

Micromachining with Picosecond Laser Pulses

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12 ps laser pulses with 100 μJ pulse energy at 100 kHz in a 10 W TEM₀₀ beam at 1064 nm are suitable to reach the ablation threshold for virtually any material on target areas of up to about 150 μm diameter. Each pulse removes about 10 nm thick material layers in an ablation process. Thus, new high quality drilling, cutting and shaping processes are now a reality for economical factory and shop applications.

Background

Lasers are a powerful tool for micromachining applications. A focused laser beam can easily be concentrated onto a small target of a few micron diameter (or a laser illuminated mask can be imaged onto the work piece with a high resolution objective). The laser-material-interaction in this target area will be controlled by laser parameters such as wavelength, pulse energy and pulse duration which determine peak power density, etc.

Certain sets of parameters can cause thermal effects for marking, cutting, drilling, annealing, hardening etc. Thousands of Q-switched solid state lasers are industrially employed in such applications.

Non thermal effects can be triggered on the material using high energy UV photons in ns pulses from excimer lasers (mostly in mask imaging arrangements), for instance to ablate thin layers of polycarbonates or for marking.

Also, non thermal interaction - cold ablation - has been demonstrated with ultra short pulse lasers in micro machining experiments of virtually any kind of material. Femtosecond lasers can reach power densities of hundreds of TW/cm^2 and machine metals, semiconductors and Isolators like glass or organic material.

More recently, picosecond lasers have been demonstrated to micro machine metals and other industrially relevant materials with the same precision and similar removal rates per pulse.

Ps-pulses are short enough to avoid thermal diffusion of the energy and reach the peak power densities necessary for these ablation threshold processes. Experiments and theoretical considerations indicate that laser pulses with a duration of about 10 ps are ideal for many machining applications [1]. They help to avoid plasma effects in the air in front of the target and the associated beam deformation and scattering.

The intrinsic concept of amplified ps-laser systems is much simpler than that of amplified fs lasers with pulse compression technology. This makes ps-lasers more stable, more reliable and cheaper. Most importantly, ps-lasers provide high average power (10 W) with very good beam quality ($M^2 < 1.5$) and repetition rates of up to 100 kHz. This high repetition rate reduces the cost per part dramatically and qualifies this micro machining technology for industrial use. If an amplified ps-laser System is properly conditioned it can remove with each pulse a material layer of a few nm up to a few tens of nm in the focus area - providing excellent Software driven 3D control for an industrial process. This results in material removal rates of up to about 1 mm³ per minute (for steel) with total laser cost of about 25 cent per min of laser operation.

Such lasers have the potential to be a new, high quality industrial tool to drill/cut or to structure material surfaces of virtually any material (metal, semiconductors, isolators including glass, diamonds, ceramics, polymers) in computer controlled machining systems.

LUMERA LASER demonstrated the first laser of this type at the LASER 2003 in Munich. The STACCATO offers 10 W TEM₀₀ at 1064 nm, pulse length of about 12 ps with 100 μJ at 100 kHz. This pulse energy is sufficient to reach the ablation threshold for virtually any material on target areas of up to about 150 μm diameter. The high peak power also guarantees efficient frequency conversion even at 100 kHz rep rate: 40 μJ at 532 nm, 20 μJ at 355 and 10 μJ at 266 nm.

Meanwhile, ps-lasers with even much higher rep rates (500 kHz) are available; they still have sufficient pulse energies for micromachining small target areas per pulse.

In many cases (even on metals) the combination of short pulse duration and short wave length has shown the best results in micro machining applications. Some of these experimental examples shall be described; they stand for many potential applications in micro mechanics (injection nozzles, ink jet nozzles, spinnerets, MEMS, microfluidic structures - lab on the chip, etc.) and micro electronics (scribing, drilling of low-k dielectric and multilayer materials, dicing thin wafers of silicon and III-V

materials; scribing, drilling and slotting of silicon or ceramics, link blowing for memory or mask repair, circuit individualization, etc.).

