Laser Micro Processing using short Laser Pulses

Pulsed laser radiation is a powerful tool for micro machining of different materials. The laser beam can be focused to spot diameters in the micron range. Depending on the material properties (e.g. heat conductivity), the thermal influence can be limited by using different pulse duration between nanoseconds (10^{-9} s) and femtoseconds (10^{-15} s).

The avoidance of thermal impact and thus the control of the heat affected zone give some advantages to the users. Mechanical properties like hardness and wear-resistance can be kept constant after the laser machining. Also, the surface quality is positively influenced by short and ultra short laser pulses. The formation of melted material and burr on the irradiated area can be minimized.
This article gives an overview about the basic mechanisms when using short and ultra short laser pulses followed by some potential applications: the generation of micro structures on macro areas for surface modifications, the finishing of cutting tools regarding the cutting edges, as well as the modification of micro-electro-mechanical systems (MEMS).

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Machining with short and ultra short laser pulses

In order to avoid thermal impact in the remaining bulk material, especially for the machining of metals, short and ultra short laser pulse durations in the range of picoseconds and femtoseconds can be used. In contrast to nanosecond laser processing, where the material is heated beyond the melting point, the material exposed to picosecond or femtosecond pulses can directly burst into plasma. This means that only the irradiated volume is heated up having a penetration of only a few nanometers, while no significant secondary heat penetration by hot material takes place over the borders of this volume.

This so-called "cold" ablation (Figure 1) process leads to precise structures limited only by the optical system employed. However, limits can be identified: working with high pulse energies and plasma induced heat. Experimental investigations of drilling metals have shown that, even with femtosecond pulses, there are sometimes deleterious thermal effects. The metal vapour plume develops on a time scale which is many orders of magnitude longer than the ultra short laser pulses. The expansion of the hot plasma transfers some heat into the surrounding material and causes a heat-affected zone in the workpiece. Generally, pulse duration on a fs and ps will increase the precision of many micromachining applications of a ns.

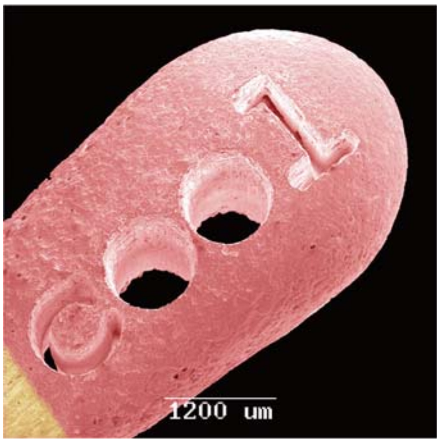

FIGURE 1: **Laser-cutted match.**

In order to compare the achievable surface and edge quality for nanosecond, picosecond and femtosecond pulse durations, trepanning of 50 µm thick silicon wafers has been carried out. The samples in Figure 2 show the dependence of the edge quality and side wall roughness on the pulse duration. The holes were only cleaned with alcohol in an ultrasound bath. The mean burr height for τ_P = 20 ns is about five times higher (15 … 20 µm) than for τ_P = 12 ps (3 … 4 µm), which corresponds to investigations on steel and aluminum. For 150 fs

FIGURE 2: **Cutting Si using different pulse durations.**

pulse duration nearly no burr can be observed. The side wall surfaces show similar dependence on the pulse duration. For the 20 ns pulses, an extremely rough surface is produced. The linear polarization creates small grooves along the walls when using picosecond and femtosecond pulses. This polarization influence also exists for nanosecond pulses but could not be observed due to the melt on the machined surface.

Surface modification

The micro-structuring of technical surfaces is a promising technique to change the mechanical, chemical, or fluidic characteristics of work pieces. In the field of fluidic for example an increasing number of investigations deal with the reduction of the drag on airplane wings. Here, the surface is coated with micro-scaled rib-structures, so-called riblets, on embossed films. These films are not useful for applications in stream machines or turbines, due to their low resistance against mechanical and thermal stress. Initial studies on drag reduction using riblets were conducted in 1982 at NASA Langley Research Center [1]. Several types of riblet geometries have been studied and they found that the optimum shapes for drag reduction have sharp peaks and a defined aspect ratio (Figure 3) optimized for each application. If groove height and spacing is too large, then drag is increased. If they are too small, the drag reduction effects are reduced [1, 2]. However, most of the works about the drag reduction effects of the riblets have been performed with mm-scale riblets since it has been very difficult to fabricate micro-scale structures in rib-shape. Therefore, the generation of micro structures on extensive metallic surfaces is under development.

