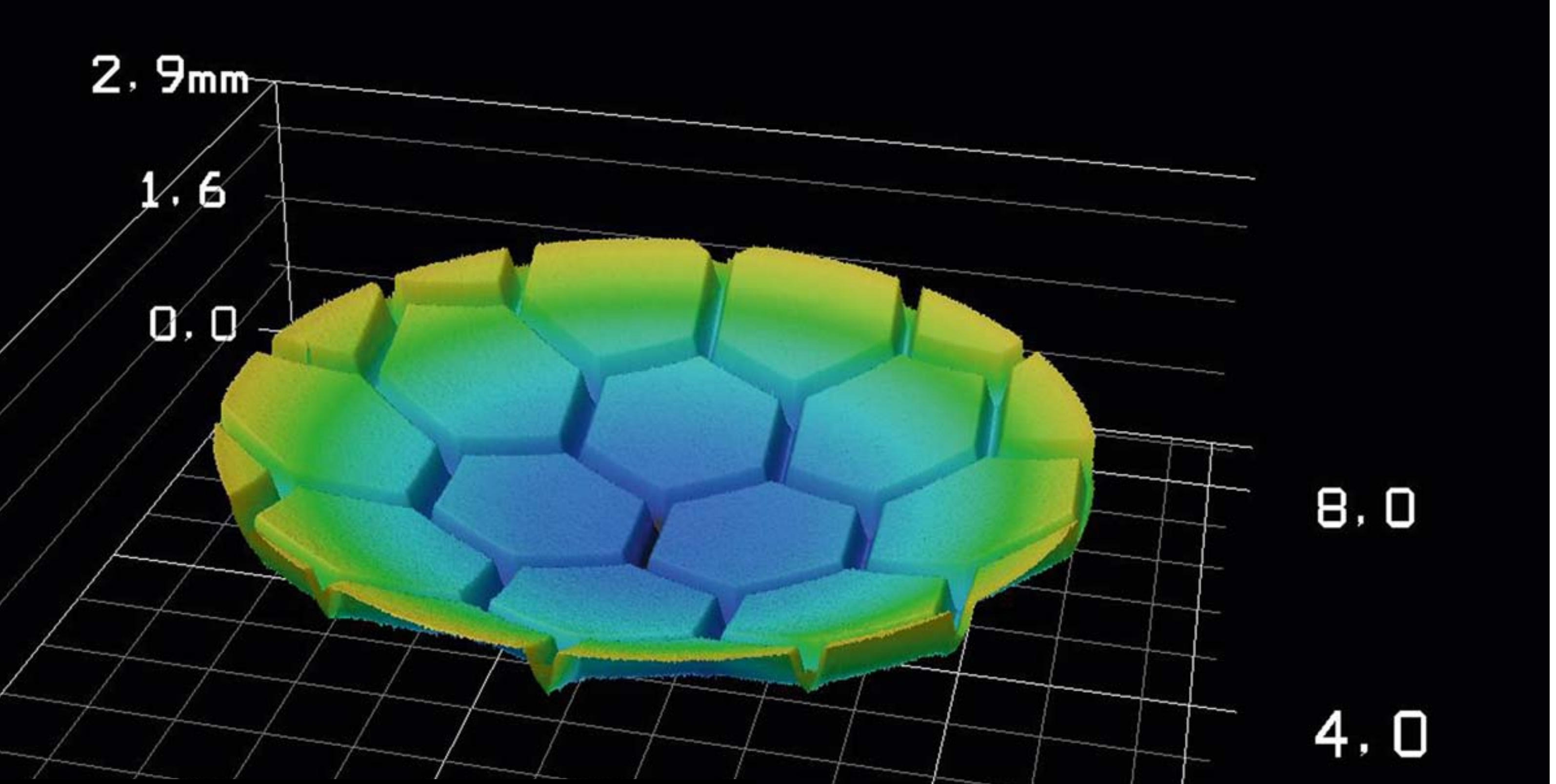

PARAMETER INFLUENCES ON THE LASER PROCESSING OF CERAMICS WITH ULTRA-SHORT PULSES

Within the scope of a sensitivity analysis, optiSLang is used to investigate the main influencing variables in complex laser material processing. With the help of real laboratory data, physical correlations can be revealed and examined.

