Thermal imaging of high power ultrashort pulse laser ablation of alumina towards temperature optimized micro machining strategies

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Abstract. The application of pulsed laser systems with pulse durations in the pico- and femtosecond regime for material processing is commonly associated with a cold ablation. Due to the minimized interaction-time between the ultrashort laser pulses and the material, this statement is almost valid as long as no heat accumulation effect appears. With the increasing demand of high productivity processes, the average power of ultrashort pulsed laser systems increases above 100 W, which leads, however, to increased thermal effects during laser processing. This is especially important for laser processing of technical ceramics like alumina. Large temperatures gradients, which locally occur during laser processing using high average power could lead to thermal modifications and cracks in the material. In this study, we present a process-optimization method for high power laser ablation of alumina based on thermal imaging. The use of a 2D IR camera enables the estimation of the temperature distribution during the laser processing. We investigate the influence of laser power up to 80 W, pulse duration between 900 fs and 10 ps and processing duration on the resulting material temperature. Beside the material temperature we evaluate the material removal rate and the resulting surface quality.

1. Introduction
Nowadays technical ceramic materials are an essential building block in different important fields of modern products. Materials like alumina (Al₂O₃), zirconia (ZrO₂) or alumina nitride (AlN) provide outstanding mechanical, thermal, electrical and chemical properties for high technical demands [1; 2]. The probably most well-known oxide ceramic material is alumina and it combines very good electrical insulation (10⁻ⁱ⁴ – 10⁻¹⁶ Ohm m), high mechanical strength (< 600 MPa), high corrosion and wear resistance, a low density (< 4 g/cm³) and operating temperatures above 1000°C [3]. These features enable the application as substrates and heat sink for power electronics e.g. for engine control unit or charging unit for e-mobility, or heavy duty forming tools and wear protection. However, the processing of this brittle material is a challenge for conventional manufacturing processes like milling or Electrical Discharge Machining (EDM) [4; 5]. Limiting factors for a suitable production technology are the material removal rate and quality factors like cracking and the resulting surface roughness.

The application of laser irradiation for ceramic processing enables versatile material processing approaches without mechanical induced stress of the material. For ceramics processing, CO₂ lasers are primarily used for processes such as cutting, drilling and perforation [6; 7], For micro structuring, however, Q-switched solid state [8; 9] and Excimer-lasers [10; 11] have been applied. While Excimer-
laser processing is linked to small ablation rates, the application of solid state lasers in the nanosecond regime enables moderate ablation rates of 1.5 mm³/min using 20 W average laser power [12]. However, micro structuring using pulse durations in the nanosecond regime still introduces a high thermal load leading to melting effects which can cause micro cracks and stress break [8; 11; 13].

To overcome this thermal induced damages generated by the processing technology, the application of laser systems having ultrashort pulses is highly interesting [14–16]. By the reduction of energy-material interaction time using picosecond and femtosecond pulse durations, the thermal penetration depth of the individual laser pulse decreases and enables a so called “cold processing”. However, with increasing pulse energy and pulse repetition rate, heat effects, e.g. by heat accumulation, cannot be avoided and lead to heating of the processed specimen. The heat accumulation is either a result of subsequent laser pulses by the pulse repetition rate or by a successive laser path during layer-wise processing. With upcoming high power industrial grade pico- and femtosecond lasers, there is a growing demand for machining strategies to deploy high average laser power and to overcome the limiting factors of the material removal rate while maintaining high quality surfaces and temperature minimized processes.

Typically, process parameter optimization is based on the resulting ablation characteristics, e.g. optimizing the material removal rate and/or the surface quality. Beyond this, in this study we focus on the thermal stress, which is introduced by the laser micromachining of Al₂O₃. Therefore the temperature of the processing region is analysed during laser micromachining and the effect of the resulting temperature as a function of the applied laser parameters is investigated. Information about the thermal load can either be gathered by a calorimetric investigation [17] or by the emission of thermal radiation using a pyrometer [18; 19] or a thermographic camera [20; 21]. The benefit of a thermographic camera is the possibility of a spatially resolved determination of the surface temperature and therefore a simultaneous measurement at different location on the processed specimen.