The exemplary rib-structures in Figure 4 have been realized using a focused diode-pumped solid-state laser 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 the metallic surface, which is especially important in order to fabricate a small radius at the edges of the generated structures, as well as to minimize wear due to changed bulk material properties. Also the formation of burrs between machined and un-machined material can be minimized [3, 4]. By scanning the surface with a defined gap between each line the scanning speed was between 1 mm/s and 200 mm/s. The riblet width is between 40 µm and 55 µm, and the height is in the range of 15 µm up to 20 µm. Such micro structures, generated on the surface of a NACA-6510 profile (see Figure 4), lead

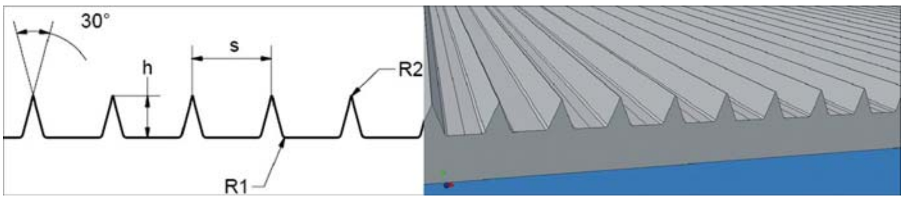

FIGURE 3: **Riblet geometry.**

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Research, development, and consulting are the main tasks of the Laser Zentrum Hannover e.V. (LZH). Since its founding in 1986 the LZH has served as a competent link between physics-oriented and engineering-oriented fields. The close cooperation between production engineers, material scientists, and physicists makes it possible that interdisciplinary solutions are found in all fields of laser applications. Laser-based micro-technology and the application of short and ultra short pulsed lasers is one of the core competences of the LZH. For more information see: www.lzh.de

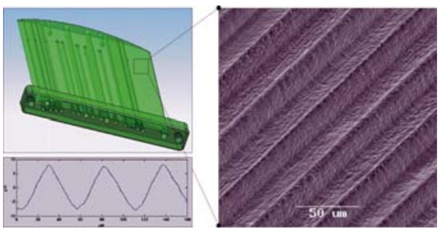

FIGURE 4: **NACA-profile and laser-generated riblet structure.**

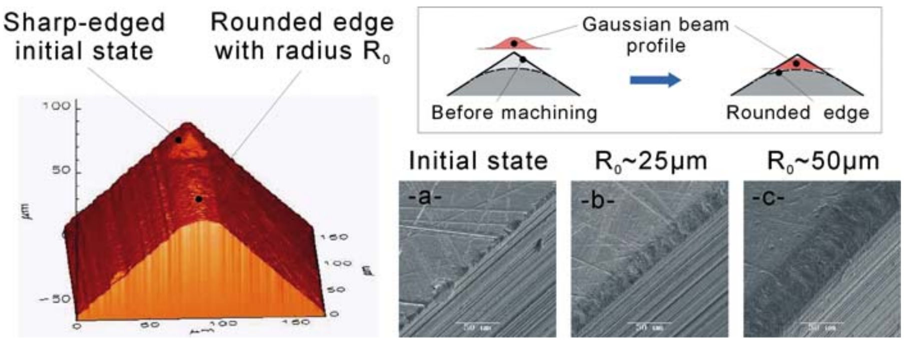

FIGURE 5: **Funcional principle and results for edge rounding.**

to drag reduction of about 7.1 % in the wind tunnel at Mach 0.8. Due to the high repetition rate of 50 kHz and focus diameter of about 30 µm the pulse overlap was between 99.3 % for 1 mm/s and 86 % for 200 mm/s and leads to current removal rates up to several cm^2/h. To increase the process efficiency and enhance this application to an industrial technology, different machining strategies like multi spot machining have been developed and will be verified.

Finishing of cutting tools

The durability of cutting inserts and also the quality of produced components depend decisively on the geometry and surface of the cutting edge. Conventional processes for tool preparation, like grinding or micro blasting do not provide an exact and consistent rounding of the cutting edge. Therefore, a new laser based technology for finishing of cutting tools regarding the preparation has been investigated. Due to the short pulse duration in the range of picosecond emitted by diode-pumped solid-state lasers (DPSSL), very high pulse peak power is achieved on the irradiated material. This leads to an efficient evaporation of the machined material, a composition of tungsten and carbide (WC-Co).

The rounding of cutting edges consists of two essential components: the rounding radius and the edge geometry. 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 [5, 6].

