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Experimental studies on effects at micro-structuring of highly reflecting metals using nano- and picosecond-lasers

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Abstract

Microstructuring of highly reflective metals was performed using high-power nanosecond- and picosecond-laser beam sources. This contribution mainly focuses on the ablation depth, achievable sidewall inclination angles and the ablation quality. Single- and multilayer structures with varying width and depth were generated to analyse the interdependency of the resulting ablation quality with the processing parameters and strategies used. As results, optimized strategies to generate different geometrical structures with specified qualities and processing times are proposed. In addition, an effect occurring at ps-multilayer ablation, which was up to now only described theoretically, will be presented.

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1. Introduction

In production, processes like milling, photolithography and eroding have been well known and proven in the field of microstructuring for several years. These processes are being successively replaced by more innovative ones like the laser-ablation, because of its rapid development in the field of surface-structuring. For instance, actual operating fields for laser ablation are electronic, sensor technology, medical science and micro system technology.

By laser radiation a highly-precise and a non-contact processing of different materials and surfaces is possible. This enables, compared to conventional methods, the production of structures within the lower micrometer range in less time. Depending on the material and laser system, structures with different parameters, like the ablation width and depth, as well as the ablation quality can be realized. The minimal structure dimension is determined by the focal diameter of the laser beam and the beam quality, represented by the beam parameter product (*BPP*).

For industrial application, the most suitable results at laser structuring of materials can be achieved by using a

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picosecond-laser, although these sources are still not wide-spread in series production. Its short pulse durations and the high local energy density lead to a sublimation of the material without the development of a liquid phase [1]. Ultra short pulse laser systems – especially amplified systems – achieve the highest energy density of all currently available beam sources, but also the lowest ablation rate per pulse. Compared to this, nanosecond lasers have longer pulse durations and pulse energies. Using these sources, the ablation rate can be increased, but more liquid melt will be created. In contrast to this, the advantage of metal treatment with ultra short pulses is that by using an appropriate amount of pulse energy, the development of melt is determined. The consequence is a very good structure quality.

Structures on metal surfaces with an accuracy grade of a few micrometers and a small surface roughness are producible by using short-pulse Q-switched solid state laser [2]. A basic challenge of the sublimation abrasion to produce accurate structures is the incoherency of a high ablation rate and a good structure quality. A high ablation rate (some mg pro laser pulse) as a result of a high laser power is associated with a big mechanical damage of the surface and a significant development of melt. This leads on the one hand to a high surface roughness and on the other hand to a geometrical deviation as a consequence of uncontrollable re-deposition of melt [3].

Since fs- and ps- lasers usually provide very high beam qualities and therefore are well focusable, it is possible to generate energy densities on the irradiated material surface which exceed those of conventional lasers by several orders of magnitude [4]. As mentioned, fs- and ps-lasers are not established in the material processing yet, because of their small ablation rate. As consequence of new studies on ps-lasers, now a higher ablation rate can be reached.

The aim of this paper is to describe and compare the phenomena during ns- and ps- laser processing. Especially, the achievable quality by using different process parameters and strategies is considered. In this context some phenomena which are well known to occur at ns-laser ablation, and which are only described up to now in a theoretical way at ps-laser ablation are shown as experimental results. Different processing examples with various structures and processing strategies will be regarded. In addition, the results are analysed concerning the suitability of ns- or ps-laser sources for each individual application.

2. Fundamentals

The fundamentals of laser ablation will be briefly described in the following paragraph. The ablation mainly depends on the absorption of the laser beam energy, which is influenced by the material and process parameters and changes during the ablation process.

2.1. Interaction mechanism between laser beam and material

To understand the structuring of a surface by laser ablation, a detailed consideration of the interaction mechanism between laser pulses and the material is essential. A material which is exposed to a conventional laser beam absorbs the pulse energy contained in the photons directly within the top surface layer. There, the energy is transformed into heat. To obtain the melting or boiling temperature of the material, the energy density of the laser radiation has to be set adequate high. The shorter the laser pulses get, the more energy they possess. At this point, the single steps of this process have to be separated from each other and have to be regarded independently. Different effects like the interaction of the laser pulse with the generated plasma or shockwaves, which are caused by plasma expansion, may influence the process [4]. At metals, as used in this investigation, the absorption is linear. As consequence, four processes during the absorption mechanism can be observed:

- absorption of optic energy by free electrons ($t_{\eta e}$);
- thermalization of the electrons to electron system (t_{ee});
- interaction between electron system and phonon system (t_{ep});
- thermalization of phonon system (t_{pp}).