In this study we use a 2D-thermographic camera to evaluate the surface temperature as a function of the applied laser power up to 80 W, a pulse duration between 900 fs and 10 ps and the number of scans of a layer-wise processing, respectively. By a scanning electron microscope analysis we determine the effect of the accumulated temperature on the material in the direct vicinity of the processed area.

2. Experimental
In this study, alumina (Ceramtec) with a purity of 96%, specified grain size of 3 to 5 μm and an initial substrate thickness of 1 mm is used for laser ablation experiments. The initial surface roughness is Ra 1.5 μm, as measured using laser scanning microscope (Keyence VH-X).

For laser surface processing, we use a micro-machining station (WSMH, Optec) equipped with a high power ultrashort pulsed laser (Amphos 200) having a variable pulse duration between 900 fs and 10 ps (FWHM) and a repetition rate of up to 40 MHz. The maximum average power is 200 W with a maximum pulse energy of 1 mJ. For the presented ablation studies, the fundamental emission wavelength of 1030 nm is used. Figure 1 shows the experimental setup for the surface treatment.

The energy of the laser is adjusted by an external attenuator based on a rotating wave plate and a polarizer. Using an adjustable beam expander telescope, the raw beam diameter is adjusted to a diameter of 5.5 mm (1/e²). A galvo scanner (Excelliscan 14, Scanlab) is used in combination with a telecentric lens (f = 163 mm) to focus the beam onto the sample with a spot diameter of 50 μm (1/e²). All given values of the pulse energy and the resulting laser fluence are derived by the laser power measured directly behind the processing optic. The pitch p between two consequent pulses is chosen to be 10 μm, i.e. 80% spatial overlap, for both, scanning direction and perpendicular thereto. Using a pulse repetition rate of 200 kHz for all shown experiments, the corresponding scanning speeds is 2020 mm/s.

The temperature profile of the Al₂O₃ substrate during the laser processing is captured using a thermal imaging camera (TIM-640-VGA, Micro Epsilon) with a measuring range of -20°C to 900°C and a frame rate of 32 Hz. The optical configuration of the temperature camera enables a spatial resolution of 100 μm x 100 μm per pixel with a total image size of 640 x 480 pixel. To avoid undesired IR reflection on the surface and to optimize the radiation of the thermal emission, we apply a thin layer of a black
paint on the Al₂O₃ substrate. A single layer ablation test performed on the substrate with and without the thin coating reveals, that within the observed parameter range the coating does not influence the ablation behaviour of the Al₂O₃, yet ensures an emissivity between 0.9 and 0.95.

![Experimental setup for thermal imaging during laser ablation of Al₂O₃.](image)

To evaluate the ablation characteristics, square cavities with an edge length of 2 mm are ablated using multifarious laser and processing strategy parameters. The measurement of the resulted cavity depth d is performed using an optical 3D profilometer (VR 3200, Keyence). For a detailed visual inspection of the cavity surface we apply a 15 nm thin gold layer on the material and use a scanning electron microscope (SEM, MAIA3, TESCAN).

The ablation efficiency AE (ablated volume per time and power) is calculated by the following equation with d being the depth d of the ablated cavities, p the pitch, n the number of ablated layers, f_R the repetition rate of the laser and P the average power of the laser [22], respectively.

\[
AE = \frac{d \cdot p^2 \cdot f_R}{n \cdot P}
\]

