HIGH-PRF ULTRASHORT PULSE LASER PROCESSING OF COPPER

P178

Joerg Schille, Lutz Schneider, Peter Lickschat, Udo Loeschner, Robby Ebert, Horst Exner

Laserinstitut Hochschule Mittweida, Technikumplatz 17, 09306 Mittweida, Germany

Abstract

This paper presents results obtained in high-PRF (pulse repetition frequency) ultrashort pulse laser micro processing of copper. In the study, a variety of ultrashort pulse laser systems supplying high average laser power were applied in order to investigate the influence of the laser parameters on copper ablation. For this, laser pulses of different wavelengths (VIS, NIR) and pulse durations, ranging between 200 fs and 10 ps, were irradiated to the sample surface by raster scanning of the laser beam. The dependencies of average laser power, pulse energy, and the pulse repetition rate on the ablation rate, the ablation efficiency, and the productivity were studied. A maximum average laser power of 31.7 W was applied in this work. The pulse repetition rate was varied in the rage between 0.2 MHz and 19.3 MHz. Finally, the machining qualities obtained were evaluated by means of surface roughness measurements and SEM micrograph analysis.

Introduction

The recent commercial availability of high average power, high-PRF (pulse repetition frequency) ultrashort pulse lasers joins together excellent machining quality and high processing throughput. On one hand, the unique advantages of ultrashort laser pulses, in particular high efficiency, fast and localized energy deposition, and minimal thermal load to the work piece, ensure high accuracy and precision of the machining process those are essential in micro machining. On the other hand, high average power lasers supply high-PRF laser pulses of sufficiently high pulse energy for material ablation which significantly increase the processing speeds. As a result, high-PRF ultrashort pulse laser processing can be seen as key enabling technology with the potential to substitute standard manufacturing technologies in micro machining, including automotive, aerospace, electro-optics, photonics, biomedical, semiconductor, etc.

Initial studies investigating high-PRF high average power ultrashort pulse laser micro processing of low heat-conductive stainless steel reported heat accumulation and particle shielding as significant material removal influencing effects [1-3]. High-PRF laser processing of copper in the range up to 1 MHz, by contrast, was not influenced by these phenomena [3, 4]. Furthermore it was shown that the removal rate on copper is almost independent on the wavelength [5, 6]. The variation of the pulse duration in the range between femtoseconds to picoseconds, however, revealed a significant drop of the removal rate for the longer pulses [4, 5].

In terms of processing speed, a maximum removal rate of 0.16 mm³/min was obtained for copper with a high-PRF picosecond laser source of 3 W average laser power [7]. By using a rotating cylinder with a processing speed of 40 m/s, the removal rate on stainless steel was 3 mm³/min [8]. A considerably higher removal rate of 7.0 mm³/min was reported so far for stainless steel, achieved by applying a femtosecond laser system of 31.7 W average laser power [9].

This laser system was used in this study, among others, to gain greater insights into high-PRF ultrashort pulse laser processing of copper by applying high average laser power. In addition, the range of the optimum processing parameters in terms of wavelength and pulse duration is still under discussion in micro machining. This work will contribute to the research by varying the wavelength (515 nm, 1030 nm) and the duration (0.2 ps to 10 ps) of ultrashort pulses irradiated to copper.

Experimental

High-PRF ultrashort pulse laser processing of polished 99.9% pure copper metal sheets of 0.45 mm thickness was studied in a wide range of parameters, supplied by a variety of ultrashort pulse laser systems with complementary beam properties. The laser sources delivered nearly diffraction limited laser beams at fundamental and frequency doubled wavelengths (1030 nm, 515 nm). The maximum average laser power applicable to the copper samples was measured of 31.7 W (Figure 1).

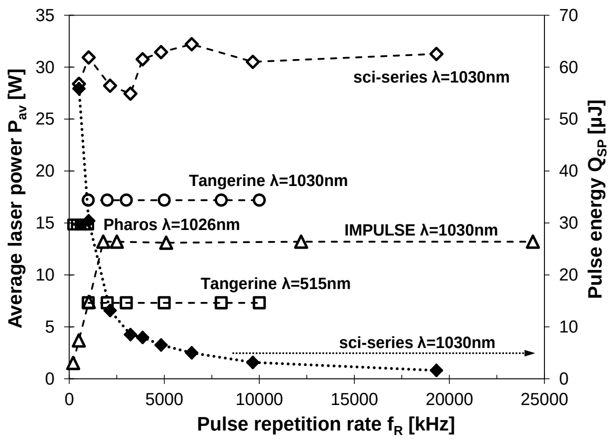

Figure 1: Average laser power $\boldsymbol{P_{av}}$ (on target) versus pulse repetition rate $\boldsymbol{f_R}$ presented for the used ultrashort pulse laser systems; the relation between pulse energy $\boldsymbol{Q_{SP}}$ and repetition rate is shown exemplarily for the *sci-series* laser.