Drilling

Stainless steel

The use of picosecond laser Systems promises precise hole drilling in metals. The edge quality of the metal surface, the quality of the inner hole walls, and high reproducibility in the micrometer range are superior to what nanosecond lasers can deliver. Processing techniques were developed to meet industrial needs. The first step to improve the hole quality is the so-called helical drilling in which the laser beam penetrates the work piece on a helical path. Using this technique, the exit side of the laser drilled holes appears circular with sharp edges. Figure 1 shows the exit side of a 100 μm diameter hole in 100 μm stainless steel made by helical drilling. The hole was drilled with an average power of 1 W (on a focus diameter of about 30 μm to reach a proper power density with 80 mm free working distance) using circular polarized radiation of the STACCATO laser System.

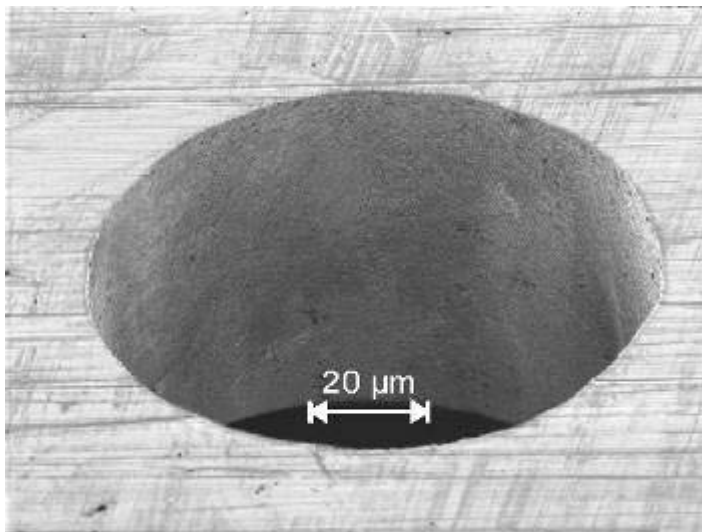


Figure 1: Hole drilling in 100 μm steel sheet with a STACCATO laser

To achieve that good quality throughout the hole, the polarization of the laser radiation must be adapted during the drilling process. Ripple formation on the surface of the hole wall and irregular hole shapes strongly depend on the polarization in relation to the wall surface. Holes without ripples are achievable by polarization control during helical drilling with special trepanning optics, where the polarization is always oriented orthogonal to the wall.

Due to the very good beam quality ($M2 < 1.5$) of picosecond laser Systems such ultrashort laser radiation can be focused to spot sizes of $10\ \mu\text{m}$ or less with practical working distance. In one application $50\ \mu\text{m}$ diameter holes were drilled in stainless steel foil of $50\ \mu\text{m}$ thickness. Holes with good edge quality, without burr, and with minimized melt layers were demonstrated. Using $2\ \text{W}$ average power of the STACCATO laser system a throughput of 180 holes per minute was achieved. In another application even $30\ \mu\text{m}$ holes were drilled in $25\ \mu\text{m}$ steel foil. Optimizing the processing parameters a good edge quality can also be observed on the entrance side of the laser radiation. Figure 2 shows the entrance side of a $30\ \mu\text{m}$ diameter hole with good circularity, high reproducibility, minimal burr or debris, and reasonable quality of the hole wall using circular polarization.