Introduction

High-performance ceramics such as alumina have been firmly established for the manufacturing of tools and components in the modern electronics industry and mechatronics. Various components, for instance circuit boards, bearings and sensors, benefit from specific characteristics, such as wear resistance, stiffness and electrical neutrality. Nevertheless, the mechanical processing of ceramics is often a difficult task. For this reason, modern laser technologies, which enable a contactless and wear-free processing, have been used to process ceramics for some time now, for instance for cutting, scribing or drilling.

However, regarding high-precision applications such as surface functionalization, micro-drilling or three-dimensional structuring, conventional laser processes reach their limits. Especially due to the thermal influences of the laser radiation, brittle edges, stresses and redeposited layers emerge. Ultra-short pulse lasers, which have been industrially available for a few years, allow for completely new surface qualities. The extremely short pulse durations in the pico- and femtosecond range lead to non-linear absorption mechanisms and an almost athermal material removal. Even brittle-hard, dielectric substrates can be processed precisely and gently.

Nevertheless, many questions regarding the ablation mechanisms and the beam-material-interactions of ceramics and ultra-short pulses still have not been entirely clarified. As shown in Fig. 1, the material removal with ultra-short pulses is an extremely complex process, which is influenced by a variety of parameters. Besides the material properties and the environmental conditions, the laser parameters such as wavelength, pulse duration and repetition rate predominantly influence the process. The pulsed radiation can be characterized by different energy-related variables, such as pulse energy, average power, or energy density, which is referred to as fluence. It often remains uncertain which of these factors describes the process best. Moreover, the parameter field is complemented by the process variables, which are defined by the scanner movement leading to a two-dimensional surface ablation. While the pulse distance within a scan line results from the marking speed, the distance between the scan lines is freely selectable.

In order to reveal and optimize the processes happening during surface ablation, investigations on alumina (Al_2O_3) have been executed. The particular aim was to examine a

