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Multi parallel ultrashort pulse laser processing

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Abstract

Ultra-short pulse lasers present a new class within high-performance laser beam sources for industrial applications [Du et al 2012]. Due to the outstanding features of the radiation emitted from these sources, which are addressing important physical principles of light-matter interaction, traditional processes of deposition of light energy into the material can be circumvented. With pulse durations in the picosecond and femtosecond range, the absorbed energy is concentrated in the material to a few nanometers, so that thermal damage to the materials can be avoided.

These properties have generated numerous processes in in precision machining at solar cells, batteries, injection molding tools and electronic components [Hartmann et al 2008]. Due to the current developments for power scaling of ultrafast lasers in the kilowatt range, also potential applications for macro processing are obtained, which opens large markets in other than the micro processing field [Russbüldt et al 2010]. Thus, with high-power ultrafast lasers, fiber reinforced composites can be processed without thermal influence and large surfaces can be provided with friction-minimizing microstructures. However, using high power ultrashort pulsed lasers with high repetition rates in the MHz region can cause thermal issues like overheating, melt production and low ablation quality as long certain parameter sets and fluence ranges have been considered. High ablation quality only can be achieved, when the processing fluence is closed to the ablation threshold, which requires new processing strategies and innovative system components. Beside ultra high speed scanning using polygon scanners the use of multiple laser beams provide the best and most versatile high power ablation solution. With switchable single beams out of a special light modulator or a diffractive optical beam splitter high ablation rates can be achieved while maintaining the high processing quality of ultra short pulse laser ablation. With this approach a next step up to an all optical manufacturing system can be provided.

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1. Motivation

During the last years, the average power of commercial ultra-short pulsed laser sources increased significantly. This is mainly due to the requirements of the application and the industry, from which the display industry can be selected as the driving force. Cutting and ablation of sapphire and glass at high speed need high intensity and high average power without losing quality of the ablation. Today, robust picosecond lasers with average powers of 50-150 W are available for industrial use. However, when looking at typical picosecond laser processes for metals and ceramics with high quality laser ablation, laser drilling or laser cutting, the average power used in most processes is in the range of 1-10 W for a single beam processing with a classic galvanometric scanning system. With this approach 3D micro-structuring of metal surfaces for tooling and printing applications with ps-lasers is boosted by the availability of new high power ultrashort pulse laser sources with high industrial performance allowing short processing times. Using this technology for large parts and high speed ablation the efficient utilization of the high average laser power in the field of material processing requires an effective distribution of the laser power onto the work piece due to several effects in the ablation process. Therefore up to now despite the fact that machining with ultrashort laser pulses offer higher precision, the technology is still not being used in the industry for large scale parts as ultra short laser ablation is still lacking productivity with an magnitude smaller ablation rate compared to the ns-laser pulse ablation. Approaches to use a combination of a fast but non-accurate ns-laser ablation followed by picoseconds-fine processing have not been successful with regard to accuracy. In Figure 1 the ablation (diameter approx. 10µm) with single laser pulses with a 1 ns laser and a pulse energy of 10µJ shows dynamical material movements in the ablation zone. A ring of melt and recast material is visible which limits the achievable resolution of this process.

Figure 1. Cu, single pulse, 1ns laser, 10µJ pulse energy, 10µm diameter

2. Effects in high power ultra short pulsed laser processing

With pulse durations of <10 ps and a fluence of <10 J/cm², copper surfaces and some other metal surfaces can be removed in a nearly melt-free way. A surface roughness of Ra >0.4 micron can be achieved in a planar erosion. Thus, through a layer by layer material removal, also gradual three-dimensional shapes can be produced, starting from a digital data set which is transferred to the surface. However, micro-structured copper surfaces do not deliver useful properties for all industrial applications. Steel surfaces are often preferred, because they have several advantages compared with other metals, such as hardness, wear resistance, heat resistance and toughness. Moreover, these properties are also individually adjustable. Therefore, it is not surprising that steel is preferably used for tools in stamping and printing applications. If, for these applications, micro-structured surfaces are required, they are currently produced by lithographic technologies, micro drilled or by direct laser ablation in some 100 ns-pulse regime. Micro-structuring of stainless steel X1.4310 or of steel St-52 surfaces by means of ultra-short pulsed lasers produces various side effects such as cone-like protrusions CLPs or hole formations (Fig. 2), which has been shown by Eifel et al 2010.