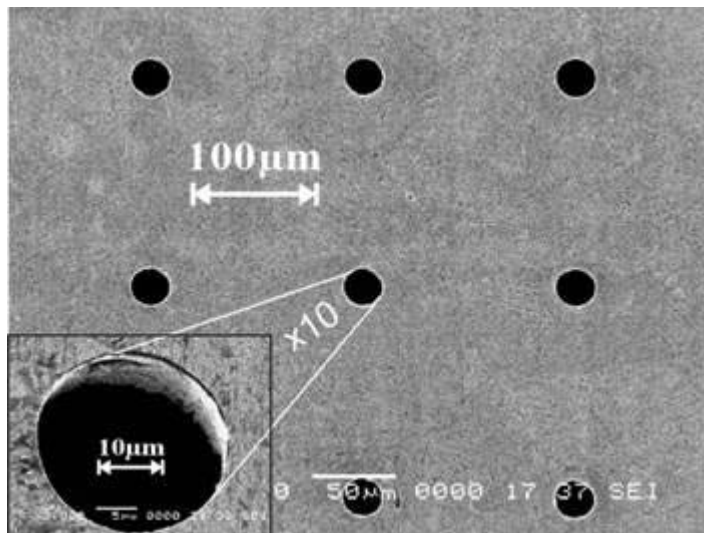
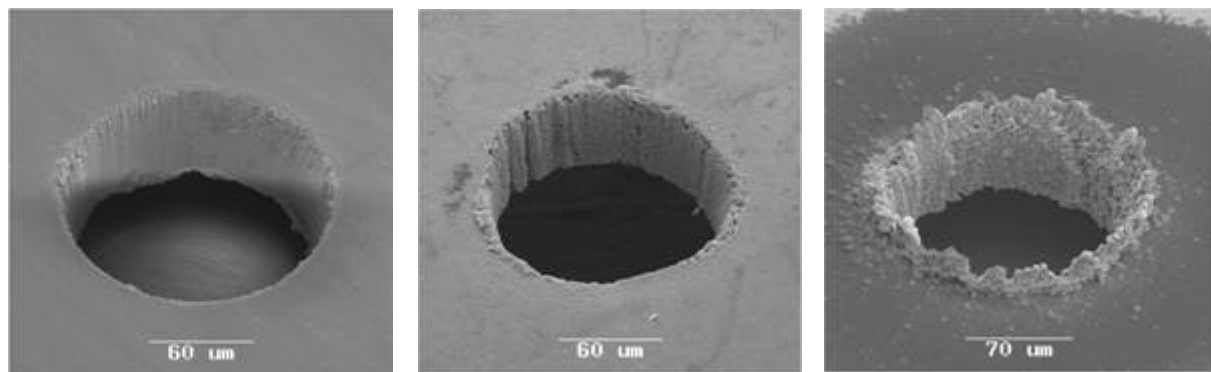


Figure 2: Hole drilling in $25\ \mu\text{m}$ steel foil with a STACCATO laser

Using $0.5\ \text{W}$ average power of the STACCATO laser system a throughput of 120 holes per minute was achieved.

Silicon

In order to figure out the potential of high energy picosecond pulses as well as to compare the readily achievable surface and edge quality with nanosecond and femtosecond pulse results, trepanning of 50 μm thick silicon wafers has been done.



<u>Parameters</u>		
τ_P	150 fs	25 ns
λ	780 nm	355 nm
E_P	100 μJ	270 μJ
f_P	1 kHz	25 kHz
	12 ps	
	532 nm	
	5 μJ	
	50 kHz	

Figure 3: Trepan drilling of silicon using different pulse duration (courtesy of LZH)

The samples in figure 3 show the characteristic influence of the pulse duration on the edge quality and side wall roughness (without having optimized the process parameters and the achievable results in each case). The holes were only cleaned in an alcohol ultrasonic bath. The mean burr height for 25 ns pulse duration is about five times higher (15 ... 20 μm) than for 12 ps (3 ... 4 μm) in this experimental set up. For 150 fs pulse duration nearly no burr can be observed. The side wall surfaces show similar dependence on the pulse duration: With 25 ns pulses an extremely rough surface forms. Using ps- and fs-pulses, small grooves along the walls are observed due to the linear beam polarization used in these set ups; (this polarization influence also exists for ns-pulses but could not be observed due to the rougher melting influence on the surface). Controlling the polarization - keeping the linear polarization perpendicular to the wall with special trepanning optics or using circular polarization - can improve the wall quality significantly (as shown in a following example).