The thermal interaction mechanisms are losing relevance with short pulse lengths. These pulse lengths (t_P) have to have a time expansion that is in the range of the duration of thermal conduction and diffusion processes within the material ($t_P > t_{PP}$). Instead of this mechanism, the process is getting dominated by special photo-chemical effects. They can only be observed when ultrashort laser pulses ($t_P < t_{ep}$) interact with material [4, 5]. The ablation with ultrashort pulses is characterized by a small thickness of the molten film and low mechanical stress. Fig. 1 shows a cross-section of a ps-ablation with an actual high power ps-laser system.

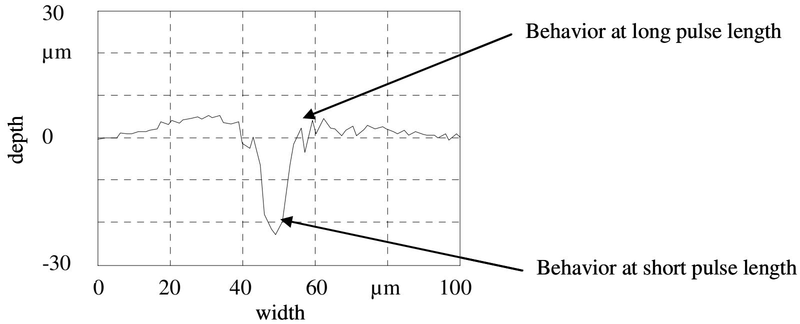


Fig. 1. Cross-section of a ps-ablation

2.2. Ablation rate

The *ablation rate* can be defined as the *area per time* or the *volume per time*. In this paper the definition of ablation rate will be the ablated *volume per time* without considering the positioning time of the scanning optic. This definition is chosen to better compare the different laser systems and the structures ablated. For the calculation of the ablation rate the following parameters are important:

- the structure length x [mm], the structure width y [mm] and the structure depth z [mm];
- the feed rate or scanning speed v [mm/s] and the y-pitch dy [mm];
- the number of ablated layers n and the ablated volume V [mm³].

Thus, the ablation rate for lines will be:

$$\Delta Z_L = y \cdot z \cdot v\,, \quad [mm^3/min] \qquad (1)$$

and the ablation rate for areas:

$$\frac{60 \cdot xyz}{\frac{x}{v} \cdot \frac{y}{dy} \cdot n}\,. \quad [mm^3/min] \qquad (2)$$

2.3. Pulse pitches

An important parameter by ablation of areas is the overlap, or the pitch in x- and y-direction. The x-pitch is preset by the repetition rate and the feed rate (or scanning speed) of the optical system. If one of these parameters is changed, the x-pitch will increase or decline. In the following, the x-pitch is kept constant and named as dx. The y-pitch dy will be varied. The principle results and consequences for the ablation process for dy < dx, dy = dx and dy > dx at producing multiple layers is shown in Fig. 2.