The pulse energy was varied in the range between 1 µJ and 50 µJ, while the maximum available pulse energy decreased with the higher repetition rates due to the limited average laser power. This decrease of the pulse energy with increasing pulse repetition rate is shown exemplarily in Figure 1 by means of the *sci-series* laser. The pulse width was tunable in the range between 200 fs and 10 ps. A summary of the range of the parameters investigated in this study is presented in Table 1.

Table 1: A summary of the laser parameters investigated in this study.

Parameter	***IMPULSE***^{TM} Clark-MXR	***sci-series*** Active Fiber Systems GmbH	***Pharos*** Light conversion	***Tangerine*** Amplitude Systemes
Wavelength $\boldsymbol{\lambda}$ [nm]	1030	1030	1026	1030 515
Repetition rate $\boldsymbol{f_R}$ [MHz]	1.0	19.3	1.0	2.0
Av. laser power $\boldsymbol{P_{av}}$ $^{*)}$ [W]	7.2	31.7	14.8	17.2 7.3
Max. pulse energy $^{*)}$ $\boldsymbol{Q_{SP}}$ [µJ]	7.2	55.5	14.8	6.7
Pulse width $\boldsymbol{\tau_H}$ [ps] (sech^2)	0.18	0.35	0.2 … 10	0.25
Focus spot diameter $\boldsymbol{2\,w_0}$ [µm]	30.1	22.3	31.0	20.4
Beam quality $\boldsymbol{M^2}$	1.4	1.2	1.2	1.3
Max. fluence $\boldsymbol{H_0}$ [J/cm²]	2.0	28.5	3.9	4.1
$^{*)}$ irradiated to the substrate				

The laser beams were deflected across the copper surfaces by using a high-performance galvanometer scan system (*intelliSCANde*®, Scanlab AG). Focusing of the laser beams through a telecentric f-theta objective of 255 mm focal length led to focus spots with diameters ranging between 20 µm and 30 µm. With these small focus spots, a maximum fluence of 28.5 J/cm² was applicable to the copper samples. By using this long-focal length focusing objective, a maximum scan speed of 17 m/s was obtained. This fast scan speed provided sufficiently high pulse spacing, as recommended in micro machining of a quarter of the focus spot diameter, even at the higher pulse repetition rates in the range of several MHz.

The focused laser beams were raster scanned across the copper surfaces. A raster scan, or raster scanning, implies laser processing of rectangular patterns consisting of a network of overlapping parallel lines, as shown in Figure 2. With increasing number of raster scans $\boldsymbol{n_S}$, indicating the number of scan passes processed on the sample surface, the depth of the irradiated area increased.

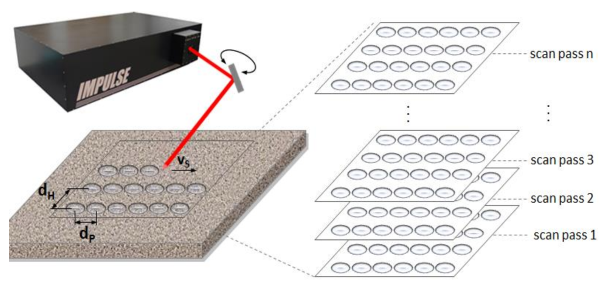

Figure 2: Sketch of the raster-scan processing regime where d_P is the pulse spacing, d_H is the hatch distance, and v_S is the scan speed.