High frequency technology requires that electronic components pass through holes in silicon wafers. These holes can hardly be produced by etching technologies. Using the STACCATO laser system with 5 W average power holes of 2 mm diameter were drilled through a 300 μm thick silicon wafer. To machine a

2 mm hole takes only a few seconds. Figure 4 shows well-performed edge and hole wall quality (in contrast to the ps-result in Figure 3, the sample in Figure 4 was machined with circular polarization). The silicon wafer was cleaned in an ultrasonic bath.

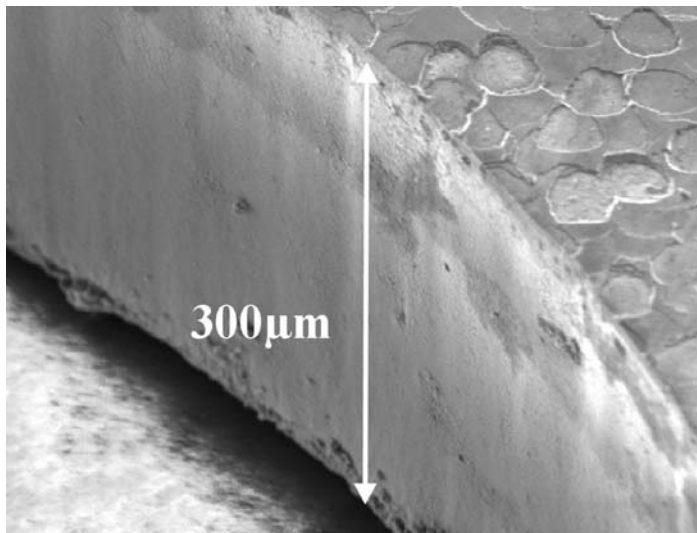


Figure 4: Cutting holes in 300 μm silicon wafer with a STACCATO laser

Ceramic and glass

Ultrashort laser pulses in the ps- or fs-regime easily reach power densities in the terawatts per square centimeter range when focused on the material surface. In materials, where no free electrons are present, the energy of the ultrashort laser pulses is deposited due to multiphoton and electron-impact absorption or interband transitions. Therefore, very hard or transparent materials, which are not easily machined by conventional lasers, can be processed in high quality by ultrashort pulse lasers.

Laser machining of ceramics are chosen when tight tolerances, small hole diameters or complex cut pattern need to be achieved. Figure 5 shows a 1 mm diameter hole drilled in a 200 μm thick ceramic sample using the STACCATO laser System at 10 W average power. The processing time was about 8 seconds. Due to the non-thermal ablation process, no thermal cracks, burr or debris were present in the vicinity of the laser machined hole. Hole diameters of 100 μm to 2 mm were drilled in ceramic sheets of up to 1.6 mm thickness and both good circularity and high reproducibility were performed using picosecond laser pulses.

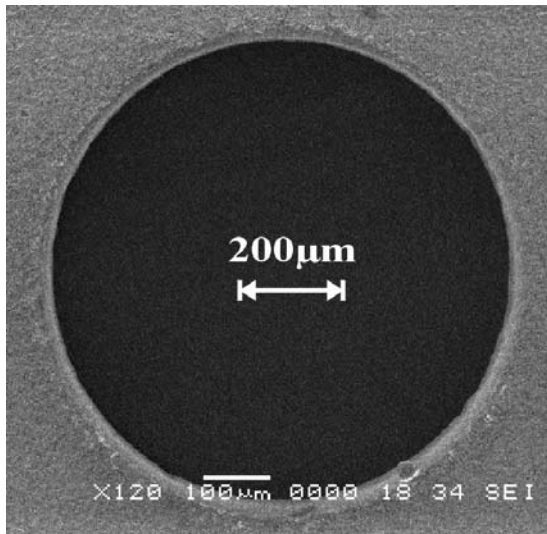


Figure 5: 1 mm hole drilled in a 200 μm thick ceramic sheet with a STACCATO laser