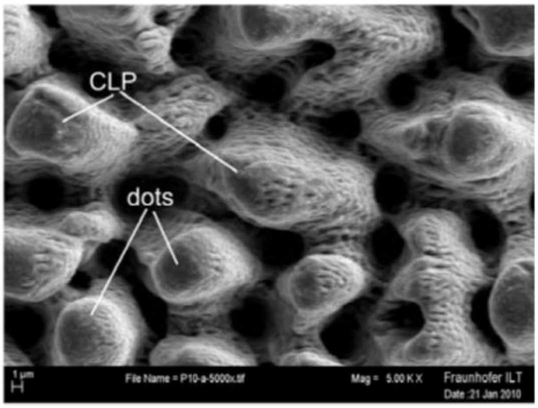

Figure 2: Laser generated micro dots and cone like protusions at high laser fluences in steel

These effects can be reduced by a suitable choice of parameters (usually in the range of a fluence in the ablation threshold), but cannot be completely prevented. In the case of stainless steel X 1.4310 and steel St-52, surface defects are emerging on the ablated area like clusters. The formation of the CLP starts at some nucleation of the surface. During a further laser ablation the clusters of CLP are being formed and are growing until the complete area of the ablation zone is covered. The pulse to pulse overlap, adjusted with the surface speed at constant pulse repetition rate of 2 MHz, has an influence on the growth of the CLP clusters. The CLP area in the ablation zone is expanding with decreasing pulse to pulse distance. As a second effect, high average power at low scanning speeds lead to thermal accumulation and subsequent heating by every scan. With a scan to scan repetition rate of several 10 kHz even at metals with good heat conductivity is continuously heated up to the melting point of the material. Thus, the result is material bending, surface melting and reduced ablation quality.

In order to achieve very high ablation qualities the accumulation of surface defects due to laser processing e.g. surface roughness, debris and fluid-dynamical movements of melt must be avoided right from the beginning of the process. This can be achieved by processing layer to layer with the same high quality of the almost cold ablation by ultrashort laser pulses. However, this concept requires an efficient engraving algorithm with well-balanced process parameters to achieve highest precision and maximized ablation rate, which has been evaluated in previous experiments. As a result, it can be stated that in order to preserve the optimized processing conditions at higher power levels, the fluencies must be kept moderate to values, which are mainly depending on the material and the absorption conditions.

3. Systems for high speed laser processing

To avoid negative surface effects like cone like protusions, surface ripples, plasma interaction and thermal accumulation a dedicated system technology together with an adapted processing strategy is necessary. From the current point of view two different approaches can be seen

- Ultrafast scanning with moderate pulse energies and high repetition rates
- Multiple beam processing with moderate fluences in each single beam

Both approaches lead to high average ablation rates and can be used to optimize the usage of high power ultra short pulsed lasers.