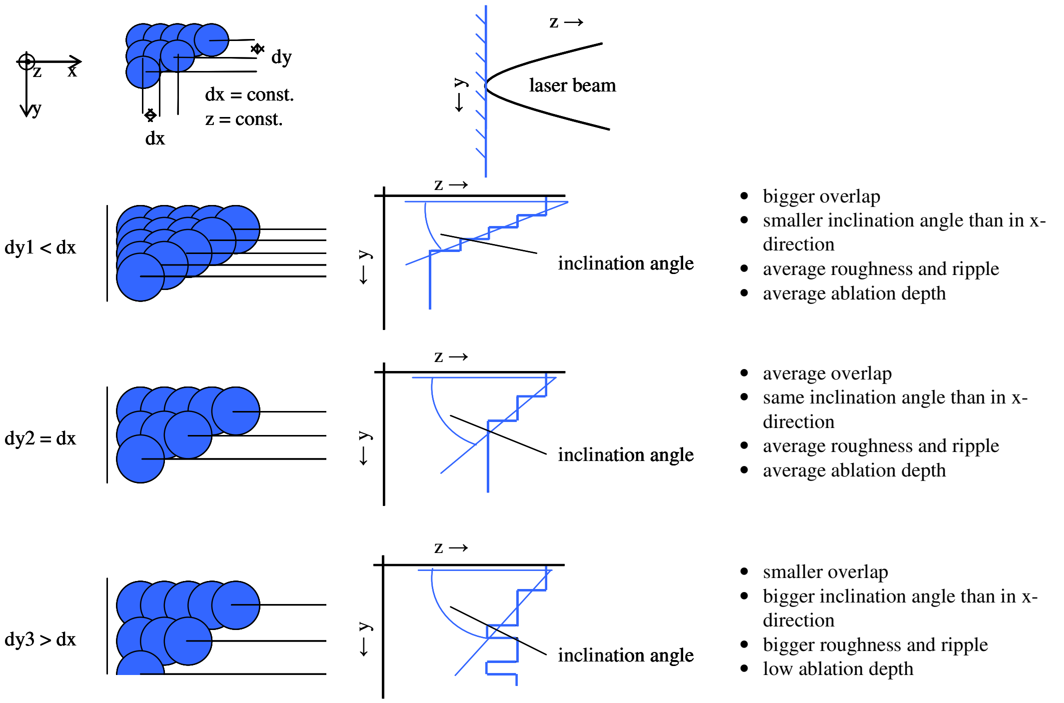


Fig. 2. Results at processing with a overlap in y-direction

3. Experimental Setup

For experiments high reflective metals like stainless steel or brass are used. As beam sources different ns- and ps-lasers are appropriated. The important process parameters are mentioned in the text. At every system, the laser beam is directed by high-reflective mirrors and a galvanometric-scanner. A telecentric f-theta lens focuses the laser beam onto the material surface, as depicted in Fig. 3.

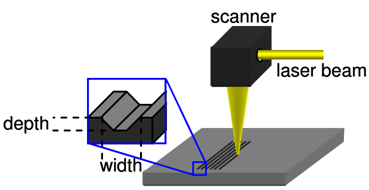


Fig. 3. Schematic system setup

4. Results

The following results use certain examples to point out the most important effects occurring at ns- and ps-laser ablation. They are only representative for the respective experiments, for other setups they will be slightly different. Nevertheless, common tendencies will remain the same.

4.1. Parameter dependence

The accuracy and the structures dimensions of an ablation process depend on the suitable choice of the different laser parameters like pulse duration, pulse energy, wavelength, average laser power and the repetition rate. The effects on the ablation result are shown with a respect on the ablation depth and the ablation quality.

4.1.1. Laser parameters

The results of this topic are shown in a compact way, where pulse length, pulse energy, repetition rate and average power are combined with each other. The higher the repetition rate at constant average power, the lower the pulse energy and thus the ablation rate are. As consequence of the different ablation mechanisms, the quality of the structures generated with ps-lasers is higher, but as it is known, the ablation depth of this process is smaller compared to ns-lasers. To get a higher amount of ablated volume, the absorption ratio has to be increased. Due to its dependency of the wavelength, laser systems emitting at other wavelength can be used. For the experimental results shown in Fig. 4, the *Lumera Super Rapid* laser system was applied. An increase of the ablation quality with shorter wavelength is observed.

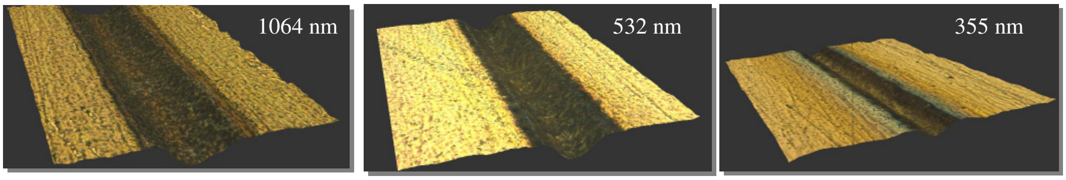
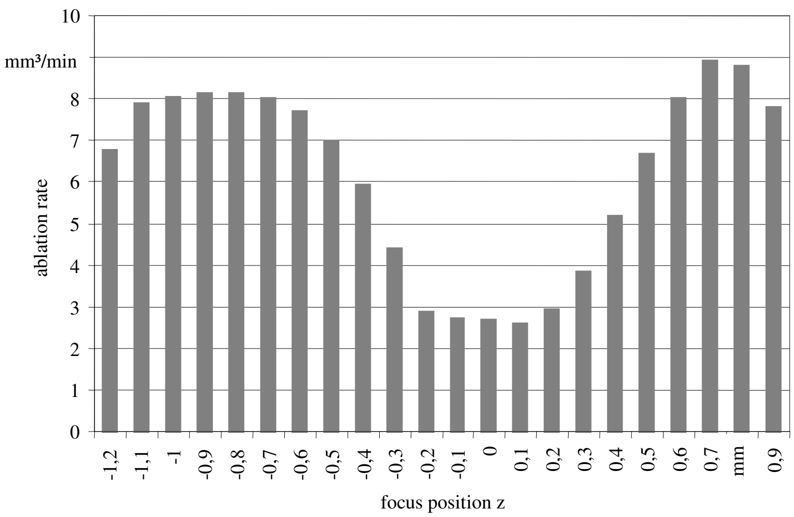