The spacing between the scanned lines is given by the hatch distance $\boldsymbol{d_H}$. The distance between the laser pulses irradiated along a processed line is defined by the pulse spacing $\boldsymbol{d_P}$. This pulse spacing can be varied by either the scan speed $\boldsymbol{v_S}$ or the repetition rate $\boldsymbol{f_R}$ or both, accordingly to the relation

$$v_S = d_H \cdot f_R \qquad (1).$$

In this study, cavities with a standardized geometry of 4.0 x 0.5 mm² in length and width were processed in copper substrates by applying varied processing parameters. This was in order to evaluate their influence on material removal. The depth $\boldsymbol{d_C}$ of the cavities achieved was measured by using a confocal point sensor (*µscan CF*, nanoFocus AG).

From these depths, the volume ablation rate $\boldsymbol{V_{SP}}$ (which defines the mean material volume that can be removed / ablated by a single laser pulse) was calculated by using a method as introduced in [3]. According to this, the volume ablation rate $\boldsymbol{V_{SP}}$ is the product of the depth of the laser processed cavity $\boldsymbol{d_C}$, the lateral pulse spacing $\boldsymbol{d_P}$ and the hatch distance $\boldsymbol{d_H}$, divided by the number of scan passes $\boldsymbol{n_S}$ as

$$V_{SP} = \frac{d_P \cdot d_H \cdot d_C}{n_S} \quad (2).$$

Further, the optimum processing parameters were derived with regard to the efficiency of copper ablation. The pulse energy, repetition rate, and wavelength were taken into consideration. Therefore, the removal efficiency was calculated by dividing the material removal rate by the applied average laser power $\boldsymbol{P_{av}}$ as

$$Removal\ efficiency = \frac{MRR}{P_{av}} \quad (3).$$

In addition, the removable material volume per minute was considered in this work, estimated by the material removal rate ***MRR***. For this, the volume ablation rate was taken into account accordingly to

$$MRR = V_{SP} \cdot f_R \cdot 60s \quad (4).$$

With regard to the processing quality, however, the roughness of the laser processed surface was evaluated by using the confovis 3D measuring assembly *ConfoSurf CLV150*. Thereby the measured average roughness value S_a represents the average surface roughness over the complete measured area.

Results and discussion

The cavity depths produced in copper by multiple crossings of a laser beam of 515 nm wavelength and 250 fs pulse duration are presented in Figure 3. The pulse energy, the lateral pulse spacing and the repetition rate were varied. The hatch distance and the scan number were kept constant of 5 µm and 25 scans, respectively. The cavity depth increased with the higher applied pulse energy and decreased with wider spacing between the pulses. The increase of the cavity depth is primarily the result of the higher ablation rate that will be achieved for pulses of higher energy, see also Figure 4. The reduced cavity depth as obtained at wider spacing is primarily caused by the lower number of laser pulses irradiated to the copper surface. Moreover, it can be seen for the pulse spacing wider than 3 µm that copper removal was almost unaffected by the repetition rate, regardless of the applied pulse energy. Almost the same cavity depths were achieved by irradiating pulses of equal energy and different repetition rates of 200 kHz and 1 MHz. From this it can be suggested that ultrashort pulse laser processing of copper by using laser beams of 515 nm wavelength is potentially unaffected by heat accumulative effects. This is in line to our previous results, where high-PRF near-infrared ultrashort laser pulses were applied [10].

For the smaller pulse spacing of 1 µm and 2 µm, by contrast, deeper cavities were obtained with pulses of the lower repetition rate. The difference between the depths values obtained increased with higher energy input, which was due to the higher applied pulse energy, or smaller pulse spacing or both. From this, it can be suggested that material ablation induced by pulses of the higher repetition rate was detrimentally affected by particle shielding. However, the effect has not been fully clearified so far and further work seems to be needed here.

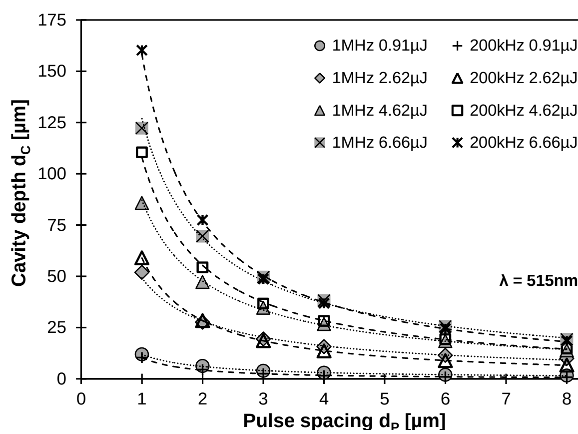

Figure 3: Cavity depth d_C versus pulse spacing d_P, obtained with pulses of varying repetition rate and energy; the wavelength was 515 nm.