3.1. High speed scanning technology with fast polygon mirrors

The available pulse repetition rates of ps-lasers in the MHz range and the relatively slow scanning speed of common galvanometric scanning devices in the range of 5-10 m/s imply a large pulse overlap. This leads to a high local thermal accumulation and a pulse-plasma interaction on the metal surface leading to a decreased machining quality that can be classified between ps- and ns-pulse regimes. In order to enable the use of high pulse repetition rates with less thermal effects, an ultrafast scanning technique is required. One solution for this is the use of a polygon mirror device. For high scanning speeds in the range> 100 m / s and a fast material removal with high repetition ultrashort pulse lasers a processing system with a fast polygon scanner and a fast beam modulator was realized. For polygon scanners a polygon mirror rotating at high, constant speed of multi 10 Hz/s was developed thereby increasing the maximum processing speed significantly. The optics is based on a high speed drive in combination with a multi facet mirror system. A conventional f-Theta-Optics can be used for a processing field of up to 100 mm with 160 mm optics and a scan speed of up to 320 m/s. The modulation of the laser beam at several MHz in syncronisation with the laser cycle and the correspondingly adjusted positioning of the laser beam on the workpiece constitute the biggest challenges. By using this technology every single laser pulse can set with a low pulse overlap for optimal results when utilizing the full laser power. For processing a large area, the laser beam is deflected along a line and by displacement of this line a two-dimensional processing is carried out with a high accuracy moving system. In this way the entire workpiece can be processed in a bitmap mode. The system has been integrated into a high precision laser cutting machine for semiconductors. In Figure 3 the system setup for the semiconductor machining is shown together with a performance result for cutting silicon semiconductors at different fluences resulting in cutting widths of around 20 – 30 µm at scanning speeds of up to 40 m/s.

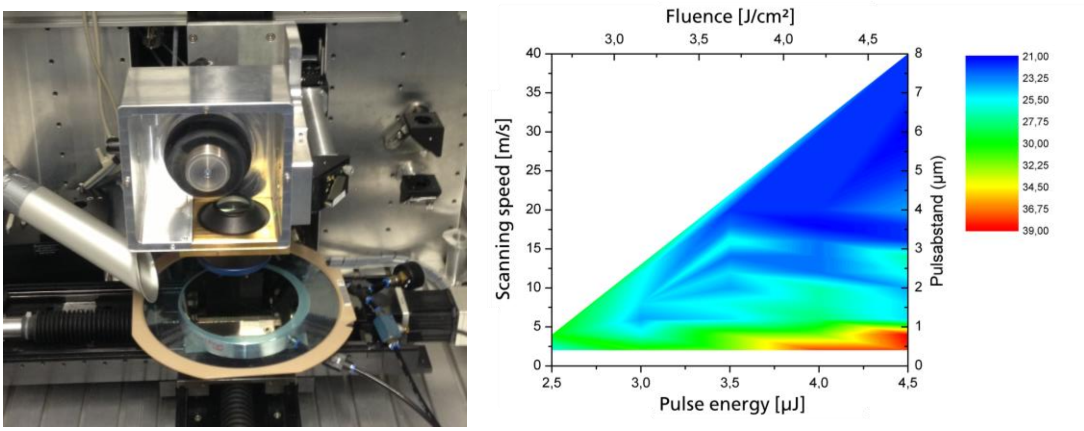

Fig. 3: Laser scanning unit with polygon mirror (left) and processing results using ps-laser source at a wavelength of 532 nm

3.2. Multiple beam processing with diffractive optical beam splitters

The second approach to increase the efficiency is the application of beam splitting devices to enable parallel processing with multiple beams at low energy levels of each single beam. However shaping and steering of multiple beams requires particular optical systems which are not state of the art today. Limitations for large spot arrays are evaluated and considered for the design concept of appropriate optical systems. For the purpose of micro structuring with high demands on the spatial accuracy, an optical system based on a diffractive 14x14 beam splitter (DOE) is designed and set up. By splitting the laser beam into several beams, significantly greater laser power can be utilized just by multiplying the number of beams. This beam splitting is made possible by a diffractive optical element (DOE). The DOE consists of an array of microstructures, which are capable of producing virtually any type of intensity distribution behind the element by means of diffraction – depending on the design. The DOE is integrated into an optical set up between the beam source and a galvanometer scanner in such a way that the split laser beams are imaged in the galvanometer scanner by a relay lens system. Furthermore, this relay lens system offers a practicable solution to remove higher diffraction orders of the DOE. Focusing the beams using an f-theta lens produces a periodic array of processing points, which can then be moved across the workpiece. This makes it possible to ablate patterns of any complexity even on a large scale. Due to the scanner a highly dynamic, simultaneous deflection of all partial laser beams can be achieved. For the alignment and the experimental evaluation of the complex optical system appropriate measurement devices are necessary. The simultaneous determination of several spot positions is realized by a camera system and adapted evaluation software. First experiments of large-area processing metal foils show promising results.