Fig. 4. (a) P = 4,5 W; f = 50 kHz; dx = 1 µm; (b) P = 2,5 W; f = 300 kHz; dx = 0,8 µm; (c) P = 2,5 W; f = 50 kHz; dx = 1 µm

4.1.2. Focus position

The position of the focal spot and its location compared to the material surface are very important for an efficient ablation process and an excellent laser structuring process. If the focus is placed onto the surface, like shown in Fig. 5, the ablation depth and the ablation rate are the smallest. A bigger distance between the surface and the focus leads to an increase of both, until a peak point is reached. After the peak point, they decline again.



Laser and process parameters:
t_P = 10 ps;
λ = 532 nm;
f = 1 MHz;
v = 2500 mm/s;
dx = 2,5 µm;
P_L = 22,4 W;
dy = 2,5 µm;
n = 1;
d_{foc} ~ 7,5 µm;

Structure dimensions:
3mm x 3mm

Fig. 5. Ablation depth against focus position

Another important structure parameter is the sidewall inclination angle. For some applications a small angle is required. Therefore, by measuring the ablation depth of the ablated structures with a confocal microscope, the cross-section of these structures are examined, see Fig. 6. As shown, the smallest inclination angle can be achieved if the focal position lies directly upon the material surface. The more it is defocused, the bigger the sidewall inclination angle becomes. An angle of 90° represents a process without ablation. The experiments show that the nearer the beam focus is to the ablation surface, the thinner the ablation structure can become. As a result, a thin ablated structure requires a focus directly upon the surface.

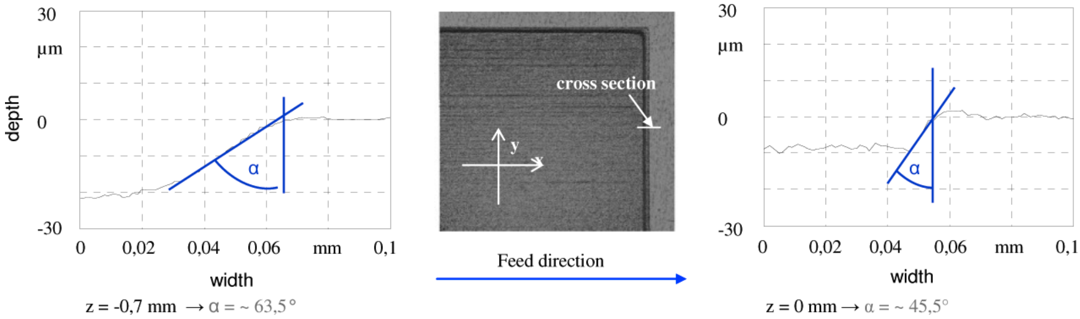


Fig. 6. Sidewall inclination angle and focus position

4.1.3. Process parameters

Applying different x- and y-pitches to the process leads to a formation of grooves. Depending on the value of the y-pitch selected, the depth of the grooves and the amount of the ablated material change. This is depicted in the left diagram in Fig. 7. In the right part of Fig. 7, the ripples are shown at a value of dy = 2.5 µm. In this case, the distance between two ripples is about 160 µm and the width ca. 60 µm. To create such ripples, more than one single pulse or a single scanning line is necessary. A similar influence can be observed by changing the feed rate or the scanning speed. Keeping the other process parameters constant, an increasing feed rate leads to a lower ablation depth. This is due to the growing x-pitch, comparable to the effect observed in the y-direction.