3. Results

3.1. Evaluation of the region of interest

In a first step of our study, we define areas of interest for a substantial analysis of thermal load and select calculation approaches towards representative statements for the thermal load of the processed area. Therefore, we define several areas and calculation approaches of temperature data selection. Figure 2a shows a schematic illustration of the evaluated regions. In general, two different categories are used, areas including the ablation area and measuring sites excluding the ablation area (heat affected zone, HAZ). The top edge of the HAZ measure area is 200 µm apart of the scan path, i.e. the distance between the ablation area and the measure area HAZ is 200 µm, to avoid an interaction of the scan path for both, HAZ small and HAZ large. Beside the choice the region of interest (ROI), the calculation method has to be defined. In this study we use either the Peak-mode, where the highest value inside the region of interest is used, or the Average-mode, where the unweighted mean value of all included pixel is calculated. Figure 2b shows the result of the temperature measurement for different ROI and calculation methods using an average laser power of 40 W, a pulse duration of 5 ps and 20 layers, leading to a total processing time of approximately 4 s, i.e. a processing time of 0.2 s per layer.
The comparison of the different temperate courses in figure 2b reveals a strong influence of the ROI and the calculation method. However, all measuring data show, by trend, an increasing temperature with time, reflecting the heating of the entire region. The temperatures within the ablation area (Avg ablation, Peak ablation, Avg centre-point and Avg centre-stripe) are approximately twice as high as the values in the conjunct heat affected zone (Avg HAZ large and Avg HAZ small). In detail, the temporal curves of the confined center areas point and stripe exhibit a strong modulation. This reflects the heating and cooling phase during ablation of a layer. The frame rate of the camera enables approximately 6 measuring values within this duty cycle and makes it possible to detect the thermal irradiation within the ablation area without the overlaid laser scan path. The excessive first peak of the temporal curves within the ablation area leads to the assumption that the emissivity changes after the ablation of the first layer, i.e. the removal of the black coating. The uncovered pure Al$_2$O$_3$ has an emissivity below 0.7 [10], which explains the temperature drop approximately of a third from the first to the second layer.

In the area of the HAZ, the black coating is unimpaired for all investigated parameters, therefore the emissivity in this region is assumed as being unaffected. The temporal curves of the HAZ show a smooth increase without a temperature modulation. The heat capacity and the inertial heat transfer lead to a homogenous temperature increase even in the direct vicinity of the ablation area (HAZ-small) 200 µm apart of the ablation area. Hence, we choose the average value of the HAZ-small area for further depiction of the temperature values. This value is a suitable indicator for the thermal load generated by the laser micromachining to the surrounding material.

3.2. Influence of laser power and pulse duration

Based on these findings, we evaluate the temperature of the HAZ-small area as a function for different laser processing parameters. Again, the temporal curves in Figure 3a–3c represent the layerwise ablation with a total amount of 20 scans. We applied three different laser powers to represent a fine, intermediate and rough processing, defined by the ablated depth per layer. Using a spatial pulse overlap of 80%, a laser power of 8 W, 40 W and 80 W lead to an ablated depth per layer in the region of 5 µm, 25 µm and 50 µm, respectively. The exact achieved ablation depth per layer, which is influenced by the applied laser pulse duration, was measured and later considered for the calculation of the ablation efficiency (c.f. Figure 3d).
Figure 3. Temperature measurement of HAZ-small for 900 fs, 5 ps and 10 ps using a laser power of (a) 8 W, (b) 40 W and (c) 80 W with the resulting values of the ablation efficiency (d).