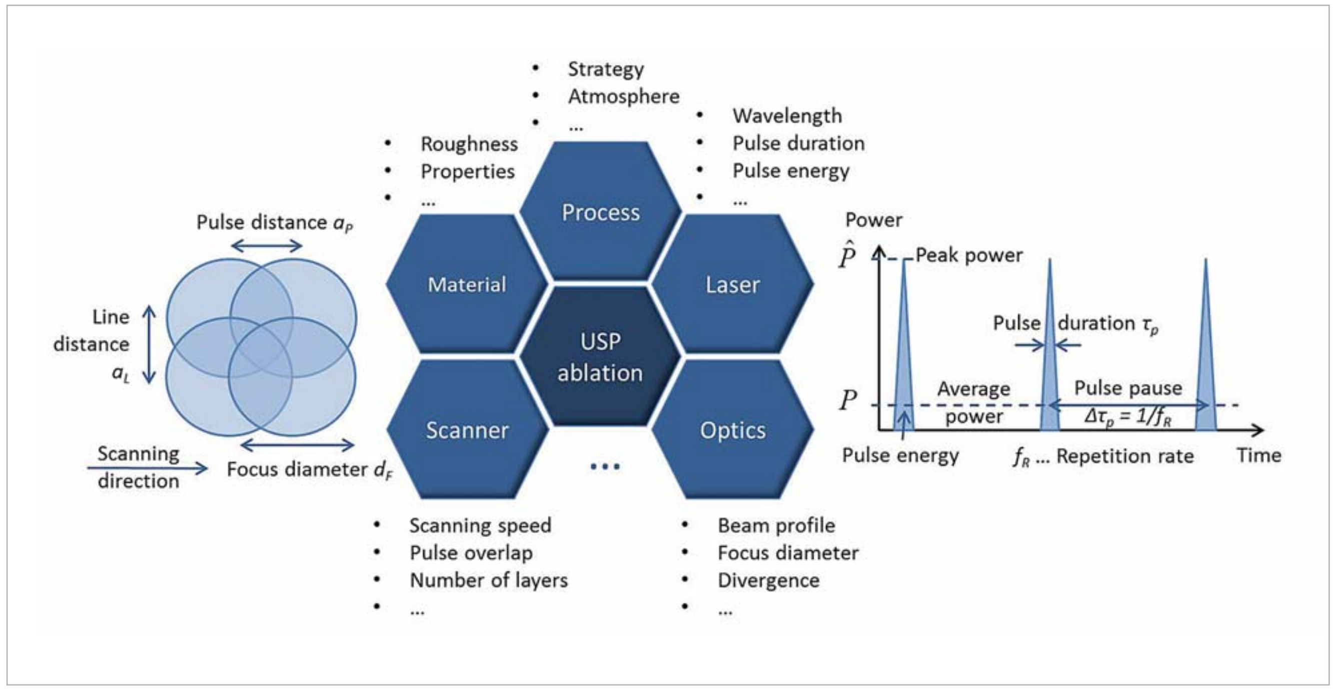

Fig. 1: The ultra-short pulse ablation is influenced by a multitude of parameters

large number of parameters simultaneously regarding their influences on the ablation process as well as their interactions among each other. For this purpose, optiSLang was used to execute a Design of Experiments as part of a sensitivity analysis.

Experimental Approach

The experiments were carried out with a mode-coupled solid state laser (Lumera Laser, Hyper Rapid 25) with a pulse duration of 9 ps and a wavelength of 1064 nm. Via external frequency conversion, the second and third harmonic are generated so that two other wavelengths, 532 nm and 355 nm, are available. The beam, which has a Gaussian shaped intensity profile, is deflected by a galvo scanner and focused with f-theta objectives of varying focal lengths.

Using the Latin Hypercube sampling, an experimental design with 100 parameter combinations was set up. These have been applied to fields of 5 mm x 5 mm filled with parallel scanning lines to remove the material within the entire area. The evaluation of the ablation process is based on the output parameters of profile depth and roughness. These have been measured with the aid of a laser scanning microscope (Keyence, VK-X100). The roughness was determined by a multiple line scan and the profile depth by measuring the step distance between initial and processed surface (Fig. 2). To evaluate the efficiency of the process, the ablation rate was calculated as the ratio of ablated volume and processing time. Furthermore, the ablation per layer has been determined as the ratio of profile depth and number of layers. This output parameter provides information on how uniformly the removal process continues into depth.

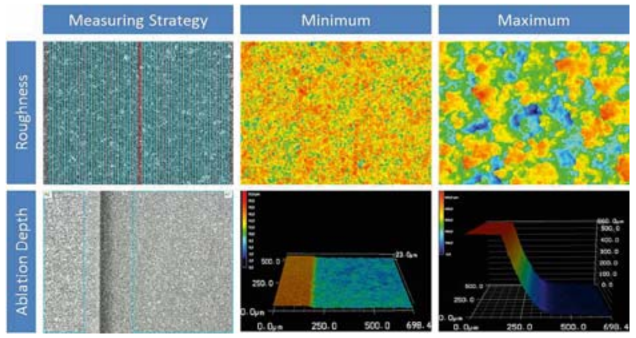

Fig. 2: Measurement of the main responses – roughness and ablation depth

Table 1 (see next page) gives an overview of the input and output parameters. While some inputs can be changed directly by the machine settings, others result from physical connections (controlled variables). Concerning the sensitivity analysis, all listed parameters have been taken into account to identify their significance for the removal process. For this purpose, the external data measured in the laboratory have been imported to optiSLang using the Excel Add-in and analyzed with the help of the Metamodel of Optimal Prognosis (MOP).