To demonstrate the ability of drilling and cutting glass, holes of 1 mm diameter were drilled in 140 μm thick coverslips. In this example borosilicate glass was processed with the third harmonic radiation of the IR picosecond STACCATO laser. Using 2 W average power at 355 nm 20 holes per minute were machined. Figure 6 shows the good edge quality with minimal heat affected zone and no cracks or chipping. In other applications small grooves of 10 μm width were scribed in glass samples or holes of 2 mm diameter were drilled in 1.1 mm thick glass with the same quality as shown in figure 6.

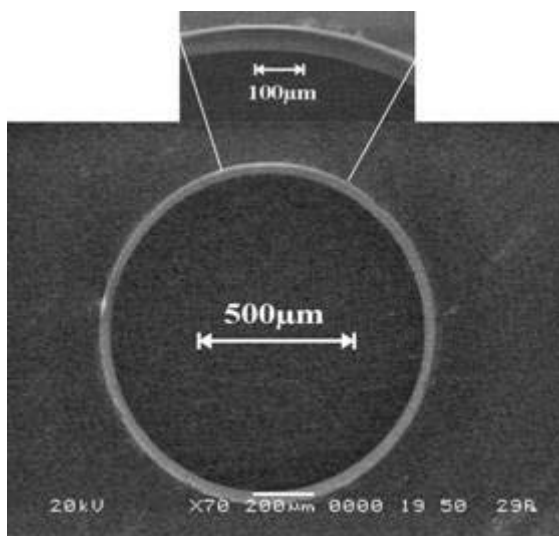


Figure 6: 1 mm hole drilled in a 140 μm thick glass coverslip with a STACCATO laser

Cutting

Stainless steel

In one industrial application, a femtosecond laser System is currently used to cut 100 μm stainless steel sheets to produce masks for production processes in the electronic industry. Using a femtosecond System with 0.37 W average power and with 1 kHz repetition rate it takes almost one hour of processing time to machine a square mask of 20x20 mm². The same pattern was cut by the STACCATO picosecond laser System using a repetition rate of 50 kHz and 0.85 W average power. The processing time was reduced by a factor of 6. Using the highest repetition rate of 100 kHz, the masks can be produced more than 12 times faster than with the femtosecond laser System. Figure 7 indicates practically the same edge and hole quality as performed with the femtosecond laser.