The volume ablation rates shown in Figure 4 were calculated accordingly to equation 2 and taking into account the cavity depths presented above in Figure 3 for 4 µm pulse spacing. It can be seen that the volume ablation rate increased with higher pulse energy, almost unaffected by the repetition rate.

In addition, ablation rates obtained with the 1030 nm laser beam are included in Figure 4 in order to evaluate the influence of the wavelength on copper ablation. A significant higher volume ablation rate was obtained for the 515 nm pulses, indicating more than twice higher ablation efficiency for the shorter wavelength. This is potentially induced by the higher absorptivity level of the copper substrate for visible laser radiation, compared to near-infrared wavelengths.

In Figure 5, the material removal efficiency versus the energy irradiated by single laser pulses is shown. The wavelength and the repetition rate are varied. For both investigated wavelengths it can be observed that the removal efficiency increased to a maximum, followed by a decline of the curve.

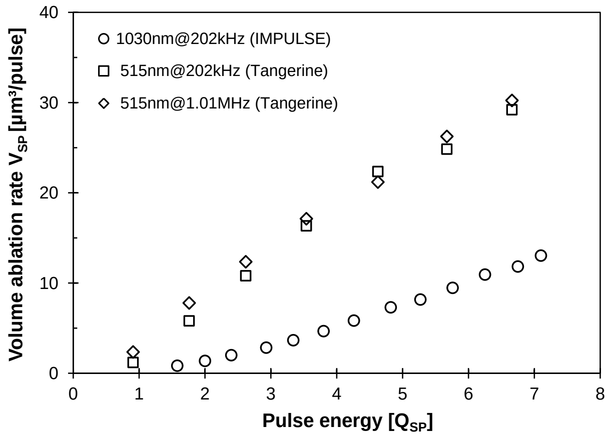

Figure 4: Volume ablation rate V_{SP} versus pulse energy Q_P presented for pulses of different wavelength and repetition rate.

In case of the 1030 nm laser beam, the most efficient material removal was obtained with pulses of 6.3 µJ, which correlates to a fluence of 3.2 J/cm². Considering the ablation threshold of 0.3 J/cm² as reported for copper in the literature [3], this fluence is about ten times above the ablation threshold. Theoretically, the most efficient material removal can be achieved at fluence of about 7.4 times above the ablation threshold [11]. However, energy losses due to particle shielding have to be considered by using high-PRF laser pulses, potentially affecting the optimum fluence range. The highest material removal efficiency with the 515 nm laser beam was obtained with pulses of 4.0 µJ. Further, in Figure 5 it can be seen for both investigated wavelengths that the removal efficiency is almost unaffected by the repetition rate.

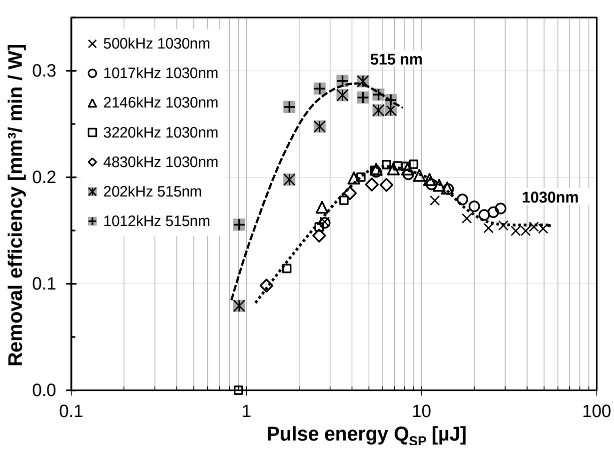

Figure 5: Material removal efficiency versus pulse energy Q_{SP}, presented for pulses of varied wavelength and repetition rate.

The volume ablation rates obtained by using near-infrared high-PRF laser pulses with repetition rates ranging up to 4.8 MHz are presented in Figure 6. The material volume that could be removed per single laser pulse is plotted versus the fluence of the irradiated laser pulses. The maximum average laser power impinging on the copper substrate was 31.7 W. With the highest fluence of 26 J/cm², achieved with pulses of 49.5 µJ at 508 kHz, a material volume of 125 µm³ was removed per irradiated laser pulse. With the higher applied repetition rate, the maximum applicable fluence decreased due to the lower available pulse energy as a result of the limited average laser power, see Table 2.