Sensitivity Analysis

In addition to the one-dimensional sensitivity analysis using the extended correlation matrix, the coefficient of prognosis (COP) has especially been used to analyze the data within a multidimensional sensitivity analysis. Considering all input parameters, it is found that the roughness is in particular dependent on fluence and pulse overlap, whereas the output parameters connected with the ab-

Input Parameters				Output Parameters	
actuating variables		controlled variables			
Power P [W]	0.3 … 20	Fluence F [J/cm²]	0.1 … 32	Roughness Ra [µm]	0.42 … 3.8
Wavelength λ [nm]	355; 532; 1064	Pulse distance a_p [µm]	1 … 15	Ablation rate A [mm³/s]	0 … 7.8
Scanning speed v_s [mm/s]	200 … 3000	Horizontal Overlap O_h [%]	-33 … 99	Ablation depth t [µm]	0.24 … 543
Line distance a_L [µm]	1 … 15	Vertical Overlap Ov [%]	-33 … 99	Ablation/layer ApL [µm]	0.018 … 31.5
Focal length f [mm]	40; 80; 100; 250	Focus diameter d_F [µm]	12 … 100		
Number of layers N	1 … 20				

Table 1: Overview of input and output parameters with associated value ranges

lation depth can be better explained by power as well as pulse and line distance. This shows that the focus diameter, which is required for the calculation of fluence and overlap, especially has a significant influence on the quality of the processed surface.

Due to the physical relation of the input parameters, high input correlations occur, which reduce the model quality and make realistic conclusions difficult. For this reason, it is necessary to filter the parameters in such a way that input correlations are avoided and physically meaningful models of high prognosis ability are generated. By filtering power, focus diameter as well as pulse and line distance, a metamodel could be created that explains roughness-related phenomena very well. However, since the design of experiments has been set up with precisely these parameters, only small COPs are achieved due to an asymmetric distribution of the experimental points. By contrast, high COPs occur by removing the calculated variables of fluence and pulse overlap. This model (Fig. 3) is of particular importance for the explanation of phenomena associated with the depth parameters. In order to investigate the processes leading to ultra-short pulse ablation of ceramics, both models have been considered, though. The essential findings are summarized in the following.

Optimization of roughness

In the majority of cases, the roughness rises if power (or fluence) and pulse overlap are increased. However, the metamodeling indicates that there exists an optimal pulse distance and therefore an optimal pulse overlap, for which the roughness can be reduced. Starting from this point, the roughness rises for both increasing and decreasing overlap.