Different rounding radii are achieved by varying the laser output power and/or the feed rate, as shown in Figure 5. Here, the functional principle of edge rounding using Gaussian beam profile is shown. Figure 5a shows the initial state of the cutting edge which has been pre-machined via grinding process. The edge in Figure 5b has been laser-machined using a focal diameter of 30 µm combined with pulse energy of about 10 µJ. This leads to a rounding radius of about 25 µm. The rounded edge shows a symmetrical and homogenous rounding, which is important for the reproducibility of the actual chip removing process. A bigger rounding radius of about 45 µm with the same surface quality is shown in Figure 5c. Here, higher pulse energy has to be used due to the bigger spot size of about 50 µm. These rounding results and the first chip removing tests show the potential and flexibility of this preparation technology in comparison to conventionally rounded cutting edges.

Modification of MEMS

Fabrication of micro-electro-mechanical systems (MEMS) requires a sequence of microtechnological processes such as deposition, etching, patterning, and wafer-to-wafer bonding. In practice, the occurrence of small imperfections in any of these processes is inevitable. Generally, every single MEMS-fabrication step contributes to the generation of asymmetric structures, misalignment of actuation mechanisms, and displacement of the mechanical balance. These immanent side-effects consequently limit the achievable performance of MEMS-components. MEMS operated at a high dynamic level are particularly subject to these side-effects. The dynamic operation of the underlying oscillating structure, in the shape of a tuning fork like given in Figure 6, reveals even smallest defects of the mechanical configuration. Inbalance phenomena and offsets in the resonance frequencies essentially limit the performance of the entire system. The elimination of mechanical inbalance and tuning of the resonance frequencies by direct manipulation of the micromechanical components has been pursued at the LZH (Figures 6, 7) [7, 8]. The concept of correcting mechanical defects on every single die of a wafer in a proper and cost-effective way encounters great demands concerning the quality of the manipulation technique, and the processing time per die. Typical sizes of MEMS-structures range from ten to some hundreds of micrometers, requiring processing resolutions in the micrometer-scale. At the same time, a 6"-wafer consists of many thousand dies. Assuming a production volume of 1 million MEMS per year, the total time per die for fabrication should not exceed the limit of approximately 30 seconds. Including the time for manufacturing and probing, only a few seconds per die remain for necessary post-processing steps. Etching based on short-pulsed laser ablation is able to fulfill the quality requirements of these supplementary processes. Ablation with short laser pulses is characterized by low thermal interaction with the immediate vicinity of the target material, and enables precise and high-resolution structuring possibilities. Creation of structures, even below the µm-scale, has been demonstrated with fs-lasers. Short-pulsed lasers combined with a suitable beam delivery potentially fulfill the speed requirements for direct MEMS-manipulation, as well.

Summary and outlook

Reproducible ablation processes in the micron range using short and ultra short laser pulses have been demonstrated. Such pulse duration allows the user to limit the thermal impact into the bulk material and to influence

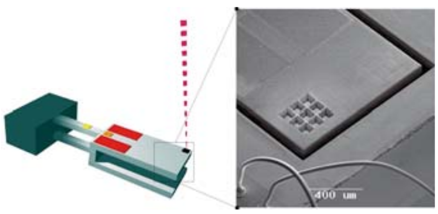

FIGURE 6: **Principle of laser trimmig of MEMS tuning fork gyroscopes.**

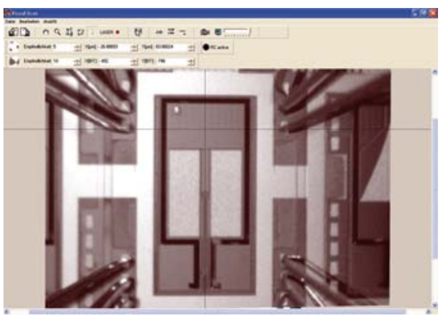

FIGURE 7: **MEMS gyroscope in laser trimming process.**

the workpiece quality positively by avoiding melting effects and burr formation.

The main limitations for this technology are on one hand the low ablation rates leading to an inefficient ablation process in comparison to ns-laser processing. On the other hand the typical repetition rates of a few kHz for fs-systems results in low effective feed rate. Both, low ablation rates and a low effective feed rate making some applications using short and ultra short laser pulses to time-intensive processes. To overcome these limitations different strategies like the beam splitting technology to generate two or more structures simultaneously are being developed at the LZH. In addition, novel laser beam sources emitting higher pulse energies and repetition rates up to 600 kHz show potential for future of micro machining using short and ultra short laser pulses.

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