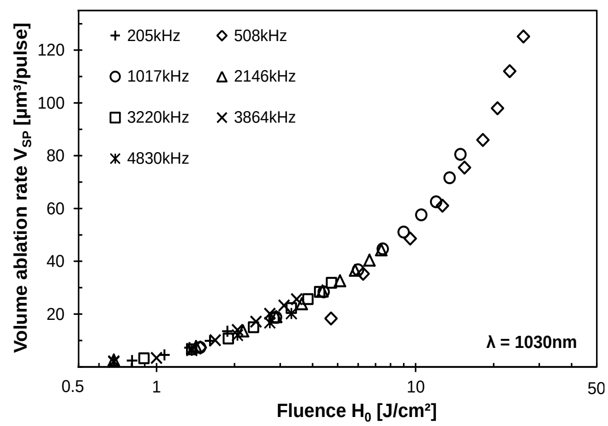

Figure 6: Volume ablation rate V_{SP} versus fluence H_0, obtained with near-infrared pulses of varied repetition rate in the range between 205 kHz and 4.8 MHz.

With regard to the productivity as shown in Figure **7** it can be concluded that the material removal rate increased with the higher repetition rate to a maximum at 6.44 MHz.

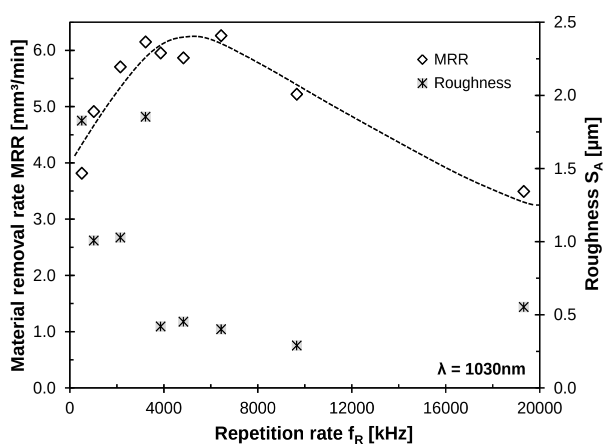

Figure 7: Material removal rate *MRR* and surface roughness S_a versus the repetition rate, obtained with a near-infrared laser beam of 31.7 W maximum average laser powers.

Moreover, it can be seen that material ablation became ineffective with further increasing repetition rates to their maximum of 19.3 MHz. This is mainly due to the reduced removal efficiency of low energy pulses which were emitted at the higher repetition rates.

The material removal rates achieved in this study by applying different repetition rates are summarised in Table 2. The highest material removal rate was found to be 6.3 mm³/min, obtained with pulses of 4.9 µJ energy at 6.4 MHz repetition rate. At this energy level material removal was most efficient, as already mentioned above in Figure 5.

In addition, Figure 7 presents the surface roughness measured on the bottom of the laser processed cavities. The smoothest surface with a roughness of $S_a = 0.29$ was achieved with the low fluence of 1.7 J/cm² at 9.66 MHz. The roughness values obtained for all investigated parameter sets can be seen in Table 2.

Table 2: Maximum achieved volume ablation rate V_{SP}, material removal rate *MRR*, and surface roughness S_a depending on the pulse energy Q_{SP}, the respective fluence H_0, and the repetition rate f_R.

Repetition rate f_R [MHz]	Max. pulse energy Q_{SP} [µJ]	Max. fluence H_0 [J/cm²]	Max. volume ablation rate V_{SP} [µm³/pulse]	Max. material removal rate MRR [mm³/min]	Surface roughness S_a [µm]
0.51	49.5	26.0	125.2	3.8	1.83
1.02	28.3	14.9	80.5	4.9	1.01
2.15	14.0	7.4	44.3	5.7	1.03
3.22	9.0	4.7	31.8	6.2	1.85
3.86	6.6	3.5	25.7	6.0	0.42
4.83	6.3	3.3	20.2	5.9	0.45
6.44	4.9	2.6	16.2	6.3	0.40
9.66	3.2	1.7	9.0	5.2	0.29
19.32	1.6	0.9	3.0	3.5	0.55

The influence of the processing parameter on the machining quality was evaluated by means of SEM micrographs, presented in Figure 8. The micrographs show bottom parts along the edges of the processed cavities. The cavities were produced by multiple near-infrared laser irradiations using 15 scan passes where the maximum available laser power of 31.7 W was applied. The pulse repetition rate was varied in the range of 0.51 MHz to 19.3 MHz, providing pulses with fluence between 26.0 J/cm² and 0.9 J/cm², respectively.