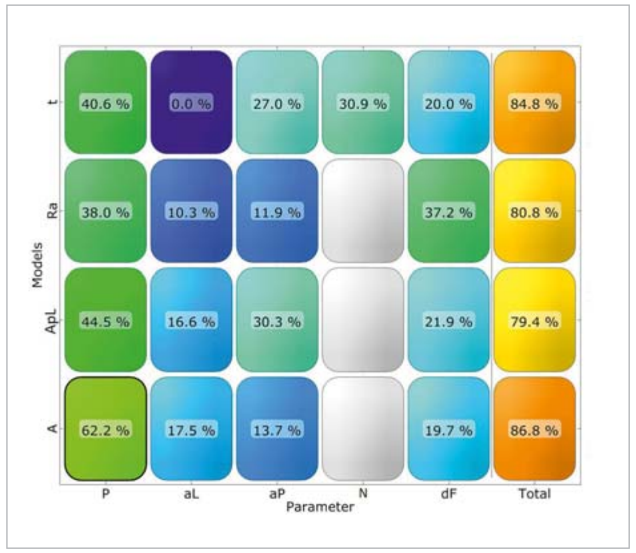

Fig. 3: COP-matrix of best meta-model

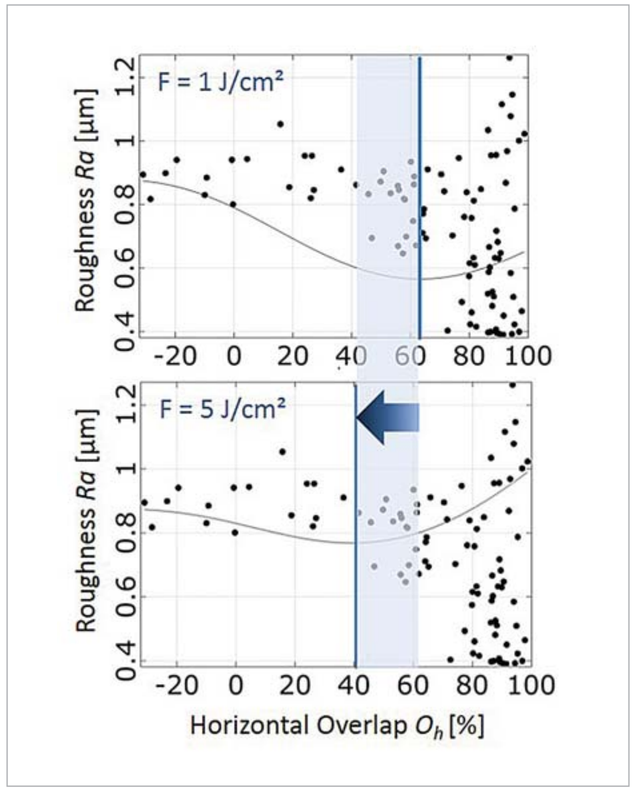

Fig. 4: Fluence dependent shifting of pulse overlap to minimize roughness

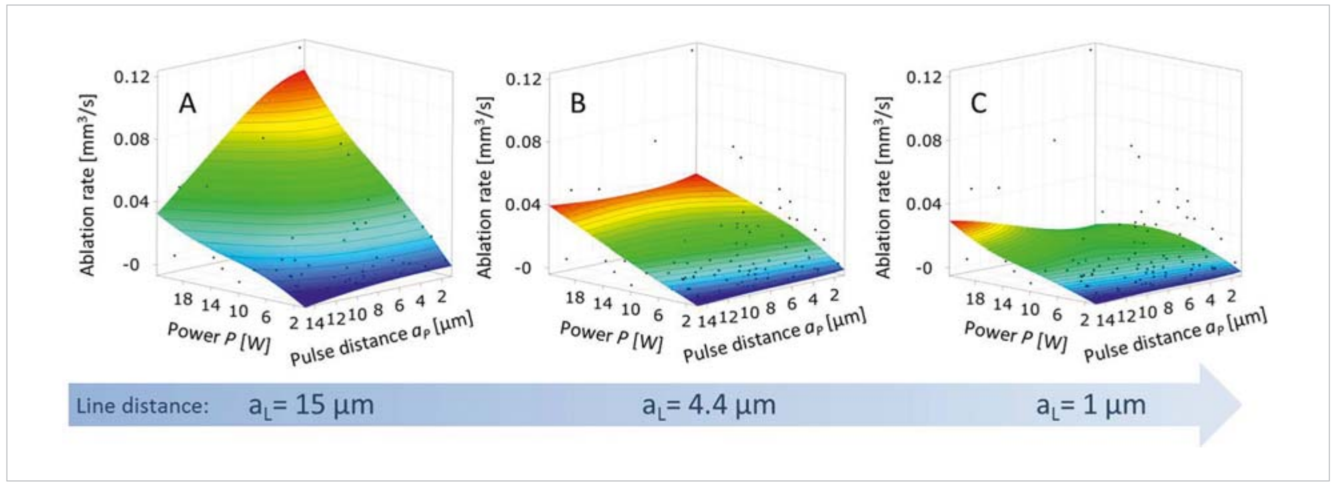

Fig. 5: Ablation rate in dependence of pulse distance and line distance

This optimum strongly depends on the energy density. As can be seen in Fig. 4, the pulse overlap leading to a minimal roughness shifts to smaller values if the fluence is increased. This observation can be explained by the fact that the effective ablation diameter increases with an increase of power which leads to a larger effective overlap. As a result, good surface qualities are achievable even for high fluences, just by adapting the pulse distance.

Optimization of ablation rate

The depth-related output parameters mainly depend on the average laser power. Fig. 5 shows that the ablation rate rises steadily with an increase of power. In addition, the pulse distance as well as the line distance have a decisive influence on the effectiveness of the material removal. The response-surface-diagrams reveal that the functional relation between ablation rate and pulse distance significantly changes through a variation of the line distance.