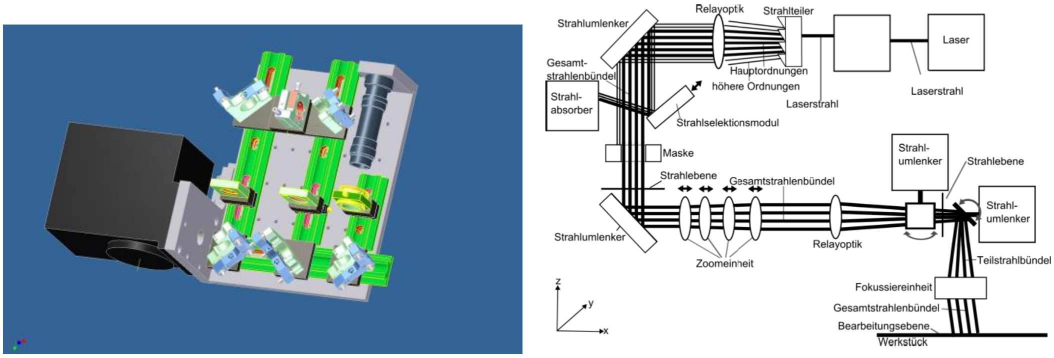

Fig. 4 Multi beam set up for parallel processing with ultra short pulsed lasers , left: 3D-sketch, right: system components

The splitting of a laser beam into 196 beamlets has already been successfully demonstrated in an optical set up and has been integrated in a laser processing machine This beam parallelization enables the workpiece to be processed at 196 periodically arranged points simultaneously, resulting in an almost 200-fold increase in processing speed compared to a single laser beam. In figure 4 the principle set up of the optics is shown for modular changing beam pitch and numbers of rows and columns. With this device and a high power ps-laser micro drilling and micro ablation has been shown in filter applications and thin film ablation as shown in figure 5.

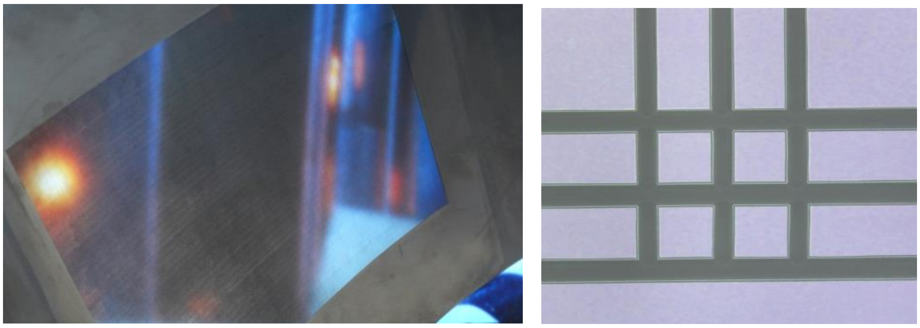
Fig. 5: Multibeam drilling of filter foils (left), Multibeam thin film ablation of ITO-layers (right)

3.3. Multi beam processing with spacial light modulators.

A more flexible approach with respect to the spot configuration and pattern shape is the use of a spatial light modulator (SLM). Which is placed in front of a galvanometric scanning system. The SLM works similar to the static DOE-devices but allows flexible modulating amplitude, phase or polarization of light waves in space and time and thus generating arbitrary patterns in the work plane of the scanning system. With the SLM a pattern of single beams or even lines and shapes can be generated by shifting the wavefront phase with a resolution of several microns. In this way an interference pattern is produced in the focal plan of an imaging lens. Using LCDs as a phase shifting system, the pattern can be changed with a frequency of up to 50 Hz. SLMs have been used for beam steering and beam shaping in microscopy and cell manipulation in the past but are available even at high lasers powers up to 100 W. In this way SLMs can be used in micro manufacturing with high power ultra short pulsed lasers with flexible multi beams. Using SLMs, the SLM is imaged into the scanning system using a 2f or 4f optical setup as shown in figure 6.