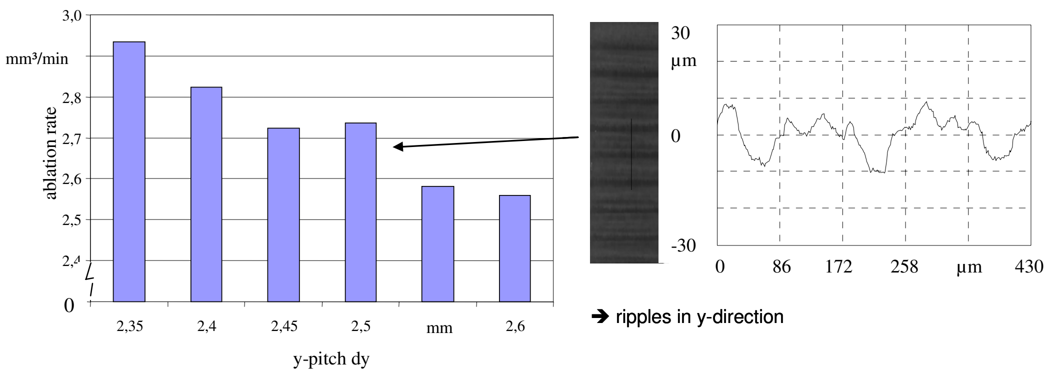


Fig. 7. Groove formation at different overlap values in y-direction

4.2. Scanning strategies

The former paragraph deals with variables which can be set by the system. In the following, the effect of different process strategies on the ablation result will be examined.

4.2.1. Structure dimension, geometry and orientation

To study the influence of geometrical and orientation-related parameters, scanning lines with a different width and orientation are engraved with identical laser parameters. In the following experiments, the *line width* is defined to be the desired value, the *structure width* the result after laser processing. Due to heat transfer, especially for thin or small structures, these two values differ from each other. The determination of the structure width for specimens with dimensions < 10 µm is done by using metallographic cross-sections, because confocal measuring methods reach their limits.

In the experiments, a interdependency of the structure width and depth could be noticed. In contrast to lines with a wide lateral dimension, thin lines are not ablated as deep. The basic principle is pointed out in Fig. 8 a. There, the focal position is included as well. It can be seen that the focal position also has an influence on the structure depth. Fig. 8 b compared the line width with the mechanical scanning direction. For the prior experiments, the scanning direction was horizontal. To generate perpendicular lines to the scanning direction only one pulse is set per horizontal line. Again, the dependence of the ablation depth from the line width is obvious. Thinner lines which are orientated in feed direction are engraved not as deep as the lines vertical to the scanning direction. From a specific line width the ablation depth in horizontal and vertical direction is equal because the generated plasma plume has no time to disappear between the laser pulses that hit the material.

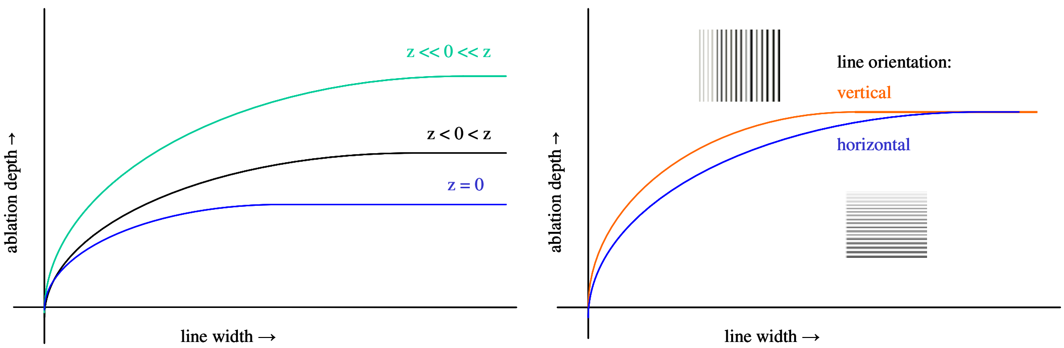


Fig. 8. a) Ablation depth dependent on line width a. focal position; b) Ablation depth dependent on line width a. orientation

4.2.2. Layer number

If the total volume of the ablated material remains below a certain amount, ps- laser processing can be applied in an economical way. In this context, to get a structure depth deeper than 50 µm (focal diameter: 8 µm; pulse length: 10 ps), there have to be multilayer ablation processes as well. The same structure has to be overrun many times before the prior specified result can be generated. At every overrun, a defined ablation depth is produced, depending on the parameters pulse energy, pulse overlap, position of the focal point and the structure dimension. Fig. 9 a) shows a structure generated by laser ablation after the first layer. The ablation depth is approx. 8.5 µm with a sidewall inclination angle of approx. 50°. After three overruns, the depth of the structure increases up to 25 µm and the angle declines to 35°. The picture on the right shows the same structure with a depth of 77 µm and a sidewall inclination angle of 25°. In this case, a groove is formed by multilayer ablation, because of the reflection of the laser beam at the sidewall of the structure. This effect increases in respect to the laser power. This so called grooving-effect is well known during ablation with ns-laser already and is supposed to occur also during high power laser ablation. In the studies performed, this effect could be demonstrated experimentally.