In the case of large line distances (Fig. 5A), the removal rate increases with decreasing pulse distance. This is due to the increasing pulse overlap, which generates higher ablation depths. The high influence of the pulse distance on the ablation depth can also be seen in the COP matrix (Fig. 3). In addition to the ablation depth, the ablation rate is also determined by the processing speed. Since small pulse distances are generated by the use of low scanning speeds, they generally have a negative effect on the removal rate. However, the steady increase of the ablation rate with decreasing pulse distance shows that this effect only plays a subordinate role.

On the other hand, regarding small line distances (Fig. 5C), a completely different functional interrelationship between ablation rate and pulse distance can be observed. Especially at high power, the removal rate now rises with increasing pulse distance, i.e. with decreasing pulse overlap. This seems to contradict the previous observations, but can be justified by the high influence of the line distance on the ablation rate. It has a considerably higher impact on the process efficiency than the scanning speed. Decreasing line distances, as well as small pulse distances, generates higher pulse overlaps and thus leads to an increase of the removal depth. However, small line distances also mean that the area to be processed has to be filled with more scanning lines. Due to the many jumping and marking vectors to be executed, the processing time increases significantly. For this reason, the ablation rate generally decreases with decreasing line distance. The loss of time at small line distances is so crucial that the scanning speed gains in importance. High marking speeds and resulting high pulse distances can now lead to an increase of the ablation rate.

In between exists a line distance for which the opposing influences of the pulse distance on the ablation depth and the processing time compensate for each other so that an independence of the removal rate from the pulse distance can be detected (Fig. 5B).

Optimization of ablation depth

In addition to the surface quality described by the roughness and the process efficiency described by the ablation rate, it also makes sense to take a closer look at the parameter dependencies for the actual material removal indicated by the ablation depth and the ablation per layer. According to the COP matrix, the number of layers is the second most important influencing factor for the ablation depth, only surpassed by the laser power. This is easy to understand and just what was to be expected. Much more interesting is the fact that the number of layers has no influence on the remaining responses at all. This indicates that the ablation process continues constantly into depth. Each layer can be processed under the same conditions, irrespective of the number of layers which have already been removed. Such a behavior is a prerequisite for the three-dimensional structuring of the material with high shape accuracy. As a result, a high agreement of calculated target contours with processed actual contours can be ensured.

Summary and Discussion

Within the scope of the investigations, it was shown that optiSLang can be used to create reliable and physically meaningful metamodels based on experimental data. These can be used for the identification and analysis of complex laser processes as well as for their optimization. It should be noted, however, that the models must always be thoroughly examined regarding their validity. In particular, a filtering of input parameters has to be executed in order to avoid input correlations and to obtain well-founded models. Moreover, the collection of experimental data always requires a special degree of carefulness since both the adjustment of the input parameters and the recording of the responses are subject to process and measurement fluctuations.

Especially in the context of investigating the beam-material-interactions and the ablation process of alumina with the aid of optiSLang, useful new insights into the ultra-short pulse laser ablation of technical ceramics could be gained. The results concerning the surface quality show that it is possible to achieve acceptable roughness values even at high laser powers by optimizing the pulse overlap. These are sufficient for at least most possible applications. In this case, the general rule of laser materials processing that quality and quantity cannot be reconciled. It can at least be somewhat softened. Regarding the efficiency of the process, it could be shown that it makes sense to consider pulse distance and line distance separately in order to generate the highest possible ablation rates. This contradicts the so far existing strategy of always equating pulse distance and line distance in favor of a homogeneous energy distribution.

All in all, it can be summarized that, in addition to the parameter optimization, optiSLang can be used to gain significant new insights into physical processes. For this reason, further experiments regarding the ultra-short pulse ablation of technical ceramics will be carried out. Due to the technical characteristics of the machinery such as the availability of varying power ranges for different wavelengths, an asymmetrical design space has been used thus far. This allowed the involvement of a broad value range, but has shown a negative effect on the model quality, characterized by reduced COP values. For further investigations, the experimental design has to be changed to validate the collected findings and to increase the model quality. Including further technical ceramics, the influence of the material shall be examined in order to gain an even better understanding of ultra-short laser processes.

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