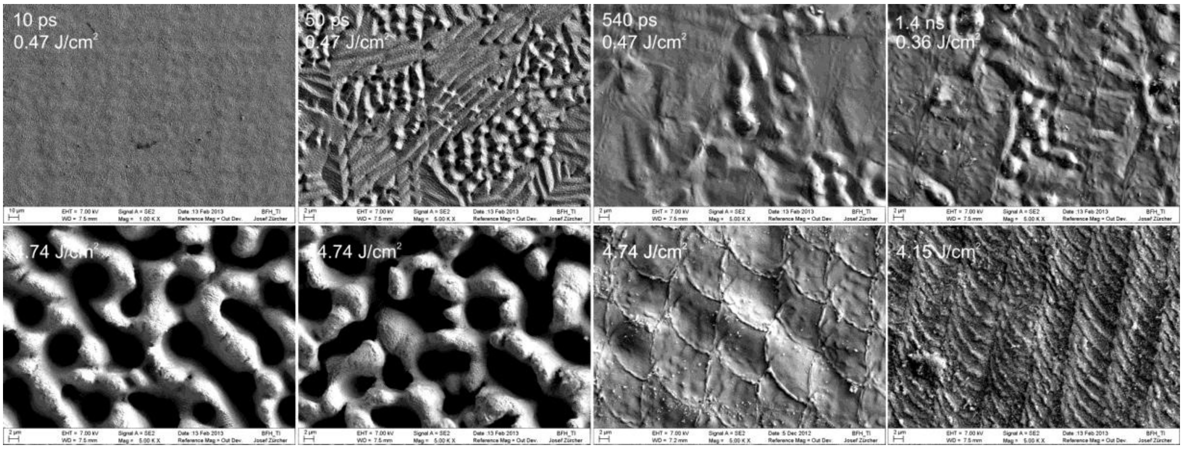

Fig. 7. SEM pictures of the surfaces of machined squares in steel with two different fluences.

5. Conclusions

The range of pulse durations between 10 ps and 1.4 ns at the wavelength 532 nm was investigated for copper and steel concerning the removal rate and the surface quality. By machining squares and measuring the removal rate the threshold fluence, the energy penetration depth and the maximum removal rate could be determined by a least square fit to a model for all investigated pulse durations. The trend of a decreasing removal rate with increasing pulse duration is confirmed up into the range of several 100 ps, but the trend is reversed when the pulse duration goes into the ns-regime. The behavior of the threshold fluence and the penetration depth indicates that heat conduction begins to dominate the energy transfer into the material when the pulse duration is raised from several 10 ps to several 100 ps. The lowest surface quality is always observed for 1.4 ns pulse duration where strong melting effects are observed. As the sort pulse durations of 10 ps and 50 ps shows tendency to crater formation in case of steel, sub-ns pulses could be, despite the lower removal rate, an alternative for machining steel with good surface quality. Further investigations have to be done to analyze the situation for thin films and non-metals.

Acknowledgements

The authors wish to thank Josef Zuercher for his help with the SEM pictures and Dr. Haupt from Coherent to pu the Heliuos Laser to our disposal. This work was supported by the Swiss Commission for Technology and Innovation CTI.

References

Chichkov B. N. et al. „Femtosecond, picosecond and nanosecond laser ablation of solids“, Appl. Phys. A, 63, 109 (1996).

Dausinger F. et al., “Micro-machining with ultrashort laser pulses: From basic understanding to technical applications”, Proc. SPIE Vol. 5147, 106-115 (2003)

S. Kanzelmeyer et al., “All-fiber based amplification of 40 ps pulses from a gain-switched laser diode”, Proc. of SPIE Vol. 7914, paper 191411 (2011)

M. Schmid et al., “Processing of metals with ps-laser pulses in the range between 10ps and 100ps”, Proc. of SPIE Vol. 7920, paper 792009 (2011)

B. Neuenschwander et al., "Processing of industrially relevant non metals with laser pulses in the range between 10 ps and 50 ps", ICALEO 2011, Paper M103

B. Neuenschwander et al., "Processing of dielectric materials and metals with ps laserpulses", ICALEO 2010, Paper M101

B. Neuenschwander et al., "From ps to fs: Dependence of the Material Removal Rate and the Surface Quality on the Pulse Duration for Metals, Semiconductors and Oxides”; ICALEO 2012, Paper M1004

B. Neuenschwande et al., “Factors controlling the incubation in the application of ps laser pulses on copper and iron surfaces”, Proc. of SPIE Vol. 8607, paper 12 (2013)

J. Lopez et al., “Comparison of picosecond and femtosecond laser ablation for surface engraving of metals and semiconductors” Proc. of SPIE Vol. 8247, (2012)