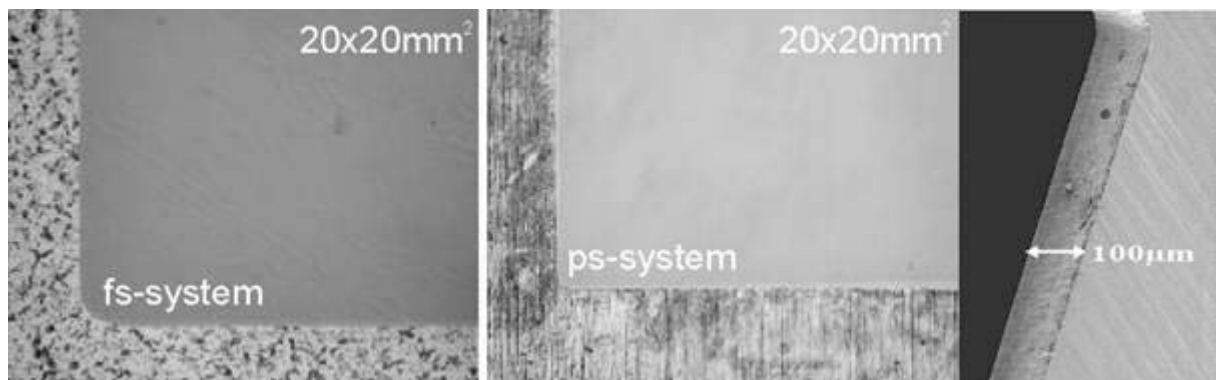


Figure 7: Cutting of 100 μm steel sheet with a STACCATO laser

Silicon

Cutting silicon wafers is used for dicing of chips in semiconductor industries. Current technology is the use of cut-off wheels fitted with diamond plates on their cutting edges. For future requirements like smaller kerfs and cutting of very thin wafers with same high cutting edge quality, the use of laser radiation is under development [3, 4]. Here, the kerfs between the ICs have to be as small as possible to optimize the packing of the chip on the wafer. Additionally, a high quality cutting edge is required to avoid post-processing. The use of femto- and picosecond laser pulses (Figure 8) minimizes the formation of cracks near the cutting edges and no cleaning or other post-machining processes are necessary.

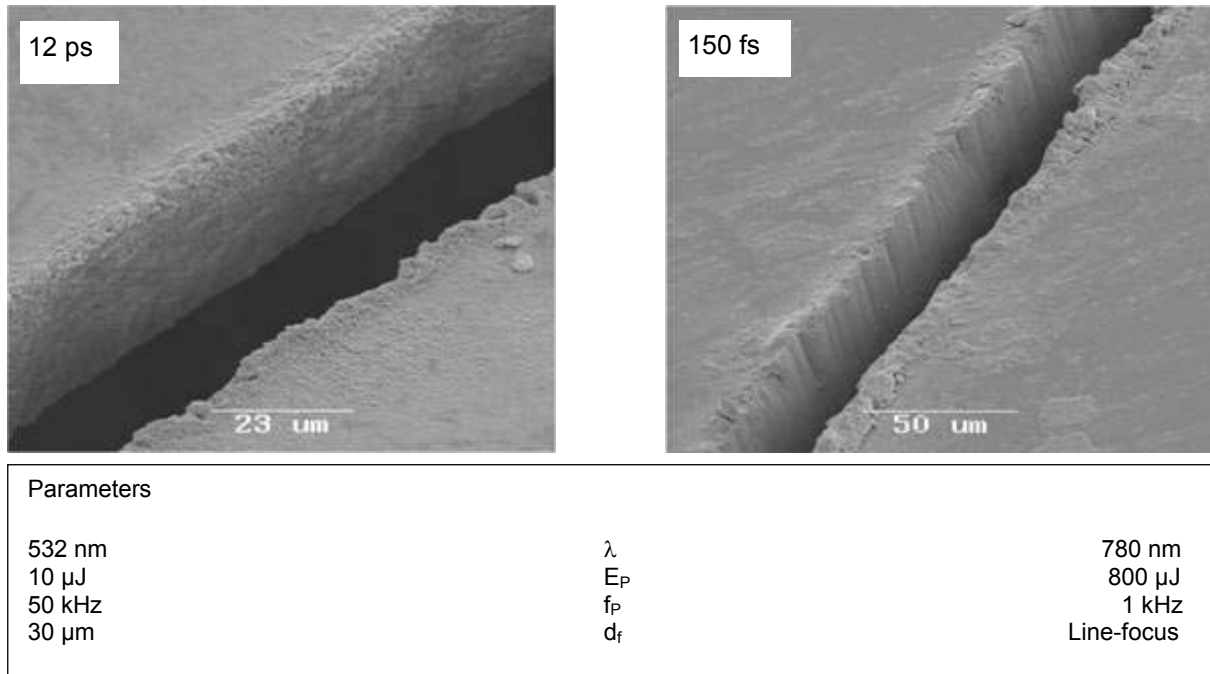


Figure 8: Cutting of silicon using fs- and ps-pulses (courtesy of LZH)

Surface Structuring

Modification of metallic surfaces

The surface Structuring of metals is a promising technique to the mechanical, chemical or fluidic characteristics of work pieces. Using laser radiation nearly every kind of structures in the range of micrometers can be realized with high reproducibility. In fluidics, more and more investigations deal with

the reduction of the flow resistance on turbine vanes or wings. Therefore, the use of extensive rib-structures, so-called ripples, on the surface of fluidic Systems is in development. Such structures, as shown in Figure 9, laminate the turbulent layer between the surface and the surrounding flow.