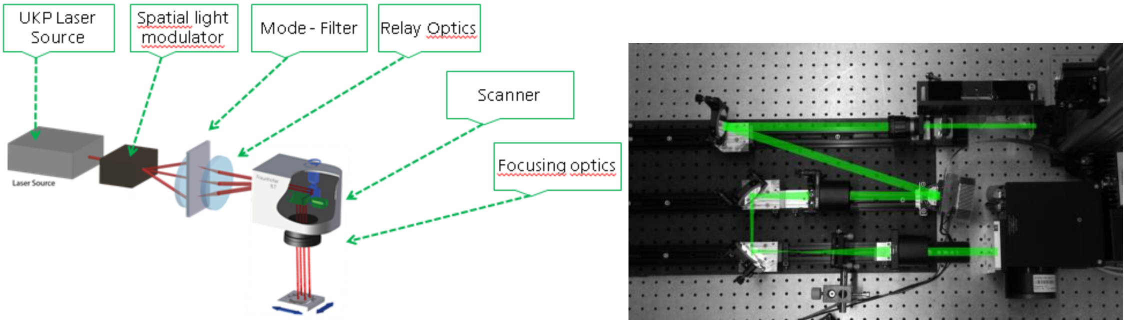

Fig.6: Set up for multi-beam processing with spatial light modulator (left), SLM combined with Galvo-Scanner (right)

With this system picosecond laser processing has been performed with different configurations of laser spots. In combination with a fast Galvo Scanning system both position and shape of the generated diffractive pattern can shaped and flexible ablation on large fields can be performed with ultrashort pulsed lasers, as shown in figure 7. With this approach SLMs will probably be an alternative for the use of static DOEs in high power applications in future.

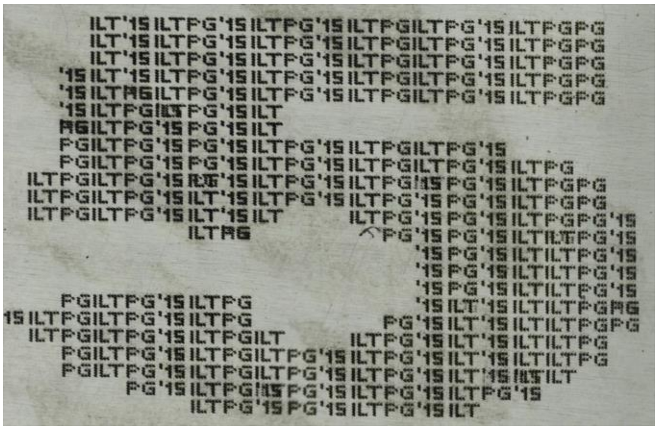

Fig.7:flexible surface pattering with spatial light modulator in combination with Galco Scanner and picosecond laser radiation

4. Conclusions

Using two different scanning techniques, the potential of high power ultrashort pulsed laser ablation of metal surfaces for respect to ablation quality and efficiency has been investigated with different approaches. Since high fluences produce negative effects such as cone like protusions and thermal accumulations, a large pulse to pulse overlap as well as high fluences have to be avoided. At high pulse frequencies with high pulse overlap, an increase of thermal effects (debris, molten parts, and oxide layers) can be seen. This can be reduced by ultra high speed scanning using polygon scanners. A more flexible way is the use of diffractive optical elements (DOE) with a significant reduction of fluence in each single laser beam. Using DOEs with several hundred laser beams, the productivity drastically can be increased. Moreover with spatial light modulators (SLM) new technologies are available to change interference patterns thus allowing large field processing with ultimate ablation quality.

In future, this technology will permit the output reserves of current high-power ultra-short-pulse laser systems to be fully utilized on the workpiece for ultrashort pulse laser processing. Processing times will drop accordingly, leading to a significant reduction in overall process costs. This will make USP lasers significantly more attractive to users from an economic point of view for manufacturing periodic microstructures. With this approach, it becomes economically feasible to structure even large surfaces. The long-term goal is to use multi-hundred-watt lasers for micro structuring before too long.

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