These visual insights to the laser processed cavity bottoms support the results obtained in roughness measuring. On one hand, irradiation of laser pulses of high repetition rate and thus lower fluence led to smoother cavity bottoms. A less debris deposition can be recognized. On the top of Figure 8 in a) and b), micro craters can be observed randomly distributed across the cavity bottom. This micro crater appeared much less pronounced with pulses of lower fluence at the higher repetition rates. On the other hand, molten and resolidified particles can be seen in Figure 8 e) to h). A few of these redeposited particles are highlighted in this figure by white arrows.

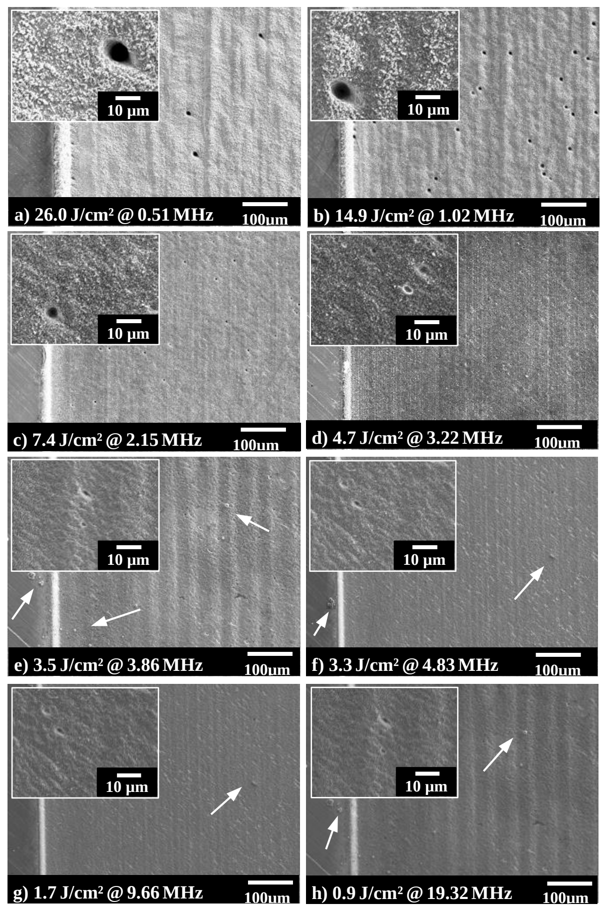

Figure 8: SEM micrographs showing the bottom of laser processed cavities over the edge to the unprocessed area, the cavities were produced with full available laser power of 31.7 W by varying the pulse repetition rate and respective the fluence.

From this it can be suggested that material melting will potentially take place by using ultrashort pulse of high pulse repetition rate, here starting at 3.86 MHz. It can be assumed that the time between two pulses is to short that the remaining energies those were not used for material ablation can diffuse away. As a result, the material can melt potentially induced by heat accumulation. This phenomenon has been already reported for low-heat conductive materials such as stainless steel, where melting starts even at the lower repetition rate in the range of 1 MHz [3].

Finally, the dependency of laser ablation and surface roughness on the pulse duration was studied in the range between 0.2 ps and 10 ps. For this, standardized cavities were produced in copper substrates by irradiating near-infrared laser pulses of 2.0 J/cm² fluence and 1.0 MHz repetition rate. The number of scan passes was 50. The cavity depth and surface roughness were measured.

In Figure 9, the volume ablation rates (derived from the cavity depths obtained) as well as the cavity surface roughness are plotted versus the pulse duration. For pulses in the range between 0.2 ps and 4.0 ps, the volume ablation rate decreases slightly. While the volume ablation rate falls to the minimum value of 9.1 µm³ per pulse with further increase of the pulse duration to 10 ps. This is about 60% of the maximum value that was determined of 15.2 µm³ per pulse for 0.2 ps laser pulses.