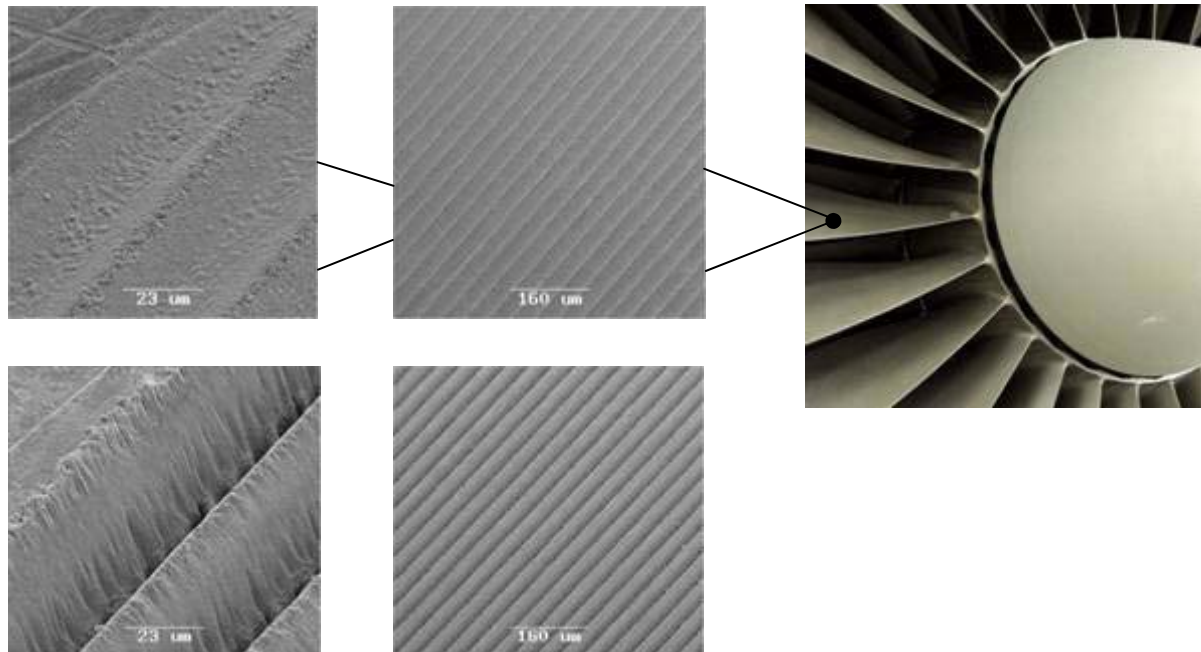


Figure 9: Potential application for rib-structures on metallic surfaces with reduced friction (courtesy of LZH)

These exemplary rib-structures have been realized using a STACCATO with pulse duration of about 12 ps. Such short pulse duration is necessary to avoid thermal damages like melting phases along the irradiated area on metallic surfaces. Also the formation of burr between machined and un-machined material can be minimized [5, 6]. By scanning the surface with a defined gap between each line the scanning speed was 1 mm/s for the lower and 100 mm/s for the structures shown in the upper photos. Due to the high repetition rate of 50 kHz and focus diameter of about 25 µm the pulse overlap was between 99,92 % for 1 mm/s and 92 % for 100 mm/s.

Current investigations refer to the 3D-structuring of complex surface geometries as well as to the extension from small sample areas to extensive surfaces.