Based on the common presumptions of pulsed laser material processing, shorter pulses lead to less material heating. However, the temperature measurements reveal, that a decrease of the laser pulse duration leads, quite the contrary, to higher temperatures in the HAZ. This behaviour is valid for all investigated laser powers and also for all analysed measuring areas. Within the considered parameter range, the temperature of the heat affected zone is approximately 20% higher using 900 fs compared to 5 ps and 10 ps at the end of the ablation test. For laser processing using 8 W and 40 W average laser power, the decreased thermal load of the substrate is also associated with an increased ablation efficiency. Especially for 8 W, the ablation efficiency for 5 ps and 10 ps is more than 2.5-times higher as compared to 900 fs, which implies a distinct higher ratio of ablation converted energy of the laser process. While the ablation efficiency of 5 ps and 10 ps processing decreases with increasing laser power, i.e. increasing laser pulse energy, the ablation efficiency using 900 fs increases with increasing laser power. The ceramic processing with 80 W reveals that the efficiency using 900 fs is slightly higher as compared to the picosecond regime. However, the higher efficiency does not reflect in a lowered temperature increase. During laser processing, several thermal processes can be responsible for the measured temperature rise. On the one hand, the absorbed laser energy cannot be fully converted for the ablation process and leads to material heating. On the other hand, the generated plasma plume emits thermal radiation that is capable to increase the substrate temperature. In addition, the optical behaviour like the reflectivity and optical penetration depth changes with altering pulse duration and laser fluence.
[23]. The complex interaction of the laser parameters leading to the measured heating effects are beyond the scope of this paper and has to be studied in further research. The high efficiency at 80 W average laser powers shows that Al₂O₃ is well suitable for high power laser ablation processes using ultrashort laser pulses. The application of 80 W laser power can be implemented in an ablation rate of approximately 45 mm³/min with a comparable small surface roughness of 2.5 µm (Ra).

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The SEM analysis of the surrounding material does neither reveal any surface modification nor visible micro cracks, in accordance to the comparative low temperature observed. However, according to Figure 2b, the temperature in the ablation area is significant higher during the laser process and therefore requires a separate consideration. The in-depth modification of the Al₂O₃ material is analysed by a cross section of a fabricated cavity. Therefore a cavity is ablated using a laser power of 75 W, a pulse duration of 10 ps, a pulse repetition rate of 200 kHz, an overlap of 80% and with 7 passes. Figure 4 shows the 65° tilted overview and the detailed SEM image of this cross section. The melting effect is clearly limited to the surface and no visible in-depth modification is generated by the laser ablation process. The unimpaired grain structure of the Al₂O₃ is directly under the molten surface, which is less than 0.5 µm thick. The inspection of the cross section also reveals, that the high power laser processing using ultrashort laser pulses produces no cracks or other visual defects to the underlying material.

![Figure 4. SEM analysis of the material cross section (65° tilt) revealing no noteworthy in-depth material modification of the initial grain structure.](image)

3.3. Temperature depending ablation
A further investigation is performed to reveal the influence of the substrate temperature onto the ablation depth. Therefore we use an average power of 80 W and a pulse duration of 10 ps for cavity ablation with successive increment of the number of scans from n=1 to 11. Figure 5a shows the temperature curves for this layer-wise ablation.
The measured temperature increment of approximately 10°C per layer is almost constant over the observed test duration. The corresponding evolution of the cavity depth is shown in Figure 5b, with increasing number of scans, the depth increases with a mean slope of 52µm per layer. The detailed analysis of the depth increment reveals a small increased depth by approximately 2 µm per layer, i.e. per 10°C. For a precise depth ablation towards a desired ablation depth this temperature depending layer depth has to be considered especially for a high number of scans.

4. Conclusion
This paper shows the possibility of high power laser micromachining of Al₂O₃ using ultrashort laser pulses with simultaneously low thermal loads of the processed material. A thermal imaging camera was used to evaluate the appearing temperature during the laser process. By the analysis of the heat affected zone in the direct vicinity of the ablation area, a maximum temperature of 220°C can be measured. The comparison of three different structuring regimes for fine (8 W), intermediate (40 W) and rough (80 W) processing reveals, that a pulse duration of 900 fs lead to higher temperatures than the application of 5 ps and 10 ps. The observed unintuitive effect of increased heating with smaller pulse duration needs further investigations to reveal the underlying heating process. High ablation rates of up to 45 mm³/min does not lead to critical temperatures and therefore does not generate structural defects or micro cracks. Overall, it turn out that the thermographic camera is suitable for online monitoring of laser processing and helps to identify critical process parameters towards a temperature optimizes laser processing.

Acknowledgments
This work has been supported within the DFG project ultrashort pulsed lasers (grant 671/39-1).

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