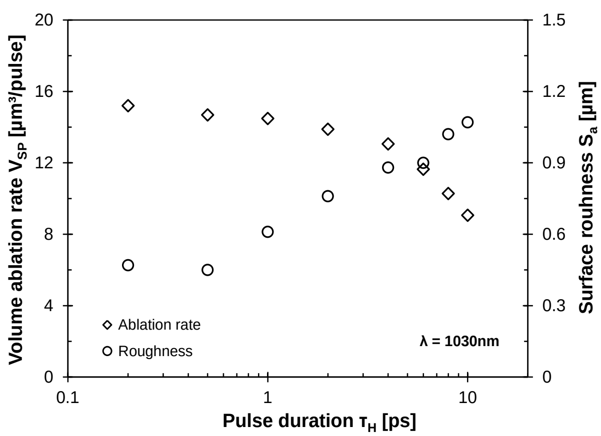

Figure 9: Volume ablation rate V_{SP} and surface roughness S_a versus pulse duration, obtained with near-infrared laser pulses of 2.0 J/cm² fluence and 1.0 MHz repetition rate.

SEM micrographs of the cavity bottoms captured along the cavity edges are presented in Figure 10 in order to illustrate the achievable machining quality. The smoothest surface was produced with the shortest pulses in the femtosecond range (Figure 10 a, b). However, the cavity surfaces produced with these pulses are covered with a large number of micro craters, causing a downgrade of the surface quality. The origin of theses micro craters has not been clearly understood so far, but it seems to be that local intensity maxima caused by near-field effects becomes into play to locally enhance material ablation.

Moreover it can be seen that the number of micro craters reduced with increasing pulse duration. This is potentially due to the lower intensity of these pulses. On the other hand, the roughness measured on the bottom of the laser processed cavities increased by using pulses in the picosecond range. This is mainly due to the origin of (sub-) micro melt structures as can be seen in Figure 10 c) to h).

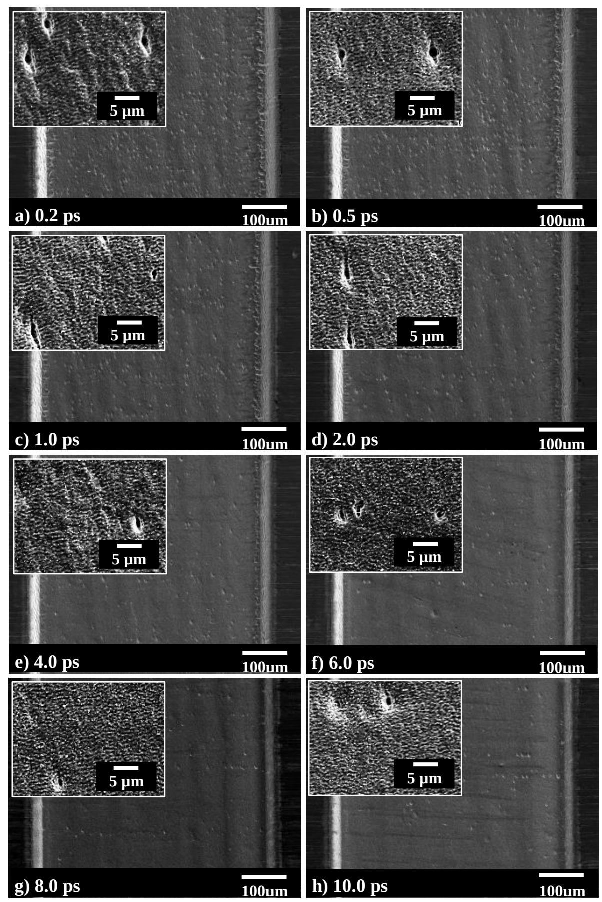

Figure 10: SEM micrographs showing the bottom of laser processed cavities over the edge to the unprocessed area; the cavities were produced with near-infrared laser pulses of 2.0 J/cm² fluence, 1.0 MHz repetition rate, and increasing pulse duration.

Conclusions

High-PRF (pulse repetition frequency) ultrashort pulse laser micro processing of copper was investigated in a wide range of parameters. For this, a variety of high average power ultrashort pulse laser systems were studied while a maximum average laser power of

31.7 W was applied. The pulse energy was varied in the range between 1 µJ and 50 µJ for pulses with repetition rates between 200 kHz and 20 MHz, respectively. A high performance galvanometer scan system was applied for fast laser beam deflection providing a maximum scan speed up to 17 m/s.