Machining of carbide metal

Carbide metals are widespread materials for cutting tools in chip removing processes. Due to its mechanical hardness ($>1300 \text{ kp/mm}^2$) and high abrasion resistance, these materials are suitable to be used for the machining of nearly every kind of steel, alloy and cast iron. The durability of such cutting inserts and the quality of the produced components depend on the geometry and the surface of the

cutting edge. The rounding of cutting edges consists of two essential components: the rounding radius and the edge geometry. Different rounding radii essential components: the rounding radius and the edge geometry. Different rounding radii are achievable by Variation of the laser Output power and/or the feed rate. The edge geometry has to be adjusted to the requirements of the different chip removing processes. Thus, the cutting force or the surface quality of produced components can be influenced. Additionally, the edge geometry must be adapted to the mechanical hardness of the machining material within the Chip removing process [6].

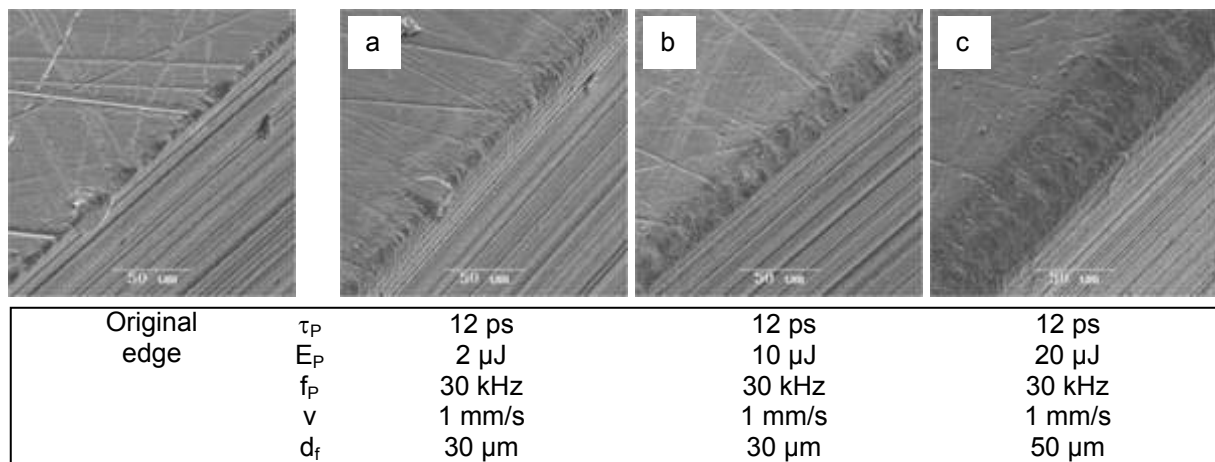


Figure 10: Edge rounding using different process parameters (courtesy of LZH)

The edge in Figure 10a has been machined using a focal diameter of 30 μm combined with a low pulse energy. This leads to a smoothing effect along the cutting edge due to the very low ablation rate. The resulting radius is between 2 and 10 μm , which is effected by the rough edge geometry of the original edge. Using higher pulse energies at the same focal diameter increases the ablation rate and, therefore, a rounding radius of about 28 μm has been achieved. A bigger rounding radius of about 45 μm with the same surface quality is shown in Figure 10c. Here, higher pulse energy has to be used due to the bigger spot size. This work is funded by the Federal Ministry of Education and Research (BMBF) within the project: "GEOSPAN - generation and measuring of the micro geometry on cutting tools" (www.geospan.de).

These applications show the potential of using high repetition picosecond pulses for micro-machining with high quality and efficiency. The pulse duration in the range of 12 ps is regarded useful to minimize thermal damage and burr formation but also to avoid disturbing nonlinear effects. Nearly the same edge quality and surface roughness have been achieved as with femtosecond output. The combination of short pulses and high repetition rates up to 100 kHz enables efficient ablation processes without post-processing. Further promising applications of picosecond lasers are e.g. the direct delamination of metal layers, the removal of thin ITO (Indium Tin Oxide) layers, or laser honing of piston liners of

truck engines.

Besides controlled removal of material (in electrical and micromechanical applications) also the internal alteration of transparent materials (change of index of refraction, color center formation, or the modification of specific additives) is a promising way to create identification or functional structures in materials.

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