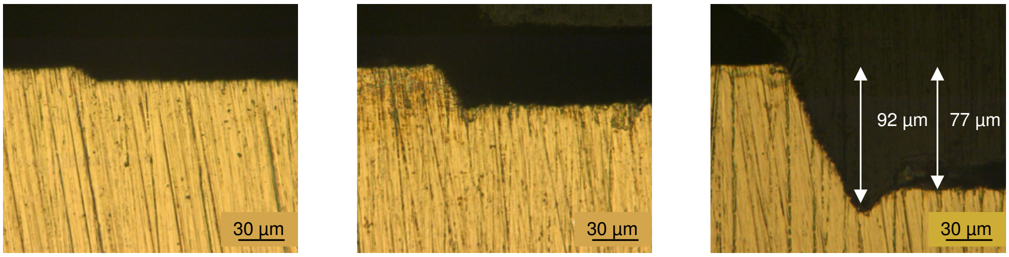


Fig. 9. Ablation with different number of layers: a) one layer; b) three layers; c) nine layers

5. Discussion

Some effects like the variation of the ablation depth by using various focal positions can be explained with the different focus or ablation diameter on the work piece surface and therefore with a lower energy density. Thus, the ablated depth per scanning line is less than in the case of a smaller focal diameter. In contrast to this, keeping the same values for the x- and y-pitch, the structure width becomes wider and the overlap higher. As consequence, the inclination angle gets bigger and the ablated depth (ablated amount of volume) per layer becomes bigger at processing wide structures. Positive effects of bigger focus diameters are a less roughness of the structure surface and less ripples in the ablated area. The reduction of the ripples seen by several y-pitches can be achieved by choosing an experimentally optimized y-pitch, depending on the system used, respectively.

For small or thin structures the interaction between plasma and laser beam plays an important role. This is experimentally proven by graving various line widths with different orientations and the resulting low ablation depth at a decreasing line width. This effect is caused by the partial absorption of the laser energy by the generated plasma plume. This effect is the reason for the ablation rate at thin line-structures being lower in a horizontal orientation than in a vertical direction. The generated plasma has not sufficient time to disappear from the ablated zone and interacts with the following laser pulse. At wider structures, containing more lines to be scanned, the plasma can leak from the work piece surface and thus more laser energy directly hits the material for ablation, without being absorbed or scattered.

Another effect causing a bad quality of the ablated structures is the re-deposition of the ejected and ablated material. The material re-solidifies at the structure walls and causes burs. The effect mentioned last in section 4 is already known as groove-forming at ns-laser ablation. This effect also occurs at ps-laser processing with its higher peak powers. There are only speculations of the reason of the generation of a groove by ps-laser ablation. The initiating effect at ns-laser ablation is the reflection at the side walls of the structure which has to be avoided by selecting an adaptive scanning strategy. If this is also the reason during ps-laser structuring a possible solution is the reduction of the scanning area depending on the actual layer ablated. This reduces the accumulation of unwanted beam reflections underneath the side walls of the structure.

6. Summary and Outlook

A precise ablation depth depends on the pulse energy, the pulse overlap, the position of the focal point and the dimensions of the structure. By changing one of these parameters, all others are affected as well. Every material and structure has its own set of optimum parameters, which are to be determined at every single task. In this paper it is shown that the ablation using high power ps-lasers is similar to the ablation with ns-laser sources if just the melt-effects are regarded. Also a grooving-effect is shown that was up to now only known at ns-ablation. The reason of this effect has to be analyzed in further research. With the rising number of ps-lasers in industrial applications the understanding of such effects is getting more and more important.

Of course, the quality of a structure generated by ps-laser ablation is better than the one produced with ns-laser systems. On the other hand, the throughput using ns-lasers is still higher than with ps-lasers. But regarding actual developments of high power ps-laser systems, the ablation rate will increases continuously. As consequence, the substantial argument of high ablation rate by ns-laser ablation is not valid anymore. It still depends mainly on the given task and the costs of the laser system to decide which laser is the favorite one.

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