As a result, higher ablation rates were obtained by using pulses of shorter wavelength (515 nm), compared to near-infrared pulses of 1030 nm. Further it was shown that the volume ablation rate increased with higher fluence while no significant effect of the repetition rate on copper ablation was observed. This indicates that neither heat accumulation nor particle shielding will have a great impact on material removal. The maximum achieved material removal rate was measured to be 6.3 mm³/min obtained with pulses of 4.9 µJ energy and 6.44 MHz pulse repetition rate. For pulses with the shorter wavelength of 515 nm, by contrast, the highest removal efficiency was achieved with pulses of little lower energy of 4.0 µJ. In addition, it was found that the volume ablation rate decreased with increasing pulse durations those were studied in the range between 0.2 ps and 10.0 ps in this work.

Finally, the machining quality was evaluated by means of roughness measurements and SEM micrographs taken from the bottom of the laser processed cavities. The best machining quality and a low degree of roughness (S_a = 0.29 µm) was achieved by using low energy pulses. The roughness increased with the longer pulse duration.

Acknowledgment

The presented results have been conducted in the course of the project "Innoprofile Transfer – Rapid Micro / Hochrate - Laserbearbeitung" (03IPT506X), funded by the German Federal Ministry of Education and Research (BMBF).

References

[1] Ancona, A., Roeser, F., Rademaker, K., Limpert, J., Nolte, S. & Tuennermann, A. (2008) Optics Express, 16 (12), 8958.

[2] Di Niso, F., Gaudiuso C., Sibillano, T., Mezzapesa, F.P., Ancona, A. & Lugarà, P.M. (2013) Physics Procedia 41, 698 – 707.

[3] Schille, J. (2013) "Investigation of micromachining using a high repetition rate femtosecond fibre laser", Ph.D. Thesis, The University of Manchester, UK.

[4] Nolte, S., Doering, S., Ancona, A., Limpert, J. & Tuennermann, A. (2011) Advances in Optical Materials, OSA Technical Digest (CD) (Optical Society of America, FThC1.

[5] Neuenschwander, B., Jäggi, B. & Schmidt, M. (2013) „Möglichkeiten und Grenzen neuer Lasersysteme für die Fertigungstechnik in der Mikrobearbeitung (written in German)", in Laser in der Produktion und Feinwerktechnik, ISBN: 978-3-87525-343-6, Meisenbach Verlag Bamberg, S. 269.

[6] Döring, S., Ancona, A., Hädrich, S., Limpert, J., Nolte, S. & Tuennermann, A. (2010) Applied Physics A: Materials Science & Processing, 100(1): p. 53-56.

[7] Neuenschwander, B., Bucher, G.F., Hennig, G., Nussbaum, C., Joss, B., Muralt, M., Zehnder, S., Hunziker, U.W. & Schütz P. (2010) "Processing of dielectric materials and metals with ps laser pulses" (paper M101) in Proceedings of 29th Intern. Congress on Applications of Lasers & Electro-Optics (ICALEO) Anaheim, California, USA.

[8] Bruening, S., Henning, G., Eifel, S. & Gillner, A. (2011) "Ultrafast scan techniques for 3D-µm structuring of metal surfaces with high repetitive ps-laser pulses", Physics Procedia, 2011. 12, Part B (0), p. 105-115.

[9] Schille, J., Schneider, L., Mueller, M., Loeschner, U., Goddard, N., Scully, P. & Exner, H. (2013) "High-speed Laser Micro Processing using Ultrashort Laser Pulses" in Proceedings of LAMP2013 - the 6th International Congress on Laser Advanced Materials Processing, Niigata, Japan.

[10] Schille, J., Schneider, L., Hartwig, L., Loeschner, U., Ebert, R., Scully, P., Goddard, N., Exner, H. (2012) „Characterisation of interaction phenomena in high repetition rate femtosecond laser ablation of metals" (paper M1003) in Proceedings of 31th Intern. Congress on Applications of Lasers & Electro-Optics (ICALEO) Anaheim, California, USA.

[11] Raciukaitis, G., Brikas, M., Gecys, P., Voisiat, B. & Gedvilas, M. (2009) JLMN Journal of Laser Micro/Nano-engineering, Vol. 4 (3), p. 186.